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WATER IN THE COAL MINING INDUSTRY

An assessment of water management issues facing the coal mining industry of the Witbank and Middelburg Dam catchments

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ABSTRACT

The coal mining and power generating industries of the Witbank and Middelburg Dam catchments in South Africa's Mpumalanga Province have received much criticism for their apparent apathy regarding water quality in the area. Although a number of previous studies have proved that several of the coal mines and power stations are directly responsible for point and diffuse discharges of acid leachate into the local water bodies, the limited case study conducted for the purpose of this thesis did not produce results that can be used to effectively describe a situation that gives cause for concern. The results do however display a number of trends:

- Coal 'grab' samples are likely to produce the most acid leachate
- Coal product samples are most likely to generate more alkaline leachate
- GIS maps are a commendable method of correlating a range of information contained in a number of databases and provide a user-friendly, interactive means to access a wide range of data at once

In order to meet the water quality management objectives of the catchment management forums, it will be necessary for all coal mines and power generation facilities in the area to come together and develop the most suitable water management programme to ensure that acid mine drainage does not render the regional water resources unfit for any use.

It is also important to be aware that the new National Water Act and associated environmental and mining laws discussed in this thesis are comparable with the highest standards internationally. At the same time, one must always include the factor of human well-being in the scope of the definition of the environment so as to ensure that opportunity is provided for the greatest benefit to be awarded to all components of both the natural and built environments.

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"He who aims for the moon,
May hit the top of the tree;
But he who aims for the tree,
May never get off the ground."

Chapter 1

INTRODUCTION

Any ore-body or rock (such as coal), which contains sulphide minerals, especially pyrite, has the potential to cause acid effluent as a result of oxidation. Acid Rock Drainage (ARD) is the result of the natural oxidation of sulphide minerals within a rock, as a result of weathering, whereas Acid Mine Drainage (AMD) is the result of mining and the associated mineral crushing activities (Steffen, Robertson and Kirsten, 1989). The acid mine drainage can be generated underground by the exposure of *in situ* material, or broken material i.e. ore, coal or backfill, to air and water; or on surface in waste rock dumps i.e. piles of coarse discard resulting from the beneficiation of coarse material, or tailings dams from the beneficiation of milled i.e. fine material. If improperly contained, contaminants in mine waste can leach out into surface and groundwater causing serious pollution problems that can last for many generations.

This study is a contribution to the Coaltech Project, which is concerned with the collection, treatment and utilisation of water on coal mines in the Witbank and Middelburg Dam Catchment areas (Figure 1). The Coaltech Project is a collaboration between research institutes, government and the South African coal mining industry. The aim is to develop solutions to a number of wide-ranging problems affecting the coal mining industry and the environment.

The objectives of this thesis were as follows:

1. To provide a reliable summary of extensively researched text relating to historical, international and South African perspectives on the problem of acid mine drainage.
2. To describe the chemistry of acid mine drainage in terms that environmental scientists from a wide variety of backgrounds could understand.

3. To perform a series of tests on selected samples taken from a pertinent study area, to indicate simply how the potential to generate acid mine drainage can be identified. Then to discuss the results of these tests in the context of the environment of the study area.
4. To highlight the importance of coal as an energy source and an economic commodity, including discussion regarding methods of recovery.
5. To highlight the importance of water as a national resource and discuss methods of testing for contamination related to acid mine drainage.
6. To develop an original Geographical Information System to enable water quality and coal characterisation data, contained in a series of vast databases, to be accessible and meaningfully presented to the environmental scientist.
7. To present a wide range of prevention, prediction, management and treatment options. Then to develop an original management design process. Then to discuss suitable management options for the study area, based on this investigation and others.

Many of South Africa's current AMD problems can be attributed to mining activities from the period before 1956. During this time there was little or no enforcement of the weak legislature passed for protecting water bodies from the potential pollution caused by coal mining. Four times more coal and discard have been generated since then.

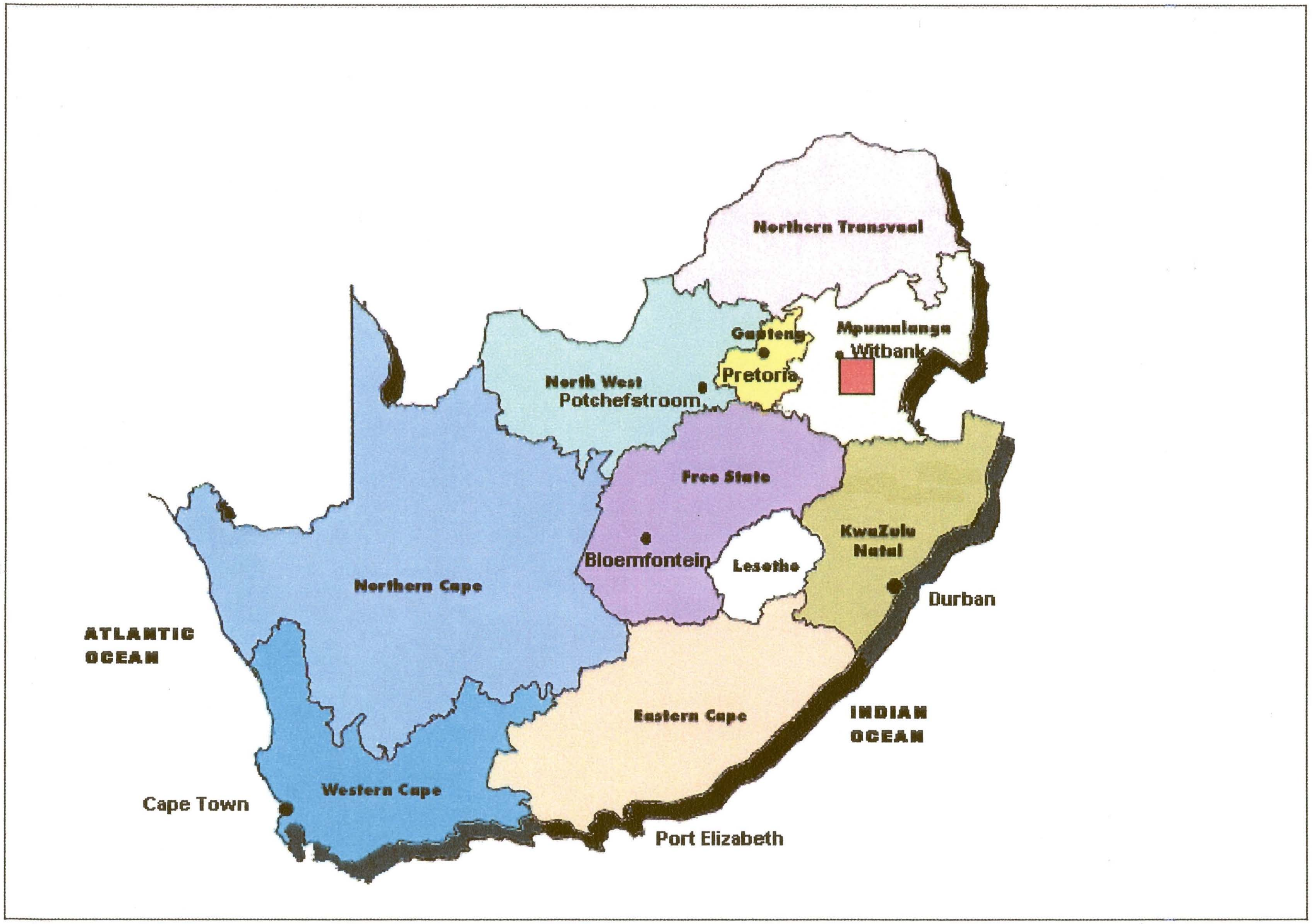


Figure 1: Location of study area

In conjunction with the unfavourable location of coal reserves in relation to important water resources, the projected future expansion in mining activity is cause for concern. The receiving water quality objectives (RWQO) approach to water quality management and associated water quality related studies will be a rational way of defining goals and standards for the mining industry. Serious doubts have been raised as to whether the necessary expertise, techniques and funding are available in the country to meet these objectives. The Department of Water Affairs and Forestry (DWAF) intends to give far more attention to water quality management in the mining industry than it did in the past and will do this in close co-operation with the mining sector through the Chamber of Mines.

Polluted mine water, estimated at a present flow rate of 18,25 million m^3/a is currently discharged in the Upper Olifants River catchment to public streams. It is expected that this volume will increase to 26,1 million m^3/a by 2020. The mine water is acidic in certain locations and generally contains high sulphate concentrations. Should this water be collected and treated to a quality where it can be re-used, it will offer a number of benefits. In addition, the area will also benefit from increased knowledge regarding the acid-generating potential of the coal and coal discard exposed here, so that the rate and quantity of acid generation in affected waters can be predicted and potential mitigation technologies can be designed (Wates, 1987).

It is hoped that knowledge gained through this project will motivate the extension of the study area and intensify the work needed to develop a water management strategy that is nationally applicable.

Chapter 2

HISTORICAL BACKGROUND & RELATED RESEARCH

2.1 Historical perspective

In countries such as Norway, which have been major mineral producers in the industrialised world for over 300 years, Acid Mine Drainage (AMD) has occurred extensively, continuously and in close association with human habitation for centuries. It has been said that the effect of AMD on human life is limited, but the impact on the aquatic environment can be very large indeed. However, when one considers its part in the degradation of the total environment and the price that man will ultimately have to pay, a very different scenario is envisaged. The coal mining industry in the United States of America (USA) has for decades been identified as a source of AMD. This is certainly the case in the Appalachian States in eastern USA. The environmental impacts in this and other coal-producing states in the early years of development were negligible. Consequently, during this early period there was assumed to be no need for either AMD prevention or wastewater treatment. Recently the scale of mining in the Appalachian region has increased dramatically and the assimilative capacity of the environment has been far exceeded (Bhole, 1994).

It is interesting to note that developments to counter the adverse environmental impacts of mining operations have received far less attention than those designed to employ sophisticated water control techniques (Van der Merwe, 1990). This is surely because numerous studies have shown that water pollution is the most serious environmental problem associated with mining.

2.2 International perspective

Coal has been used and traded internationally, as an energy source, since the days of the Roman Empire. Currently, approximately 36% of the world's electricity is produced from coal. It is forecast that coal will regain its status as major primary energy source in the first half of the 21st Century. (This position is presently held by oil). Current coal reserve / production ratios confirm more than 200 years of resource availability. The importance of alternative energy sources, for example nuclear power, cannot be ignored. However, these alternatives do not yet guarantee a trouble-free, long-term and economical source of energy. Water, wind, solar energy, biomass, wave and tidal sources provide alternative sources of power generation. They will not offer meaningful energy supplies for decades to come, in terms of economic viability and environmental acceptability (Durkin and Herrmann, 1996).

The demand for energy is closely related to economic growth and a rise in standards of living. In the developing world, the supply of electricity has been a representation of a rise in living standards. Developing economies are thus consuming electricity at a rapidly expanding rate. This rate is only expected to increase into the next century, therefore it is vital that coal is used with increasing efficiency in order to conserve this valuable resource (Fletcher, 1994).

International trade in thermal coal has increased by approximately 7% each year since 1970. It is forecast that international trade will continue to increase at this rate. Of the total 505 million tonnes of hard coal traded internationally in 1997, 60% was thermal coal and about 40% coking coal (Steffen, Robertson and Kirsten, 1992).

The World Coal Institute (WCI) is a non-profit, non-governmental association of coal producers and coal consumers. The WCI is the only international body working on a global basis on behalf of the coal industry. The chief objectives of the WCI are to:

- Provide a voice for the international coal industry community in debates on energy and the environment.

- Improve public awareness of the merits and importance of coal as the single largest fuel for the generation of electricity.
- Inform decision-makers on the advances in Clean Coal Technologies.
- Widen understanding of the vital role that metallurgical coal fulfils in the steel industry.
- Support other sectors of the world-wide coal industry in emphasising the importance of coal and its qualities as a plentiful, clean, safe and economical energy source.
- Promote the merits of coal and upgrade its image as a clean, efficient fuel, essential to both the generation of the world's electricity and the manufacture of the world's steel (Fletcher, 1994).

In British Columbia, mining history is relatively short compared with countries such as Norway and the USA. However, Acid Mine Drainage (AMD) has caused significant environmental impacts at a number of mine sites and is the single most threatening environmental impact from mining in British Columbia. Until recently, the potential for a new mine to generate AMD was often not adequately anticipated during the planning stages. Thus, very costly treatment or rehabilitation measures have had to be implemented, at a later stage in the life of the mine, after severe environmental damage has already taken place (Fletcher, 1994).

Considerable work has been carried out in Sweden on cover design technology that could also be applied to conditions in British Columbia.

Coal mining wastes in Eastern Canada are a major source of AMD, as they are in the USA. Much work has been conducted within the coal mining industry of the USA. Guidelines for acid mine drainage control, aimed primarily at surface mine operators in the Appalachian coal region have recently been published (Fletcher, 1994).

A prerequisite of sustainable development must be to ensure uncontaminated streams, rivers, lakes and oceans. In Canada, the law and technology used to protect these vital resources are far from adequate. Water has been called "mining's most common casualty". Mining, by its nature, consumes, diverts and can seriously pollute water. These impacts depend on a variety of factors including the sensitivity of the terrain, the composition of minerals being mined, the type of technology employed, the skill, knowledge and environmental commitment of the mining company and our ability to monitor and enforce compliance with environmental legislation (Tilton, 1994).

2.3 South African perspective

South Africa has more than 70% of the known African coal reserves. South Africa ranks fifth in the world in terms of recoverable hard coal and coal production (Table 1) and third in terms of coal export.

Table 1: World recoverable hard coal reserves 1996 (after Prévost 1996)

COUNTRY	GROSSE TONNAGE	% WORLD RESERVE	RANK
USA	106.5	20.5	1
CIS	104.0	20.0	2
India	68.0	13.1	3
China	62.2	12.0	4
South Africa	55.3	10.6	5
Australia	45.3	8.7	6
Poland	29.1	5.6	7
Germany	24.0	4.6	8
Canada	4.5	0.9	9
Colombia	4.2	0.8	10
United Kingdom	2.0	0.4	11
Indonesia	1.0	0.2	12
Venezuela	0.4	0.1	13
Other	12.7	2.7	-
TOTAL	519.2	100	-

In 1996, coal was by far the most used energy source available in South Africa (Figure 2)

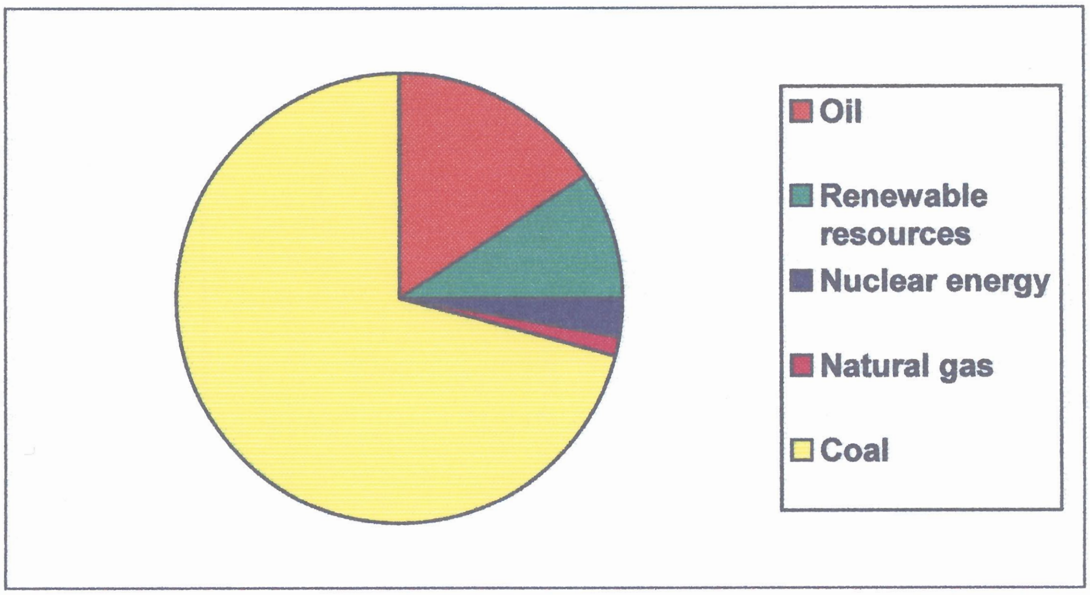


Figure 2: Energy sources in the South African economy in 1996 (Snyman, 1998)

In 1995, the major percentage of coal produced in South Africa was used for the generation of electricity (Table 2).

Table 2: Coal consumption in the domestic market in 1995 (Snyman, 1998)

Uses	Consumption	
	Mt	%
Electricity generation	82.6	56.2
Industry and petrochemicals	49.7	33.8
Metallurgical processes	7.3	5.0
Small consumers	7.3	5.0

Coal mining has played a major role in the economic development of South Africa. Any estimate on the total lifespan of South Africa's coal reserves can be nothing more than an educated guess, as it depends on a set of interdependent and highly unpredictable geological, technological, economic and political factors. South African coal sales over the last century represent less than 6% of the estimated saleable reserves.

Many of South Africa's current acid mine drainage problems originated before the Water Act of 1956, when mines were abandoned without water pollution control measures. The Water Act was amended in 1984 and rewritten more recently in 1998. As a result of changing demands, the Department of Water Affairs and Forestry has shifted its emphasis from resource development to resource management. This shift in emphasis has been accompanied by a greater awareness of water quality and how it should be managed properly (Van der Merwe, 1990).

Due to the socio-economic state of South Africa, there is a great need to increase the pace of development. Many people hold the view that the country cannot afford to spend much on conservation at a time when so many people are living in poverty. However, there is growing evidence that resource destruction from pollution and over-exploitation is now occurring on a scale that could endanger the process of development. Thus, even greater poverty could be suffered in the future. 'True economic development is the process of using resources to improve human well-being for this and succeeding generations through a careful balance of development and conservation. The supreme challenge of resource management is to make the right trade-offs between conservation needs and development needs' (Fuggle, and Rabie, 1983, 1992).

The South African mining industry consists of a large number of independent mines, recovering a number of distinct minerals, including coal. These mines cover a vast geographical area and as such they experience different water management problems in terms of both quantity and quality.

Chapter 3

ACID MINE DRAINAGE

3.1 An introduction to acid mine drainage

Iron pyrite, FeS_2, also known as 'fool's gold', is the most important source of nearly all water pollution originating from mines and their residue deposits. When pyrite is exposed to air and water, it oxidises to form sulphuric acid and iron oxides and hydroxides ('yellow boy'), which causes the pH of the resultant leachate to drop to about 4. This oxidation reaction is accelerated and extended by bacteria. The most important of these bacteria is *Thiobacillus ferrooxidans*. This causes the pH of the solution to drop to as low as 1.5. The acid that is produced reacts with bases in the country rock or residue deposit to form salts and to mobilise heavy metals that may be contained in the rock or residue. During this reaction, the acidity is often neutralised. The resultant drainage contains elevated levels of salts (primarily calcium and magnesium sulphates) and metals (mainly iron). According to Sullivan and Yelton (1988) the greatest contribution to acid mine drainage (AMD) can be ascribed to residue deposits and spoil heaps. The longer water is in contact with the pyrite, the more chance the oxidation reaction has of proceeding and the more chance bacteria have of speeding it up and producing more acid. Coal discard (with exposed pyrite due to processing the coal) and old workings (due to long time exposure) produce the highest concentration of AMD (Fuggle and Rabie, 1992).

Depending on the bulk composition, an acid-generating mine can become a 'perpetual pollution machine'. In the USA, AMD from abandoned mines has polluted 180 000 acres of reservoirs and lakes and 12 000 miles of streams and rivers. It is estimated that cleaning up these waterways will cost US taxpayers between \$32 billion and \$72 billion. Not only is AMD treatment and collection very costly to the environment, it is a big bill for industry. Site rehabilitation costs in the USA can be as high as $410 000 per hectare. The US Bureau of Mines estimates that the US industry spends over $1 million each day to treat acidic mine water. Once it starts, AMD can effectively sterilise an entire water system for generations to come – turning it into a biological wasteland and a huge economic burden (Salomons, 1995).

3.2 Sources of acid mine drainage

The sources of acid drainage from mining operations include:

- Drainage from underground workings
- Surface runoff from open pit mine faces and pit workings
- Waste rock dumps from metal mines and spoil piles from coal mines
- Tailings deposits
- Ore stockpiles and spent ore piles from heap-leach operations.

The acid drainage from underground workings generally occurs as point discharges of substantial flows of low pH water. Many of the earliest sources were drainage tunnels or mine adits.

The effects and consequences of acid drainage from open pit mines have become a concern far more recently. The large areas of exposed rock in open pits can result in large volumes of acid drainage. Long-term slope deterioration can result in a continual exposure of fresh rock to the natural elements and hence acid drainage generation.

Waste rock is generated by the excavation and construction operations undertaken to gain access to the ore being mined. These wastes are subsequently exposed to precipitation, runoff and possibly seepage. Rock wastes that contain sulphides are a large source of acid drainage. The quantities of rock waste from earlier underground mining operations were proportionately less than the more recent large open pit mining operations. Thus the potential for acid drainage generation is on the increase.

Spoil piles are wastes generated by coal strip mining in order to gain access to the coal deposit. Sulphur exists in three chemical forms in coal-bearing rocks: sulphides, sulphate and organic sulphur. Pyrite (FeS_2) is the most predominant acid-producing sulphur mineral present within coal and the overburden strata. Due to the extreme variability in the geochemical properties of overburden strata it is very difficult to predict the acid-generating potential of the eventual spoil piles.

The potential for acid generation in tailings has long been recognised. The concern is generally that acid drainage may develop after the mine has been abandoned, when the facilities are no longer in use or maintained.

The ability of a particular rock sample to generate net acidity is a function of the relative content of acid-generating and acid-consuming minerals. It is important to consider the scale of examination when investigating acid drainage. A rock, which generates pH-neutral conditions in water flowing over it, may have acid generation occurring in microenvironments around sulphide grains. The resulting acidic water may be neutralised by the remainder of the sample as it leaves that particular microenvironment. The time interval between initial disturbance of the rock and the peak rate of acid generation may range from days to years, depending on a number of environmental factors and the neutralisation potential of the rock. As a result, acid generation is not a simple process; rather, it is a complex set of chemical reactions changing through time (Pulles *et al*, 1996).

The problem of flooding of abandoned workings, either naturally or artificially, is that it causes widespread AMD. Water coming into contact with remnant coal pillars or an underground surface littered with coal from a collapsed roof or pillars may become rapidly acidified. This is the result of the presence of pyrite in the coal, which is readily oxidised in the presence of air. In addition, this acidification process may be accelerated by fluctuations in water level or heat from burning coal pillars in the vicinity. Where this water decants from the mine it is generally extremely acidic and rich in sulphates and metals. This water causes acidification and/or sterilisation of soil with which it interacts. Vegetation is also ultimately killed. Such acid mine water is characterised by its orange brown colour. Associated precipitates include 'melanterite' (a turquoise-coloured iron sulphate) and 'yellow boy' (a yellow ferric hydroxide).

Although discard dumps have been identified as a source of acid mine drainage, not all dumps produce acid water. This is probably related to the type of pyrite present i.e. fine, porous and granular pyrite vs. pyrite that is mostly compact and crystalline. Burnt dumps are also more likely to create acid water than those that have not burned owing to the presence of water soluble sulphates that are more amenable to leaching and oxidation (Viljoen, 1991).

3.3 Chemical and biological reactions related to acid generation

The primary ingredients for acid generation are:

- Sulphide minerals
- Water, or a humid atmosphere
- An oxidant, particularly oxygen from the atmosphere or from chemical sources

The first important reaction is the oxidation of the sulphide mineral, producing dissolved iron, sulphate and protons:

$$FeS_2 + 7/2\ O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

The dissolved products represent an increase in the total dissolved solids (TDS) and acidity of the water. If the surrounding environment is sufficiently oxidising, much of the ferrous iron will oxidise to ferric iron:

$$Fe^{2+} + \tfrac{1}{4} O_2 + H^+ \leftrightarrow Fe^{3+} + \tfrac{1}{2} H_2O$$

At pH values of 2.3 to 3.5, the ferric iron will precipitate as iron hydroxide, leaving little ferric iron in solution, while lowering pH at the same time:

$$Fe^{3+} + 3H_2O \leftrightarrow Fe(OH)_3 \text{ (solid)} + 3H^+$$

Any Fe^{3+} that does not precipitate from solution may be used to oxidise additional pyrite:

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

Acid generation may be represented by a combination of the above reactions:

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$$

The above reactions assume that the oxidised mineral is pyrite and that the oxidant is oxygen. It is important to note that other sulphide minerals have other ratios of metal:sulphur and other dissolved metals will be produced.

Following the oxidation of a sulphide mineral the resulting acid products may be flushed away from the sulphide mineral and eventually encounter an acid-consuming mineral. The most common acid-consuming mineral is calcite, which consumes acidity through the following reaction:

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-$$

and

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + H_2CO_3^0$$

(Pulles *et al*, 1996)

Ca^{2+} will combine with SO_4^{2-} to form $CaSO_4$, which is sparingly soluble and the carbonic acid will decompose by liberating carbon dioxide.

3.4 Rate of acid generation

The primary factors, which determine the rate of acid generation, are the following:

- A low pH (although the initial oxidation can take place under neutral conditions)
- Temperature
- Oxygen content of the gas phase
- Oxygen concentration in the water phase
- Degree of saturation with water
- Chemical activity of Fe^{3+}
- Surface area of exposed metal sulphide
- Chemical activation energy required to initiate acid generation
- Presence of certain bacteria that promote sulphur and/or iron oxidation e.g. *Thiobacillus ferrooxidans*

In certain instances where bacterial acceleration is significant, there are additional factors, which determine bacterial activity and the associated acid generation:

- Biological activation energy
- Population density of bacteria
- Rate of population growth, which depends on temperature, pH, the presence of nutrients e.g. nitrate concentration, potassium concentration, ammonia concentration, phosphorus concentration, carbon dioxide content and the concentrations of any bacterial inhibitors e.g. certain trace elements and certain fungi that consume bacterial nutrients.

3.5 Case studies

Gélinas et al (1992) conducted a study to monitor AMD in a waste rock dump. The findings of this study were as follows:

- There is a good relationship between mineralogical and textural properties of the different rock types and their relative AMD generation potential.
- Air convection is an important mechanism for oxygen supply.
- Mineralogical and chemical data should be used to describe the mechanisms of chemical leachate transformation within and outside of the dump.

According to Kwong (1992), natural attenuation in a small pond receiving acidic drainage near the Mount Washington Mine, Vancouver Island, is effected by dilution and bacterial sulphate reduction. In this case, reclamation activities have focussed on reducing the supply of oxygen and water to the acid-generating waste-rock dump. The natural acid and metal attenuation capacity of a series of wetlands downstream from the site should perhaps be developed and utilised.

Phinney (1992), argues that the present state of knowledge of the acid generation process allows proposed mine developments to be evaluated and planned with confidence. However, the reclamation of historical sites will remain an economically and technically difficult task.

3.6 Mine planning and acid generation

Considerations related to AMD arise during the later phases of exploration. Cores can be carefully examined by a mineralogist and samples taken for acid-base accounting. Samples of both sulphide- and non-sulphide- bearing rocks should be analysed. Elevated levels of sulphate in drill hole water, springs and seepages are an excellent indicator of acid-generating activity. The acid-generating history of the geological region is perhaps the most important indicator of potential for acid mine drainage (Prévost, 1996).

During the bulk sampling / test mining phase, acid-generating characteristics of the deposit may be confirmed. However, as acid generation develops over an extended time span, there are a number of instances where acid generation situations have not been predicted on the basis of bulk sampling (Robertson and Ferguson, 1995).

During the operation phase, if there is any potential for acid generation, the acid generation must be assumed to occur and the mine should be developed accordingly. The control of acid generation and an effective reclamation plan can be assured if the following guidelines are applied:

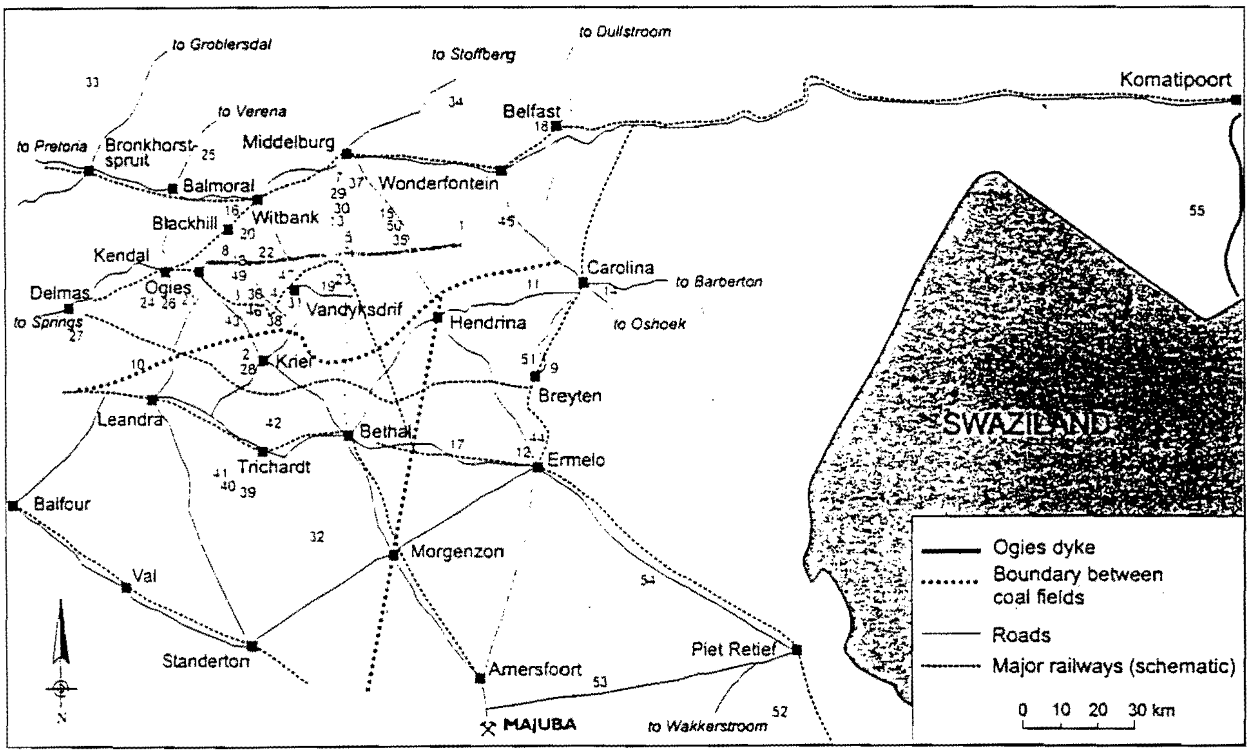
- The treatment system for acidic waters must be capable of being expanded in phases to meet increased chemical requirements and sludge generation.
- Waste rock removed during mining must be carefully separated and stored in accordance with its potential for acid generation.
- The reclamation method must be designed to minimise the rate at which atmospheric oxygen can be transported to the reactive sulphides.

(Robertson and Ferguson, 1995).

Chapter 4

THE STUDY AREA

The chosen study area includes a number of mines and power stations in the Witbank and Middelburg Dam Catchment areas, situated in South Africa's Mpumalanga Province. All the sites included in the study, as well as a number of other mines in the Witbank coal field, are indicated in Figure 3.



Collieries in Mpumalanga. 1. Anglo Power (Arnot), 2. Anglo Power (Kriel), 3. Arthur Taylor, 4. ATCOM, 5. Bank 2, 6. Bank 5, 7. Blackwattle, 8. Boschmans, 9. Bothasrust, 10. Delmas, 11. Dover, 12. Driehoek (Wesselton), 13. Duvha, 14. Eastside, 15. Eikeboom, 16. Elandsfontein, 17. Ermelo, 18. Glisa, 19. Goedehoop, 20. Greenside, 21. Khutala, 22. Kleinkopje, 23. Koornfontein, 24. Lakeside, 25. Landau (Kromdraai), 26. Leeuwfontein, 27. Leeuwpan, 28. Matla, 29. Mavela, 30. Middelburg, 31. New Clydesdale, 32. New Denmark, 33. Northfield, 34. Olifantslaagte. 35. Optimum, 36. Phoenix, 37. Polmaise, 38. Rietspruit, 39. Secunda: Bosjesspruit, 40. Secunda: Brandspruit, 41. Secunda: Middelbult, 42. Secunda: Syferfontein, 43. South Witbank, 44. Spitzkop, 45. Strathrae, 46. Tavistock, 47. Van Dyks Drift, 48. Waterpan, 49. Witbank Consolidated, 50. Woestalleen (Noodhulp Section), 51. Consbrey Dump, 52. Protea, 53. Mpisi, 54. TBS, 55. Nkomati Anthracite (after Smith and Whittaker 1986; Jordaan 1986; Schoeman and Boshoff 1996).

Figure 3: Collieries in Mpumalanga Province (Snyman, 1998)

4.1 Geology

Although there are a number of variations in the thickness of the formations in the regional geology, a general overview is given in Figure 4.

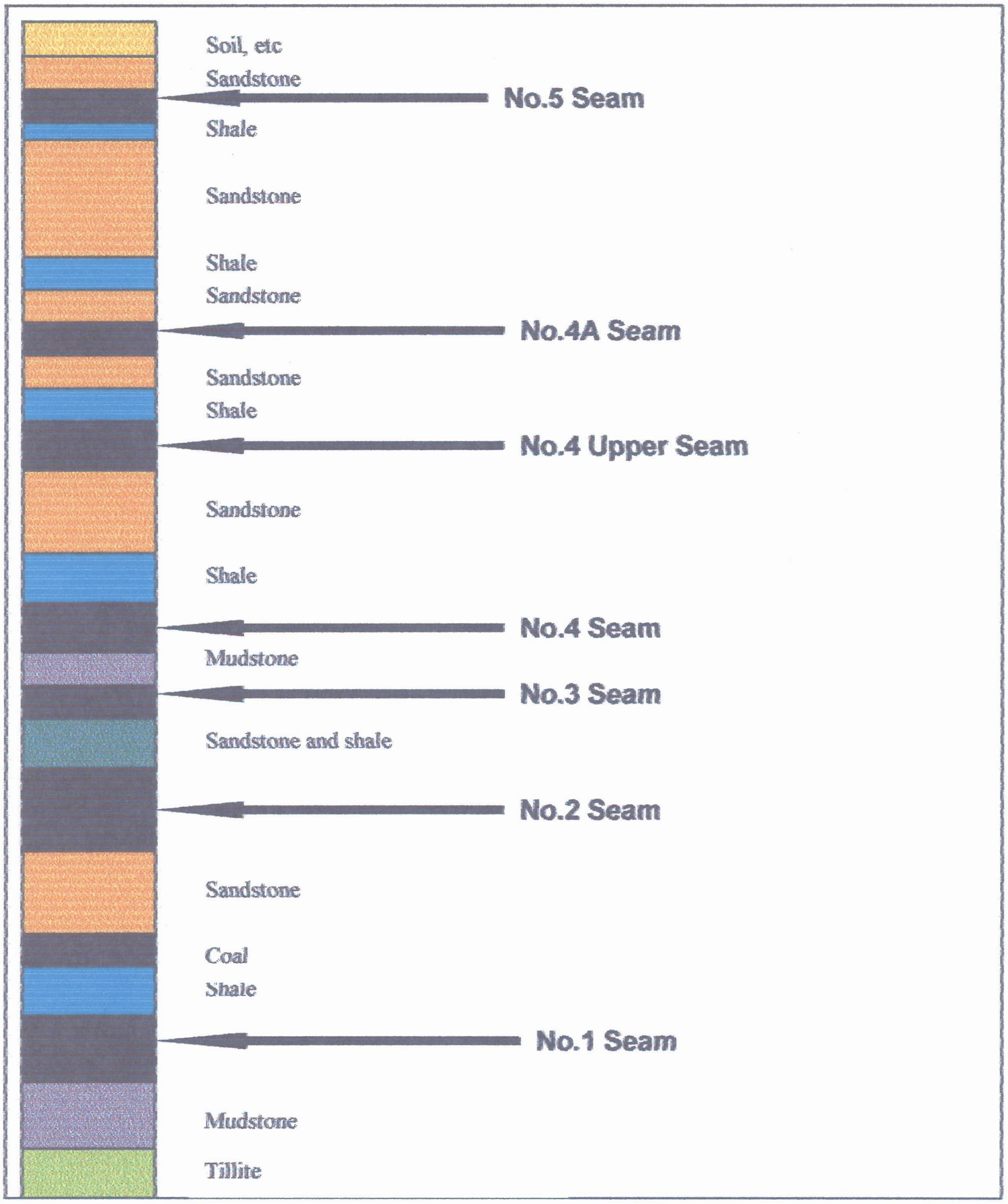


Figure 4: Schematic representation of geology in the study area (Lurie, 1987)

Five coal seams of varying grade are contained in a 70m thick succession. The geology consists mostly of sandstone with some siltstone and mudstone. The No.1 seam ranges from 1.5 to 2m thick in the vicinity of Arnot. Elsewhere it occurs as irregular patches. The No.2 seam contains the majority of the coal in the area (Figure 5) and averages 6.8m in thickness in the centre of the Witbank coal field. This seam may consist of up to 5 benches and it is usually the lower three seams that are mined for economic reasons. The distribution and attitude of the No.1 and 2 seams depends on the pre-Karoo topography. The No.3 seam is rarely more than 0.5m thick and is generally not mined because it is considered to be uneconomical. The No.4 seam ranges from 2.5 to 6.5m in thickness. The No.5 seam has an average thickness of 1.8m. The distribution of the No.4 and 5 seams is determined by the present-day surface.

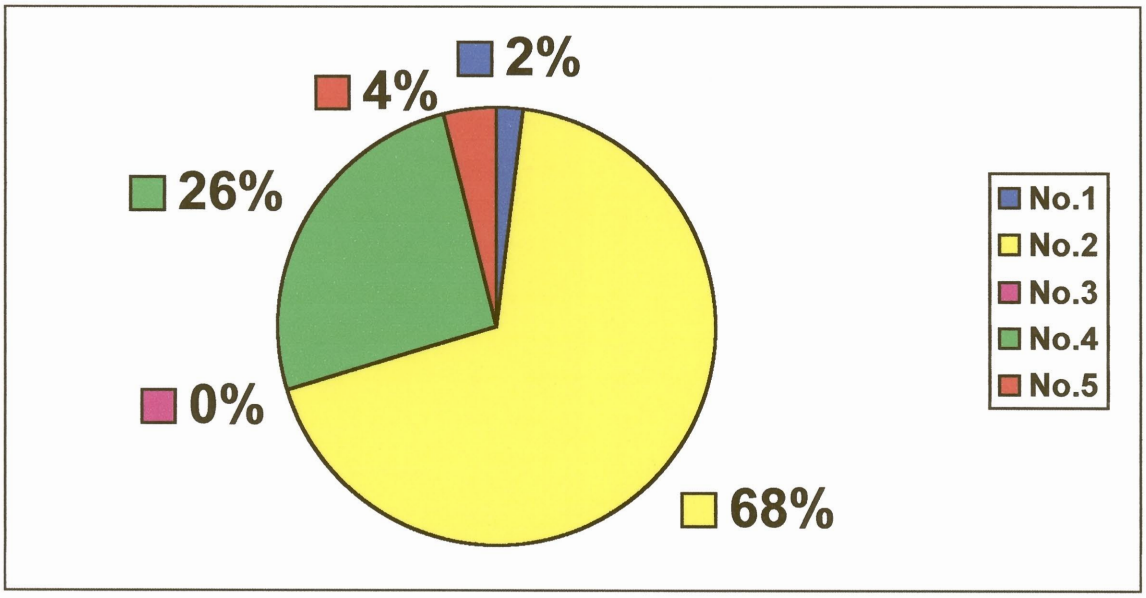


Figure 5: Contribution of seam to in situ demonstrated coal resources (Snyman, 1998)

The Ogies dyke (Figure 2) is approximately 15m thick and covers a distance of 100km. Considerably smaller dykes and sills also occur and they are more common south of the Ogies dyke than to the north.

4.2 Climate

The climate is generally moderate and dry with harsh winters coupled with heavy frost. Rainfall is typical of Highveld conditions and occurs mainly during summer. The average rainfall per month, as well as the number of days per month during which rainfall occurs are given in Table 3. The average annual rainfall recorded for the study area is 621 mm per year.

Table 3: Average rainfall per month, over a 10 year period from 1989 to 1999 (DWAF, 1999).

Month	Average number of rainy days per month	Average rainfall per month (mm)
January	9.9	87.5
February	7.1	99.5
March	7.6	82.3
April	2.9	31.6
May	0.8	4.1
June	1.5	14.2
July	0.4	1.6
August	1.0	6.1
September	3.2	30.4
October	6.4	79.1
November	7.8	98.9
December	9.7	85.7

The following statistics presents an overview of the rainfall intensity over specific periods, experienced in the area:

60 min (1995)	57 mm
24 hours (1994)	95 mm
24hours/50 year period	133 mm
24 hours/100 year period	158 mm

The highest average monthly temperature is 27°C, recorded for January, while the lowest average minimum monthly temperature is –1.6°C, during July. The average monthly minimum and maximum temperatures are presented in Table 4.

Table 4: Average monthly minimum and maximum temperatures over a 10 year period from 1989 to 1999 (DWAF, 1999)

Month	Maximum (°C)	Minimum (°C)
January	27.0	14.0
February	26.3	13.4
March	25.6	11.7
April	23.8	8.0
May	21.8	3.0
June	18.1	-0.6
July	18.9	-1.6
August	20.7	1.2
September	24.1	6.2
October	25.1	10.1
November	25.2	12.4
December	26.4	14.0

The mean annual wind direction, frequency and speed calculated over the period June 1993 to May 1994, based on daily readings at 08h00, 14h00 and 20h00, are presented in Figure 6.

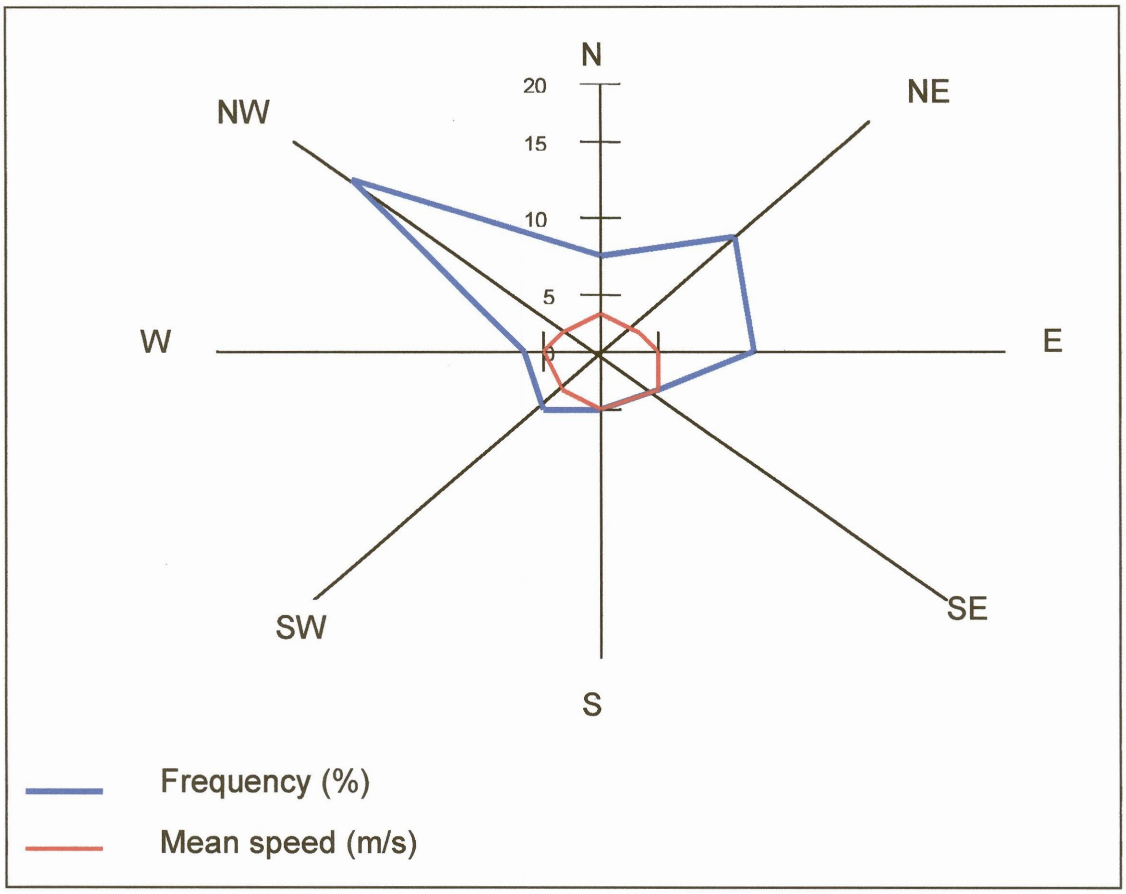


Figure 6: Mean annual wind speed, frequency and direction (DWAF, 1999).

The monthly average evaporation is presented in Table 5. When compared to rainfall data, it becomes apparent that the area has an average water deficit of –1081 mm per annum.

Table 5: Average monthly evaporation over a 10 year period from 1989 to 1999 (DWAF, 1999).

Month	Evaporation (mm)
January	179.8
February	151.1
March	147.8
April	111.1
May	94.8
June	79.2
July	89.0
August	132.0
September	167.0
October	186.6
November	167.6
December	195.9
Total	1701.5

The following weather features are typical of the study area:

• Thunderstorms	5.7 days/year (1.6%)	
• Hail	2.8 days/year (0.8%)	
• Snow	0.8 days/year (0.2%)	
• Mist	19.0 days/year (5.2%)	
• Cloud	-08:00	35% of the year
	-14:00	44% of the year
	-20:00	34% of the year

4.3 Topography and drainage

The study area is situated in a fairly flat, softly rolling landscape where the gradient seldom exceeds 1:35. The Olifants River and Steenkoolspruit are the major drainage valleys in the Witbank Dam catchment and the Klein Olifants River is the primary drainage valley in the Middelburg Dam catchment (Wates, 1985).

4.4 Agriculture

The study area is situated in one of the most fertile agricultural regions in the country. Maize is the chief agricultural product. The portion of the catchment area exploited by agriculture will decrease as further coal mining and power generation facilities are developed. Rehabilitated open cast coal mines will hopefully all be returned to grazing. In some cases this has already been done. Irrigation from rivers and constructed farm dams is widely practised in the catchment areas (Wates, 1985).

4.5 Urban development

Several towns contribute urban runoff and discharge purified sewage effluent to the catchment. The future sewage effluent quality with respect to sulphate concentration is expected to remain constant. The actual sulphate concentration will obviously depend on the quality of potable water consumed by the different user communities. Witbank town was originally the only local authority that abstracted raw water from Witbank Dam and catchment. Middelburg town now also relies on some water transferred by the Usutu-Vaal Government Water Scheme to the Upper Olifants River (Wates, 1985).

4.6 Coal mining activity

The majority of collieries in the study area still have a long remaining life. It is hoped that point and diffuse sources of pollution will be changed in the future by the improved house-keeping policies of the collieries, better rehabilitation practices and the separation of clean and dirty stormwater runoff.

Extensive underground and open cast coal mining takes place across the area. A range of coal products is produced for sale on domestic and foreign markets. Two prime coalfields are exploited by the mines i.e. Highveld in the south and Witbank-Springs in the north (Wates, 1985).

4.7 Power generation

There are currently four power stations located in the Witbank Dam catchment. Raw water is supplied by the Usutu-Vaal Government Water Scheme. Atmospheric deposition, although a concern for local interested and affected parties, is not expected to change over the next 20 years. It is also assumed that the ability of the soil profile to abate and adsorb sulphate will not be exhausted over the next 20 years (Wates, 1985).

Chapter 5

COAL

5.1 General

Coal is a sedimentary, organic, combustible rock. Carbon, hydrogen and oxygen are the primary constituents. It is formed as a result of diagenetic processes acting on vegetation, originally accumulated as plant material in swamps and peat bogs, which consolidated between other rock strata. In this way, coal seams are formed. Significant accumulations occurred during the Carboniferous, Permian and Cretaceous periods. Peat, the precursor of coal was initially converted into lignite (brown coal). This rank of coal has low organic maturity i.e. relatively high original organic content. Continued high temperatures and pressure transform lignite into sub-bituminous coals. With further chemical and physical changes and a progressive increase in organic maturity, these coals are transformed into anthracite (Figure 7).

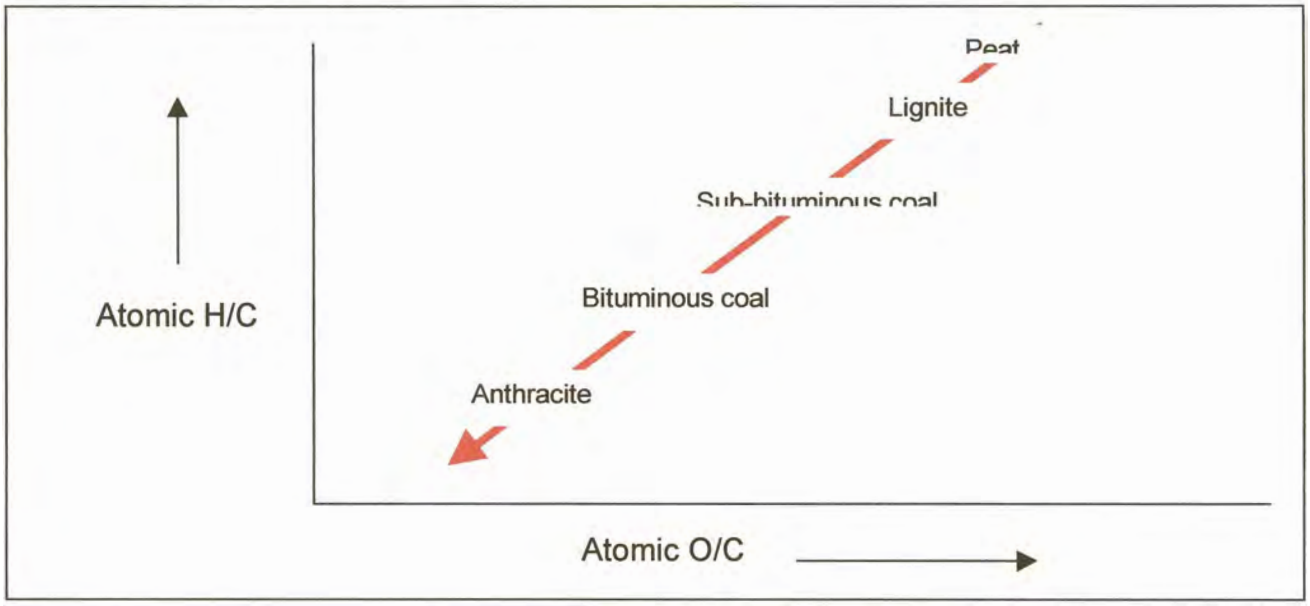


Figure 7: Metamorphism of organic matter as it increases in rank from peat to anthracite

Coal is the most abundant fossil fuel in the world. It is mined in more than 50 countries. Such abundant reserves ensure consumers a guaranteed supply at competitive prices. Coal is also stable and therefore the safest fossil fuel to transport, store and use, despite its potential to spontaneously combust. When used in accordance with current technologies, coal is a clean-burning fuel .

5.1.1 Mining methods

Coal is either mined on the surface or underground. The choice depends on the geology of the coal deposit. Figure 8 presents the choice of mining method as a function of seam thickness and mining depth. Most of the world's hard coal is extracted by means of deep mining. There are two principal methods of underground mining. These are room-and-pillar ("board-and-pillar") and longwall mining. The board-and-pillar method involves cutting a network of 'rooms' or panels into the coal seam and leaving behind 'pillars' of coal to support the roof of the mine. It is possible to recover the coal left in the pillars at a later stage. Longwall mining makes use of mechanical shearers to cut and remove the coal at the face. Self-advancing, hydraulically powered supports temporarily hold up the roof while the coal is removed. The roof over the area from which the coal has already been mined is allowed to collapse. Over 75% of a coal deposit can be extracted using the longwall method. Surface mining is only economically viable when the deposit is very close to the surface. A far higher proportion of the coal is recovered by this method. The overburden is removed by draglines. Large trucks transport the overburden and coal. The equipment used has increased dramatically in size, in order to promote the most efficient removal of coal and overburden alike. In developing countries, the high cost of importing this equipment can favour the selection of underground mining (UN/DTCD, 1991).

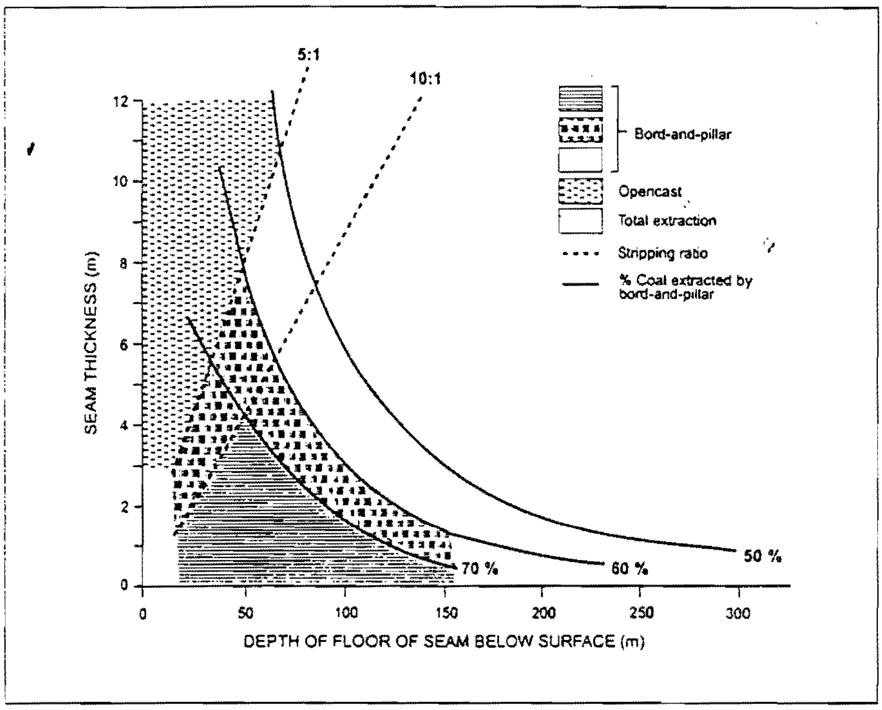


Figure 8: Mining method as a function of seam thickness and mining depth

5.1.2 *Coal preparation*

Coal consumers require coal of a consistent quality and size grading and each consumer may have different specifications. Run-of-mine coal contains a mixture of different size fractions and unwanted impurities. Coal preparation, or beneficiation, is the processing of run-of-mine coal into a range of graded and uniform coal, agreeing with the requirements of the commercial market. (In some cases the run-of-mine coal meets the user specification without the need for beneficiation. In this case, the coal would simply be crushed and screened) (Atwood, Redden and Bennett, 1994). Likely stages of environmental pollution in the production of coal are shown in Figure 9.

5.1.3 *Transport and storage*

Coal is generally transported by conveyor or truck over short distances. Trains, barges, ships or pipelines are used for longer distances. It is required by law that a number of preventative measures are taken during both transport and storage to reduce potential environmental impacts, such as water contamination should the load be released near an open surface water body (Atwood, Redden and Bennett, 1994).

5.1.4 Uses of coal

Coal is the predominant fuel for electric power generation. More than half of global coal production is used for making electricity. Other important uses are in steel and cement manufacture, industrial heating and gasification for the production of liquid fuel, organic chemicals and hydrogen, as well as for ammonia, fertiliser and explosives manufacture.

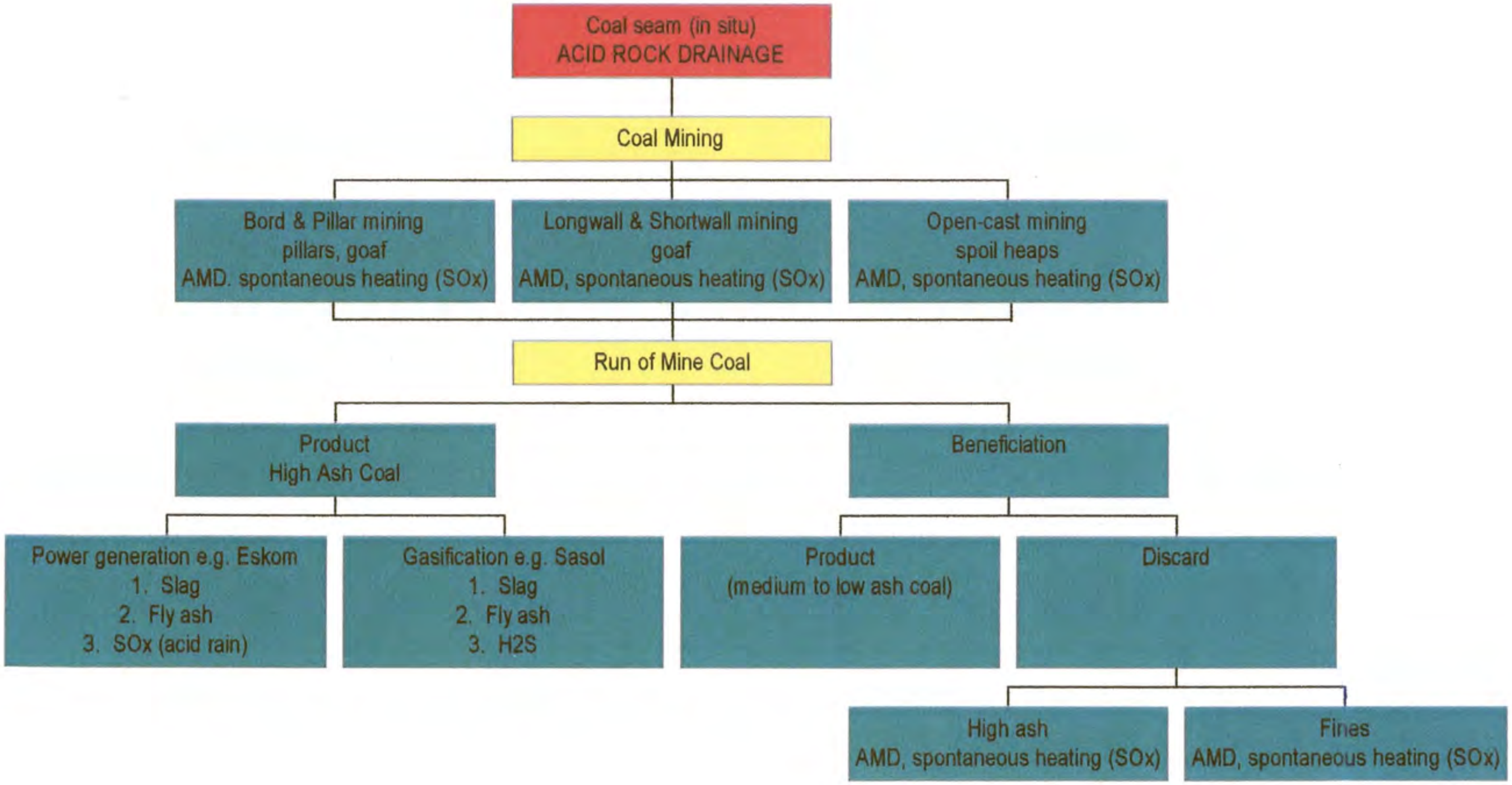


Figure 9: Scheme showing the likely stages of environmental pollution in the production of coal

To meet forecast electricity demand over the next 25 years, it is estimated that 1000MW of capacity, equivalent to a major power station, will have to be built every week throughout the world – 36% or more based on coal.

About 630 kg of coal are used to produce 1000 kg of steel. For the foreseeable future, coal will remain indispensable to the steel industry (Atwood, Redden and Bennett, 1994).

5.1.5 Coal in the environment

Although the coal industry of today is much more efficient and environmentally aware, it still has much work to do to rectify the false image which lingers from its past. Technologies have been developed to improve the environmental effect of coal-use techniques. An example of this is the use of electrostatic precipitators and/or bag filters, which means that power stations no longer emit large amounts of dust and fly-ash (Blight, 1987).

A more recent concern is that high amounts of greenhouse gases are being emitted as a result of the combustion of fossil fuels. However, greenhouse gases from coal contribute less than 20% to any enhanced greenhouse effect. The world community has largely accepted that every practicable step should be taken to improve the efficiency of all processes that involve fossil fuel combustion.

5.1.6 Clean coal technologies

Modern Clean Coal Technologies (CCTs) reduce CO_2 emissions per unit of electricity by up to 30%. CCTs are 'technologies designed to enhance both the efficiency and the environmental acceptability of coal extraction, preparation and use'. CCT programmes are being enthusiastically initiated in many countries. CCTs for the extraction of coal are readily available. Improved exploration techniques, such as geophysical techniques, also minimise potential environmental impacts. Clean Coal Technologies for the preparation of coal can reduce its ash content and clean the coal in terms of impurities. Pulverised Fuel combustion is the most widely used method for burning coal for the purpose of generating power. Post-combustion CCTs can reduce emissions from PF combustion. Flue Gas Desulphurisation methods can remove 90-97% of the oxides of sulphur from flue gases by converting it into gypsum, which can be used in the building industry. Application of advanced PF combustion results in relative reductions in CO_2 emissions, because less fuel is used per unit of electricity generated. Use of fluidised bed combustion has been stimulated by its better environmental performance (Bursky, 1992).

An alternative to coal combustion is coal gasification. In new developments of this method, over 99% of the sulphur present in the coal can be recovered by a process of electrostatic precipitation, for sale as chemically pure sulphur. Hybrid combined cycles are also under development. These combine the best features of gasification and combustion technologies (Bursky, 1992).

In addition to these CCTs, a development, which can apply to all generating systems, is the co-firing of coal with biomass or wastes. Benefits include reductions in CO_2, SO_x and NO_x emissions and the recovery of useful biomass and wastes at high efficiencies, depending on the composition of the waste. Hence, the coal-fired power industry can support the renewable energy and waste industries (Kruger, 1987).

5.1.7 Rehabilitation

It is now possible to restore mined land to a state whereby it may be used for its original purpose or another productive use. Today, the international coal mining industry is committed to the protection of the environment and land reclamation is an integral part of most mining operations (whether legally required, in the form of an Environmental Management Programme, or not).

5.1.8 Safety

Health and safety issues have been of primary concern to the coal industry for a long time. The technological advances in mining techniques have simultaneously led to improvements in productivity and safety. In most countries, miners receive regular job-skill and safety training. Coal companies recognise that improved productivity and safety are closely linked.

Coal does not present the same leakage and spillage hazards as oil and gas. The sinking of coal-carrying ships is fortunately rare and in no well-documented case has the coal cargo presented a pollution hazard. Distribution of coal on land, by conveyor, road or rail is relatively safer than in the case of other fossil fuels, despite the possibility of spontaneous combustion (Pulles *et al*, 1996).

5.1.9 The future

As the result of Clean Coal Technologies, coal will continue to be used more efficiently. These technologies also ensure that coal-fired power stations will meet the stringent environmental standards enforced globally. The coal industry will continue to adapt to community expectations (Bursky, 1992).

5.1.10 Economic implications

Mining activities incur two types of costs. Firstly, there are those that the producing firm must pay i.e. labour, capital and material inputs. Secondly, there are those that the producing firm does not pay, as is often the case for water pollution and other forms of environmental damage. The latter costs are commonly referred to as externalities. Society as a whole may never avoid these costs (Camm, 1995).

There is an optimal level for use for any given environmental resource. In economic terms, this occurs when the marginal social benefits equal the marginal social costs. The social benefit of an additional unit of pollution is the net value to society of the goods and services that the additional unit of pollution makes possible i.e. Marginal Social Benefits = Marginal Social Costs

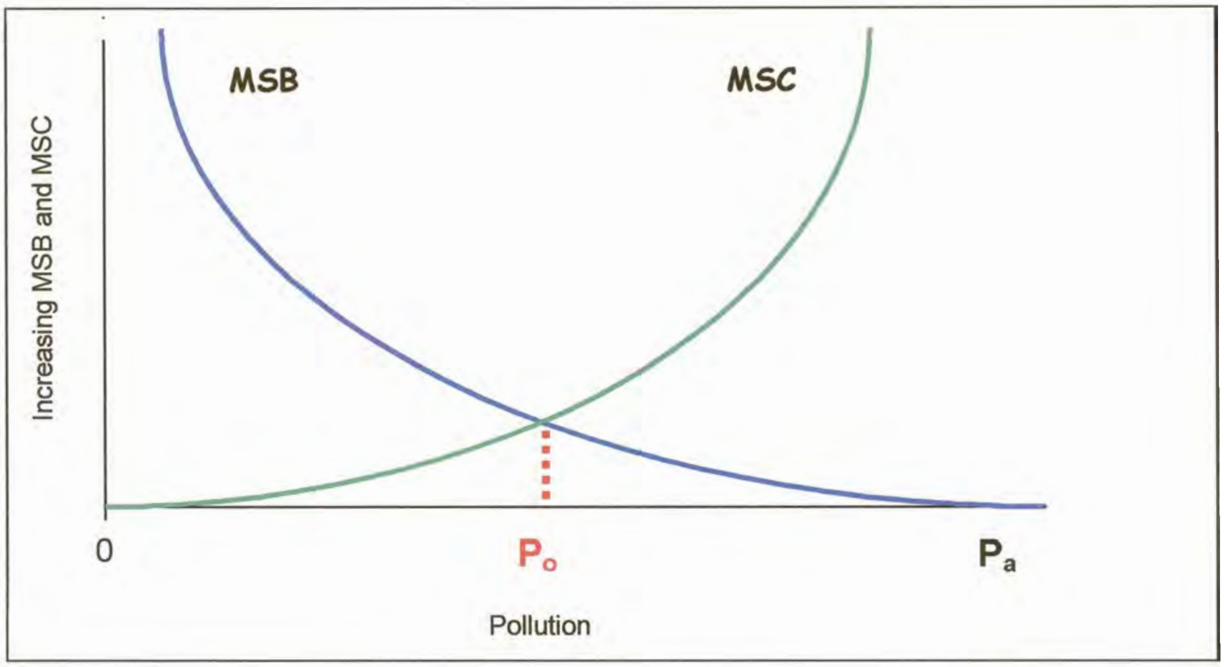


Figure 10: The marginal social costs (MSC) and marginal social benefits (MSB) of pollution.

Po represents the optimum level. The negative slope of the MSB curve represents the assumption that goods and services with lower social benefits per unit of pollution will be produced as the permitted level of pollution increases. The positive slope of the MSC curve implies that as the level of pollution increases the social costs incurred for each additional unit of pollution rise (Tilton, 1994).

Another way of representing this relationship is presented in Figure 11. Figure 11 counteracts the impression that may be given by Figure 10 i.e. that there can only be an inverse relationship between pollution/development and social benefits. In Figure 11, Po represents a critical value rather than the optimum.

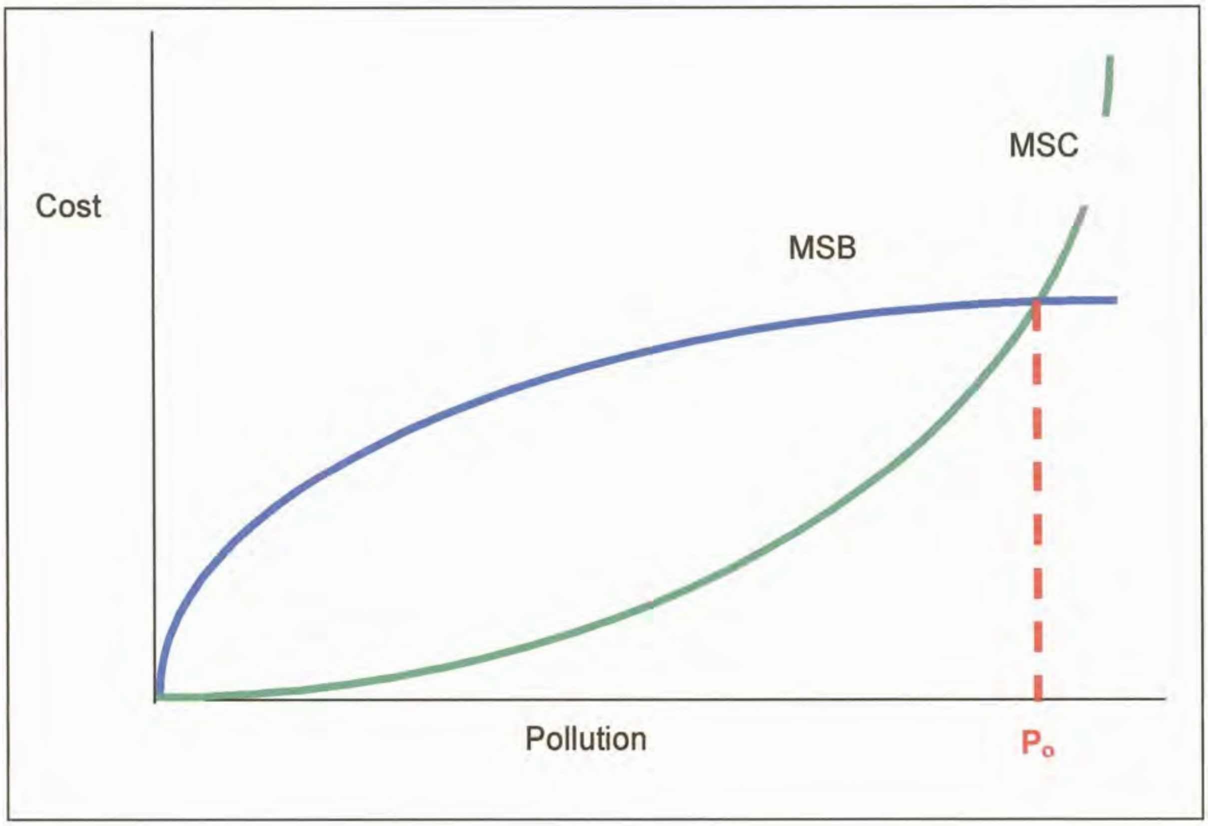


Figure 11: An alternative representation of the marginal social costs (MSC) and marginal social benefits (MSB) of pollution.

5.2 Coal characterisation

As was mentioned in the introduction, the rank of coal refers to its degree of development from peat to anthracite.

5.2.1 Proximate analysis

Proximate analysis comprises the moisture, volatile matter, ash and fixed carbon contents of air-dried coal and is determined under stringently specified conditions to ensure reproducible results. Fixed carbon is obtained by the difference between the total mass and moisture, volatile matter and ash percentage:

%fixed carbon = 100 - %moisture - %volatile matter - %ash

The moisture content is determined by heating the coal to constant mass to a temperature of 105°C – 110°C. The moisture content is calculated from the loss in mass.

The volatile matter is determined as the loss in mass, less that due to moisture, when coal is heated to 900°C in the absence of air under standard conditions.

The ash remaining after coal has been incinerated in air is derived from inorganic material present in the coal, mainly discrete mineral matter. The amount of sulphur retained in the ash is dependent on the lime content of the coal and the conditions of ashing.

The percentage of ash is calculated from the mass of the residue remaining after the sample is heated in air at a specified rate up to a temperature of 815°C.

5.2.2 Ash analysis

Ash analysis is essentially the same as any silicate analysis and can be done by atomic absorption spectrometry, X-ray fluorescence spectrometry, etc. In atomic absorption/emission analyses, the ash is fused with lithium tetraborate, followed by a final dissolution of the melt in dilute hydrochloric acid. The lithium tetraborate pellet can also be analysed by X-ray fluorescence spectrometry.

It should be noted that the chemical composition of coal ash is not identical to the composition of mineral matter in the coal or the composition of fly ash and slag resulting from combustion of pulverised coal. In the latter case chemical segregation takes place so that some components are preferentially enriched in the fly ash and others in the bottom slag.

The chemical composition of the ash gives an indication of the fouling and slagging potential of the coal during pulverised fuel combustion and pulverised fuel gasification, and also of the potential uses of the coal ash.

5.3 Coal in the study area

Table 6 provides a summary of the characteristics of the coal found in the study area.

Table 6: Characteristics of coal in the study area

MINE	Mining Methods	Washed/ Unwashed	Product	CV MJ/kg	Gross CV	H_2O %	Ash %	VM %	FC %	Tot S %
Greenside	underground; longwall	Washed :	Greenside	28.03	27.99	2.8	13.8	25.4	58.0	0.46
			Power station small	27.61	27.52	2.4	15.1	24.3	58.2	0.99
			Low ash	31.24	31.19	2.4	7.8	31.9	57.9	0.54
Kleinkopje		Washed :	Large nut	27.33	27.29	2.5	15.8	24.2	57.5	0.39
			Small nut	28.16	28.13	2.7	13.1	24.0	60.2	0.28
			Pea	27.43	27.39	2.8	15.5	21.9	59.8	0.41
			Small	27.74	27.70	2.8	14.5	21.3	61.4	0.42
			Duff	27.97	27.93	2.6	14.6	21.9	60.9	0.43
			Anglo	27.44	27.39	2.3	15.4	24.4	57.9	0.51
			Low ash	30.82	30.77	2.5	7.5	31.2	58.8	0.49
Matla	underground; #2=long and short-wall; #1 and #3 = underground	Unwashed:	Crushed coal	20.53	20.43	4.2	28.9	23.3	43.6	1.09
Kriel		Unwashed	Crushed coal	19.45	19.40	4.8	30.0	22.4	42.8	0.55
		Unwashed	Crushed coal	22.22	22.14	4.9	22.9	23.2	49.0	0.83
Syferfontein		Unwashed:	Crushed coal	20.13	20.08	5.9	28.3	22.8	43.0	0.57
Eikeboom	opencast	Washed :	High phosphorus:							
			Large nut	28.57	28.54	3.4	11.4	26.3	58.9	0.35
			Small nut	28.61	28.58	3.2	11.7	25.2	59.9	0.27
			Pea	28.46	28.41	3.0	11.8	29.2	56.0	0.50
			Grain	29.06	29.01	3.7	8.9	32.4	55.0	0.50
			Duff	26.90	26.86	3.7	14.3	26.2	55.8	0.44
		Washed :	Low phosphorus:							
			Large nut	28.51	28.47	3.7	11.3	31.3	53.7	0.47
			Small nut	28.55	28.50	3.0	12.3	31.0	53.7	0.57
			Pea	28.42	28.37	3.7	10.4	31.9	54.0	0.52
			Grain	28.29	28.25	3.8	11.5	28.6	56.1	0.47
			Duff	28.58	28.53	3.8	10.6	29.8	55.8	0.54

Table 6 (continued): Characteristics of coal in the study area

MINE	Mining Methods	Washed/ Unwashed	Product	CV MJ/kg	Gross CV	H_2O %	Ash %	VM %	FC %	Tot S %
Woestalleen	opencast	Washed	High phosphorus:							
			Large nut	26.10	26.04	4.1	15.5	24.1	56.3	0.59
			Small nut	27.44	27.37	3.7	13.8	26.4	56.1	0.77
			Pea	27.46	27.39	3.9	13.1	28.7	54.3	0.71
			Duff	27.25	27.19	4.1	13.1	28.4	54.4	0.67
			Low phosphorus:							
			Large nut	28.88	28.83	3.3	11.1	31.9	53.7	0.54
			Small nut	27.84	27.77	3.8	12.2	29.1	54.9	0.72
			Pea	28.77	28.70	3.4	10.8	33.4	52.4	0.73
Arnot	underground; board and pillar; shortwalling	Unwashed:	Duff	27.46	27.38	3.8	13.6	30.9	51.7	0.84
Koornfontein	underground; board and pillar	Washed :	Export	28.06	28.01	3.1	13.1	26.1	57.7	0.49
Middelburg	opencast	Washed :	Small	27.97	27.93	2.7	14.2	23.5	59.6	0.38
Goedehoop	Washed :	Goedehoop	28.33	28.27	2.6	13.6	26.6	57.2	0.62	
		Low ash	31.00	30.94	2.5	7.5	32.4	57.6	0.65	

(CSIR, 1999).

It may be stated that most calcium and magnesium will occur as carbonates and most iron will occur as pyrite in these coals (Gaigher, 1980).

Chapter 6

WATER

The correct sampling methods of water circuits are vital for the gathering of reliable information for the formulation of effective water management systems. Depending on the nature of the quality analyses to be performed, different pre-treatment and preservation techniques must be employed. Also, the integrity and accuracy of the data obtained from the analyses must be verified. Two methods can be used for this purpose i.e. preparation of an ionic balance and analysis of duplicate samples at a number of independent laboratories.

6.1 Characterisation of waters

It is essential that the characteristics of input water and wastewater be known in order to design efficient treatment systems. Regular testing is necessary so that processes can be adapted to accommodate changing loads. Such routine testing also enables the long-term assessment of processes. The use and discharge of water is regulated by statutory bodies, which may insist on regular testing and record-keeping. The type of test performed depends on the accuracy required, the use of the data and the use of the water. These tests can be broadly classified as follows:

- Tests for gross pollution: biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, ammonia and grease.
- Tests for appearance and aesthetic acceptability: taste, colour, odour, and turbidity.
- Tests for materials that are a health risk: fluoride, nitrate, chloride, magnesium, heavy metals and sulphate.

- Tests that determine suitability for incidental uses: corrosivity, iron, manganese, calcium and magnesium salts, coloured ions e.g. copper.
- Operational tests: used to optimise or check plant performance, coagulation and flocculation, sludge assessment and simple analytical tests.

(Brady *et al.*, 1994).

6.1.1 Chemical equilibria, pH and buffers

Many chemical equations can be described as chemical equilibria, where reactants A and B form products C and D and vice versa as shown below:

$$A + B <-> C + D$$

The concept of chemical equilibria is valuable in predicting the behaviour of several important species in wastewater. In this regard, the concept of solubility product constant (Ksp) is important to evaluate the maximum concentration of a sparingly soluble salt in water under specific conditions (normally one atmosphere and 25°C):

$$CaSO_4 <-> Ca^{2+} + SO_4^{2-}$$

$$\begin{aligned} Ksp &= [Ca^{2+}] \,.\, [SO_4^{2-}] \\ &= 3\text{x}10^{-5}\ \text{moles/l} \end{aligned}$$

Due to the "common ion effect" the solubility of Ca^{2+} is even farther reduced by the presence of excess sulphate ions (e.g. from another sulphate like Na_2SO_4) in solution.

The ability of a sample to resist change to its pH is referred to as its *buffering capacity*. An understanding of this characteristic of a sample is important when later considering treatment processes in which acid or alkali is added to a sample, as in anaerobic digestion, nitrification, chlorination, coagulant addition and pH correction. Buffers are usually composed of mixtures of weak acids (or bases) and the salts of a weak acid. The degree of buffering capacity can be measured by titrating the sample with N/50 acid and is recorded on a calcium carbonate scale as alkalinity (Clark, 1994).

6.1.2 Physical tests

Tests for colour, turbidity, taste and odour are widely used to establish the aesthetic quality, or potability, of waters.

Colour in water means that the water will absorb light energy in the visual spectral range. Water is colourless, so any colouration will record the presence of impurities in that sample. Colour is usually measured visually and is thus subjective.

Turbidity is a measure of the ability of water to scatter light. Small particles in the water scatter and absorb light, so that the light does not pass directly through the water. The overall turbidity of a sample will depend on the number, size, shape and refractive index of the particles in suspension. Turbidity is measured on a turbidity scale of units established for a standard suspension. The presence of taste and/or odour in water is detected by the response of human senses to the particular chemicals. Thus it is also largely subjectively measured, usually by a panel of individuals.

The conductivity of a water sample measures the ability of the sample to carry an electric current. Compounds that dissolve in solution to give individual ions will result in a high conductivity relative to those compounds that do not dissociate. The major influence on conductivity is therefore the concentration of dissolved inorganic salts in the water. The relationship between dissolved salts and conductivity depends on the materials present, temperature, concentrations and pH of the sample. There is thus no consistent relationship between conductivity and total dissolved solids. Conductivity is used to gather routine data and highlight changes in the water, which may warrant further investigation. Conductivity is determined by measuring the electrical resistivity of a sample between two electrodes. Resistivity is the product of the resistance and the distance between the electrodes (Clark, 1994).

6.1.3 Principles of analytical chemical methods

Concentrations are normally determined on a mass per volume basis. They are conveniently expressed in mg/*l*, which is equivalent to g/m^3. As 1*l* of water has a mass of approximately 1kg, these values can also be taken as parts per million (ppm). The types of analytical method used in wastewater analysis can be described as titrimetric, colorimetric, spectral and potentiometric. The first two are more traditional techniques, while the last two are based more on instrumental techniques (Drew Chemical Corporation, 1978). (These methods have not been used in the practical section of this thesis and are thus not discussed in any detail).

6.1.4 Solids determination

To determine the total amount of solids present in a sample, a fixed volume of the sample is evaporated and the residue dried at 105°C and weighed.

To determine the amount of material not in solution i.e. suspended solids, the sample is filtered and the dried residue weighed. Soluble solids can be separated from the filtrate and then weighed or they can be determined by subtracting the suspended solids from the total solids. The suspended solids indicates the material that might be removed by a settling process.

If a dried sample is heated to 600ºC in air, the organic material will burn and the weight loss can be attributed to the organic content of the sample. This is usually interpreted as the degradable fraction of the sample, although not all organic materials are degradable and some inorganic compounds, like clay minerals and inorganic colloids (e.g. $Al(OH)_3$), decompose and lose weight at this temperature. The material remaining after heating is recorded as the fixed residue.

6.2 Water use in the coal mining industry

Water use in the mining industry includes the following:

- Potable water
- Recreation
- Irrigation and rehabilitation
- Cooling water
- Dust suppression
- Process water in plants
- Mine service water
- Tailings

The surface and ground water environments of individual mines vary, as do the effects of point and/or diffuse effluents on these environments.

Chapter 7

METHODS OF INVESTIGATION

7.1 Sampling

7.1.1 GIS maps

The data used to create the GIS maps were taken from databases compiled by Wates Meiring and Barnard (unpublished, 1998, pers.comm.) for a previous project, the CSIR Coal Bulletin No. 105 and the South African Water Quality Guidelines. Tables containing these source data are given in Appendix A.

The databases compiled by Wates Meiring and Barnard contained water quality data, generally including analysis for pH, conductivity, TDS, SO_4^{2-}, Mn, Al, Ca and Mg. The data was compiled over a 12-month period from 1997 to 1998 as part of a regional water quality monitoring programme that included the study area selected for this thesis.

The CSIR Coal Bulletin contains percentages moisture, ash, volatile matter, total sulphur and fixed carbon in raw coal, coal discard and beneficiated coal products.

The South African Water Quality Guidelines is a set of seven volumes providing threshold values for elements and compounds in water, in terms of the desired use for that water i.e. domestic, recreational, industrial, agriculture, livestock watering, aquaculture and/or aquatic ecosystems.

Each of the coal characteristics was represented against a full set of water quality parameters to determine the nature of the water pollution problem, if any, and also to identify any relationship between coal chemical characteristics and water quality at any specific site.

7.1.2 *Collection of samples for chemical leaching studies*

Sample sets, comprising 10 samples in total, were collected from 4 sites in the study area. Three samples were collected at each of 3 sites, and a fourth sample set was collected from a power station and its captive colliery. Grab samples were all collected directly from the middle of the face of the middle coal seam at a point that is representative of the seam's average width and mineralogy. Product samples were collected from within the plant once all beneficiation was complete. Discard samples were collected from waste dumps at approximately 50 cm depth. The power station ash was taken from a set of samples selected by the particular power station as a representative sample for the purpose of in-house analysis. These samples therefore included:

- Grab samples - 3
- Product samples - 3
- Discard samples - 3
- Power station ash -1

7.2. Analysis

7.2.1 *Presentation of data by means of GIS*

It is important to note that the GIS map yields information once the user has activated any icon representing a sample site. The user is then given the choice of quickly viewing a small text box, which has summarised the characteristics of that site, or to enter the original database to examine data sets and view graphical representations of any relationships found. For the purpose of this document, only one site has been selected in figure 12 to be viewed with the information text box, as would be seen on the computer screen.

7.2.2 Chemical leaching studies

Chemical leaching studies give an indication of the amount of directly leachable acid water generated during the test, from coal and coal discard samples that are exposed to water and oxygen over a specified time period. For this purpose, beaker studies were conducted on all the samples.

50g of each sample was suspended in 1l of water and continuously stirred, by means of a mechanical stirrer, over a 24 hour period. The change of the water composition against time elapsed was monitored at selected intervals over this period.

The water samples from the beaker tests were analysed for the following parameters:

- pH
- Sulphates
- Alkalinity
- Acidity
- Iron (II)

The methods of analysis are detailed below:

pH:

The pH electrode was calibrated with buffer 7 and buffer 4 before each suite of samples was tested. The pH was then read on each filtered sample.

Sulphates:

2ml of the filtered sample was made up to 50ml with distilled water in a 50ml volumetric flask. 2.5ml conditioning reagent and 1 spatula of barium chloride was then added. The solution was mixed until the barium chloride had completely dissolved. A turbidity reading was then taken. Sulphate concentration was then read off a spreadsheet of values devised by the CSIR.

Alkalinity:

Alkalinity tests were carried out on all samples with a pH value of more than 6. 5ml of the filtered sample was made up to 50ml with distilled water. The solution was then titrated with 0,02 N HCl until pH 4.3. Alkalinity was then calculated using the following equation:

$$\text{mg } CaCO_3/l = \text{titration volume} \times 200$$

Acidity:

5ml of the filtered sample was added to 45ml water and 0.2ml 1000 x diluted H_2O_2. 5ml 0.1N NaOH was then added to the solution. The solution was then titrated with 0.1N HCl to pH 8.3. Acidity was then calculated using the following equation:

$$\text{mg } CaCO_3/l = \text{titration volume} \times 1000$$

Iron (II):

10ml of the filtered sample was mixed with 10ml 1N H_2SO_4 and 10ml Zimmerman Reinhardt solution. The solution was then titrated with 0.1N $KMnO_4$ to a pink colour. Iron(II) concentration was calculated using the following equation:

$$\text{g Fe(II)}/l = 55.85 \times (0.1N \times \text{titration volume} / \text{volume of sample})$$

Tables containing the results of these tests are included in Appendix B.

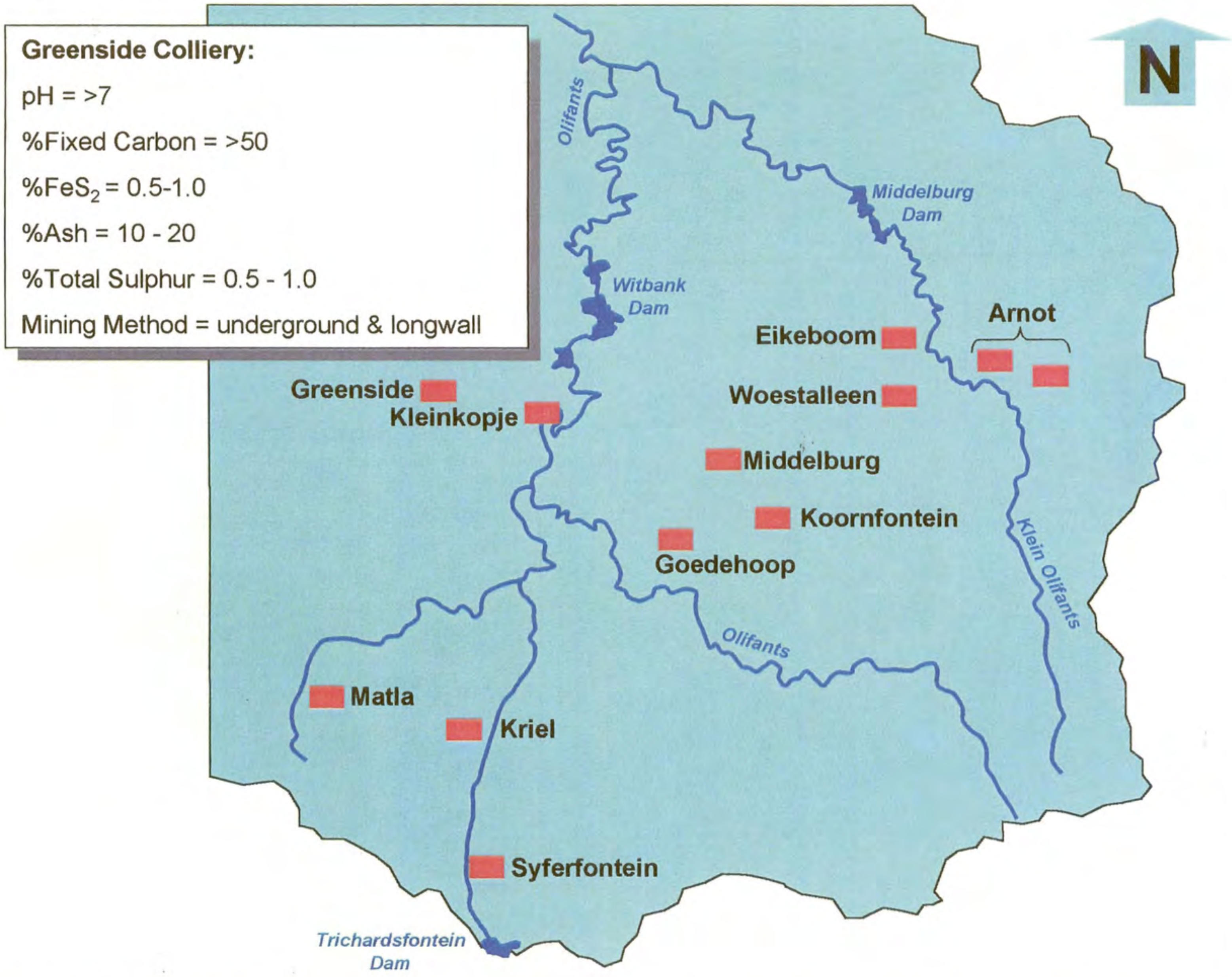
Chapter 8

DISCUSSION OF RESULTS

8.1 GIS map - database results:

Figure 12 indicates the view that is afforded to the user by clicking on a particular site once the GIS programme is in use i.e. a short summary of data contained in various databases. The user may also choose to enter the original database to manipulate data and observe immediate changes in the display, should conditions change. In addition, a number of searches may be performed against a user-defined set of conditions.

Figures 13 to 17 demonstrate the illustrative ability of the GIS maps. In these figures, water quality is compared against a number of coal characteristics i.e. fixed carbon, pyrite, ash, total sulphur and mining method, as well as the South African Water Quality Guidelines for specific uses i.e. domestic, recreational, industrial, irrigation, livestock watering, aquaculture and aquatic ecosystems. These comparisons were made possible by tabulating a full chemical analysis of water samples taken in the Witbank and Middelburg Dam catchments and comparing them with those standards stipulated in the South African Water Quality Guidelines (Appendix A). It is important to note that the objective of this exercise was to create a fully interactive user-friendly GIS-based database. In order to develop meaningful water management options for the catchments, it would be necessary to consider the contaminant loading in each stream and identify point sources of pollution.



Greenside Colliery:

pH = >7

%Fixed Carbon = >50

%FeS_2 = 0.5-1.0

%Ash = 10 - 20

%Total Sulphur = 0.5 - 1.0

Mining Method = underground & longwall

Figure 12: Location of database sample sites in the study area, showing the summary data provided by activating the site icon for Greenside Colliery

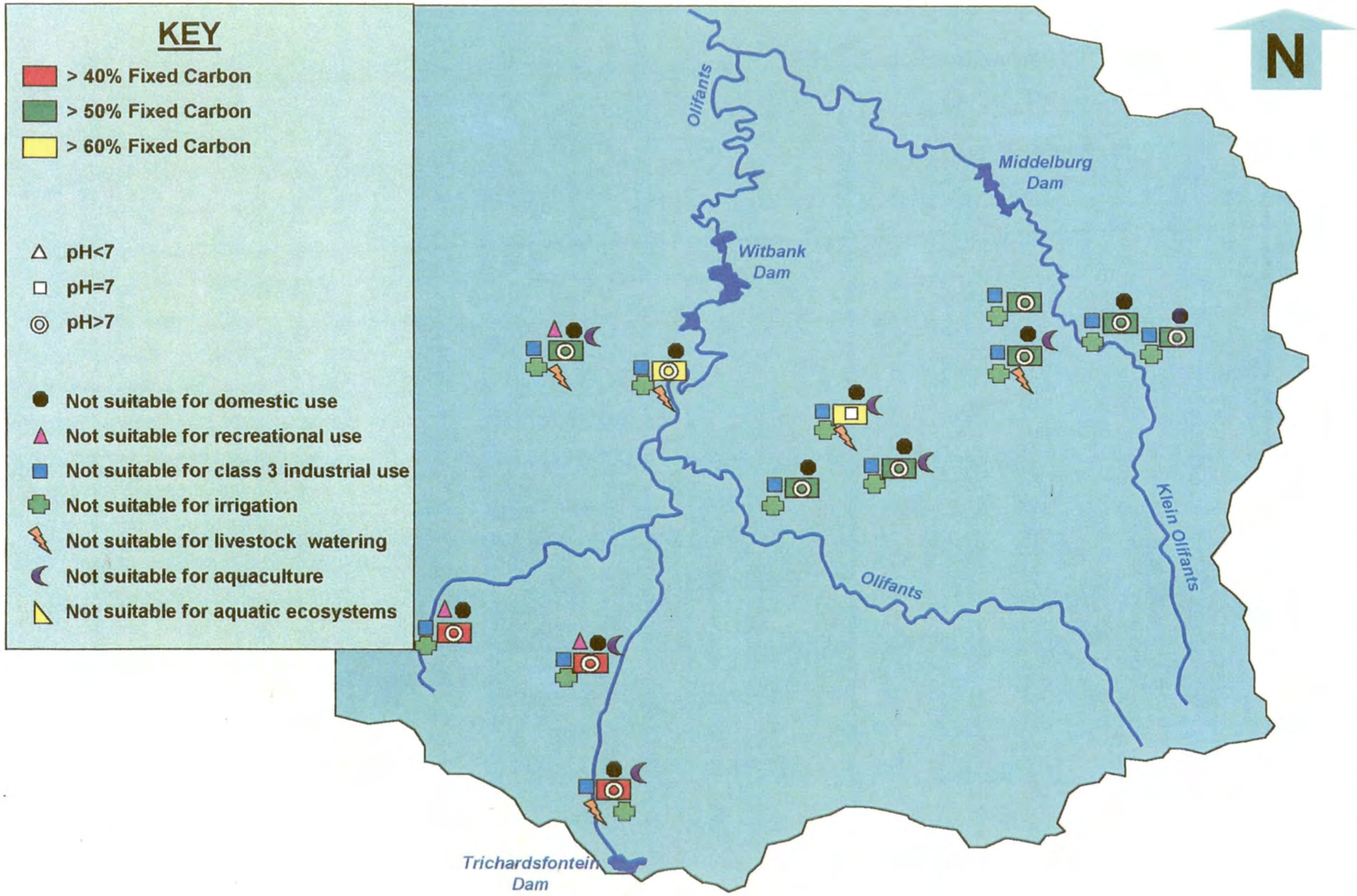


Figure 13: Fixed Carbon % vs water quality

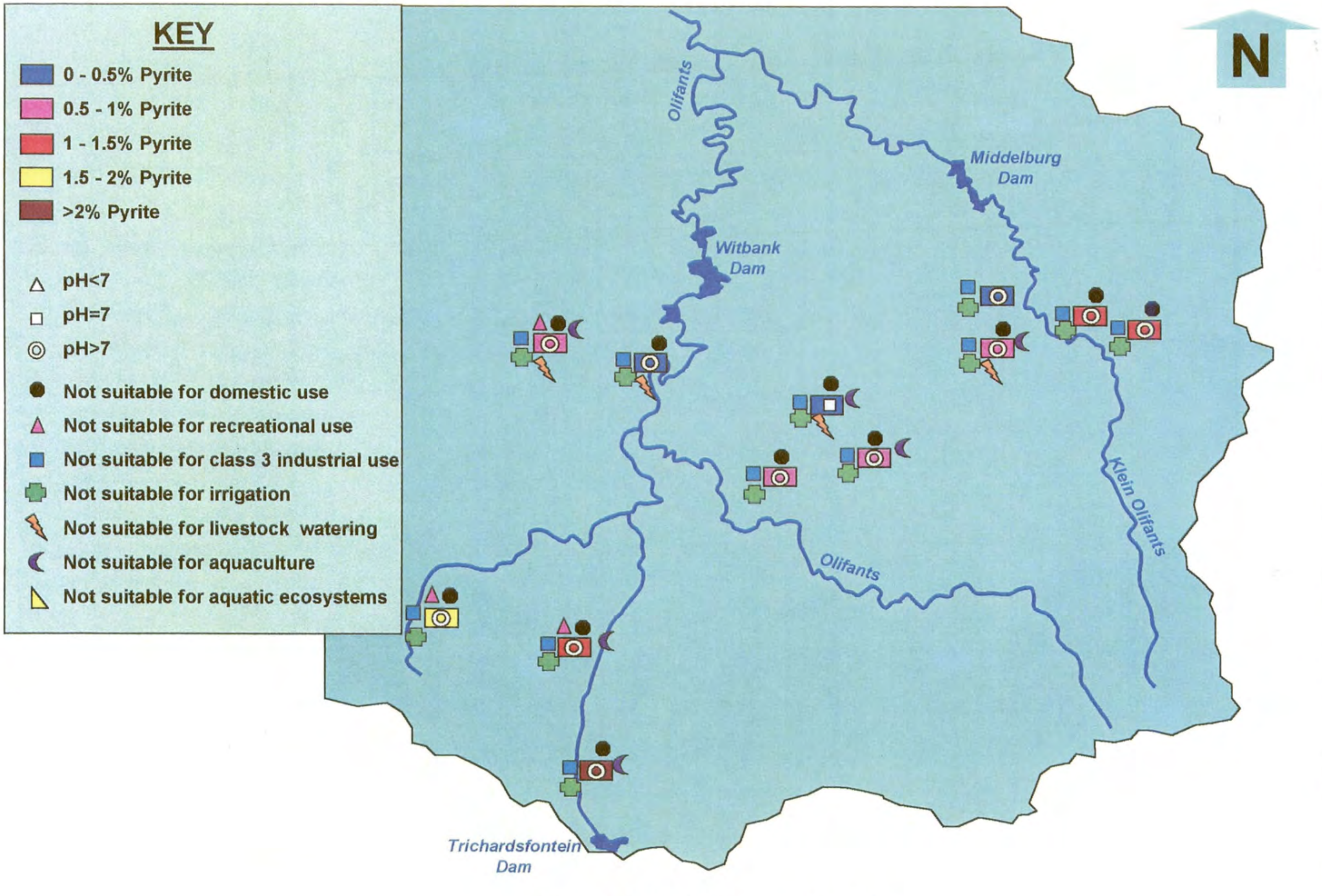


Figure 14: Pyrite % vs water quality

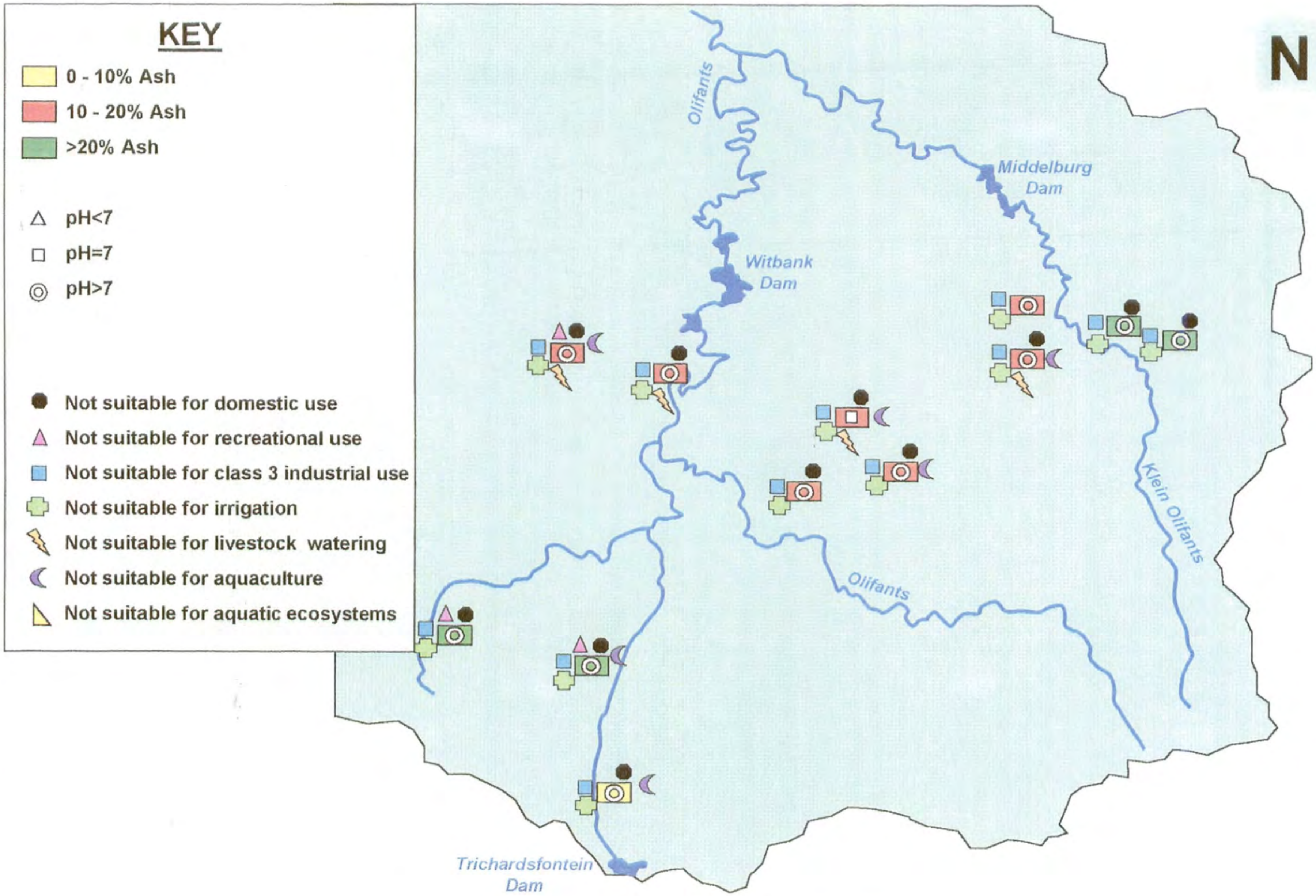


Figure 15: Ash % vs. water quality

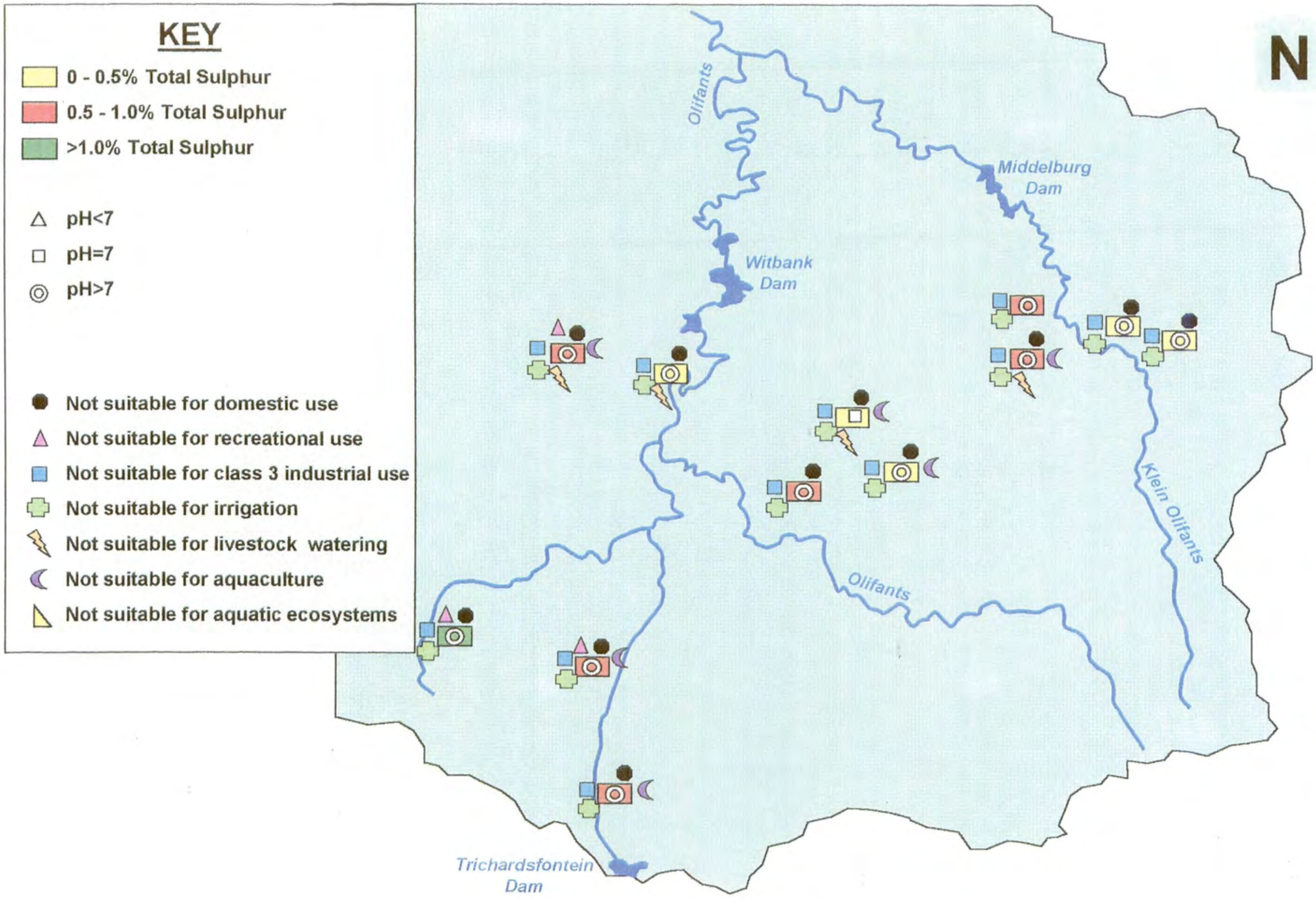


Figure 16: Total Sulphur % vs. water quality

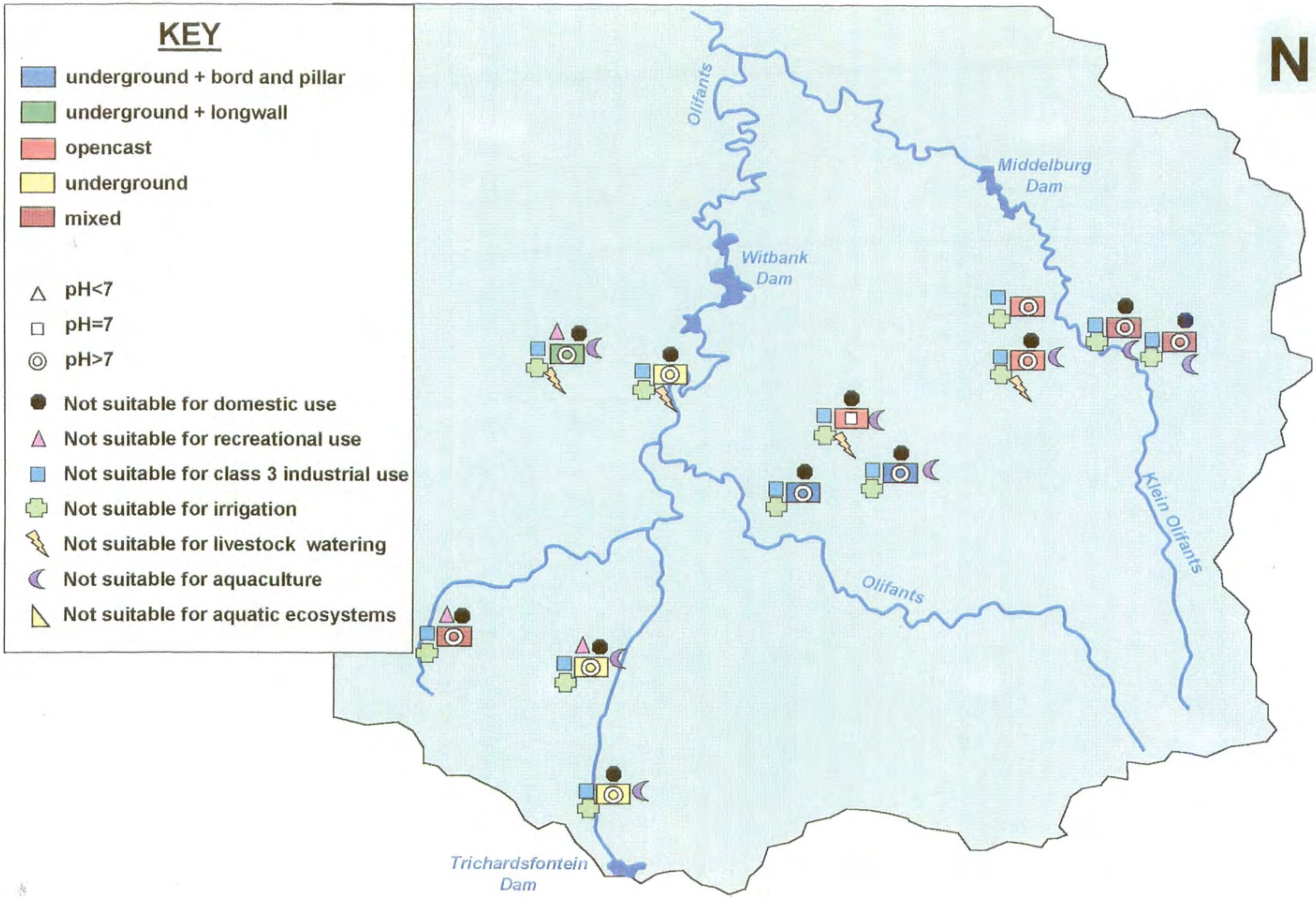


Figure 17: Mining method vs water quality

Initially, there are a number of logical results, which can be expected:

- It is not expected that there will be a strong correlation between fixed carbon and water quality.
- Pyrite is expected to have a strong correlation with water quality as pyrite is the primary cause of acid mine drainage. It provides both the sulphur to generate acidic pH and iron which is leached out to contaminate both water and soil.
- Depending on the composition of the ash content of a coal, one can expect some sort of correlation between ash percentage and water quality.
- Similarly, one would only expect a correlation between metallic sulphates and water quality, as these are the sulphur compounds responsible for acid generation. Total sulphur is not as indicative a variable of the capacity of a coal to generate acid water.
- Mining method can be expected to show some correlation with water quality. Generally, it has been found that the more coal that remains in situ the greater the opportunity for coal-water interaction and ultimately the acidification and contamination of the water concerned. Therefore, one would expect poorer quality water where there is bord and pillar mining with some pillars remaining and loose pyrite-rich material lying on the floor.

8.2 Results of beaker tests

The results of beaker tests have been graphically presented in Appendix C. The sites selected for such testing of selected samples are indicated in figure 18.

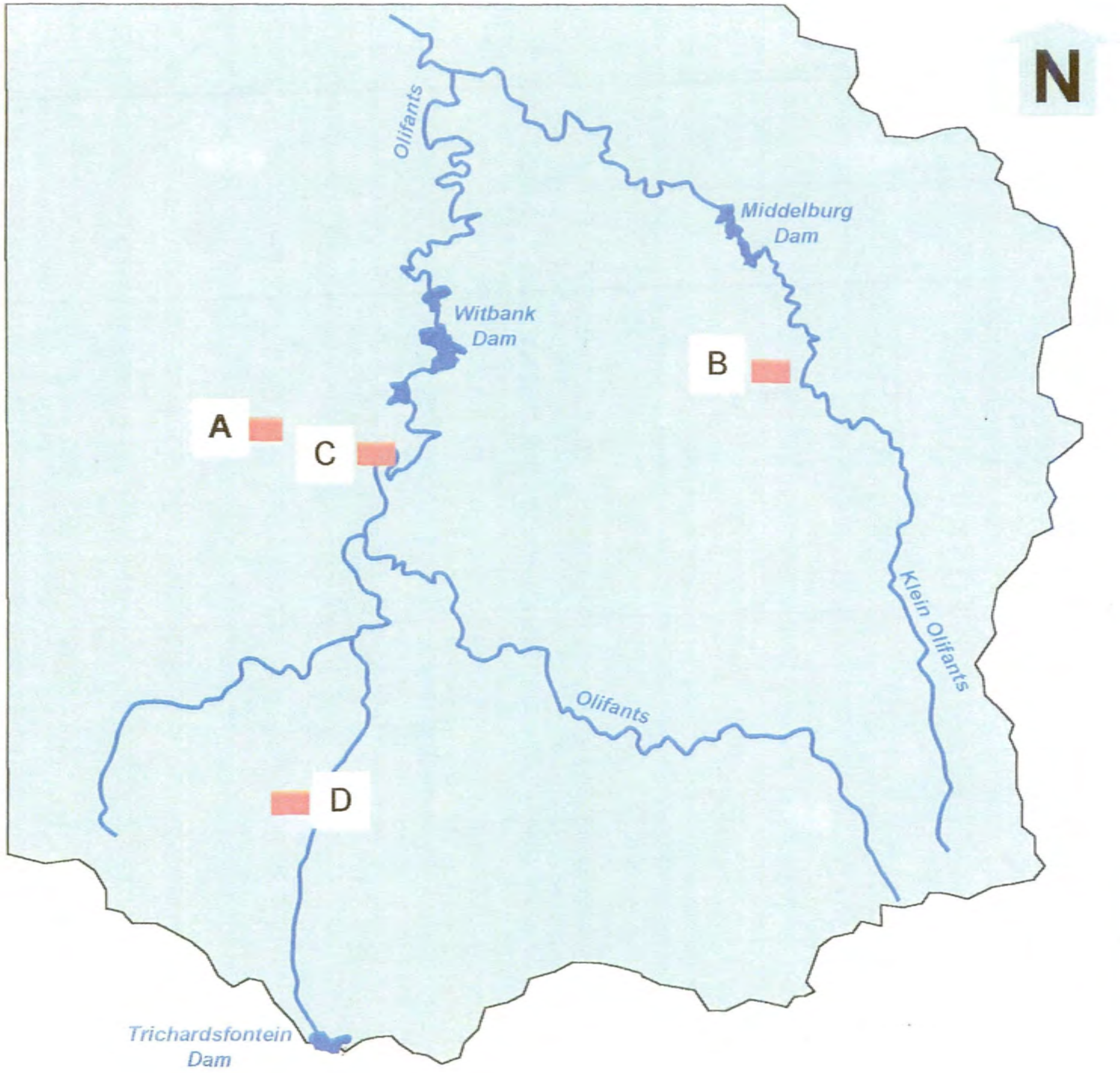


Figure 18: Location of sample sites used for chemical analysis

8.3 Discussion

The following conclusions can be drawn from the results of the GIS map:

- A GIS map is a good way to display the data held within one or more databases. It makes the analysis of that data easier and more accessible to the layperson.
- Those samples with >1% pyrite content are most likely to yield the poorest quality water i.e. not suitable for any use.
- However, in terms of pyrite content alone, there are no sites that are expected to yield water that is unsuitable for aquatic ecosystems.
- Those samples with high pyrite content are generally those with high total sulphur content. In those cases where the resultant water quality is not as poor as might be expected, it is assumed that the sulphur compound is something other than pyrite and/or that there is a neutralising effect caused by a mineral such as calcium carbonate.
- Water quality is poorest in those areas where samples exhibit an ash content of >20%. However, such water is still suitable for livestock watering, aquaculture and aquatic ecosystems.
- % fixed carbon also has a definite role to play in determining the resultant water quality. Samples with a total carbon % that is >60% yield water of the best quality. This simply means that the mineral content of the coal i.e. ash is low.
- The coal used in this study did not exhibit a significant sulphur content. However, it may be said that the higher the sulphur content of the coal, the poorer the quality of the water into which the leachate enters.
- The method of mining employed does not have as marked an effect on the resulting water quality.

The following conclusions can be drawn from the chemical leaching beaker studies:

- The pH for all sites and all samples (except ash) ranges between 5.6 and 9.0, as can be seen in Figure 19. pH increases most rapidly from 0 minutes to 30minutes and then starts to level off. This is an indication that the most acid water is released within the first 30 minutes of contact with water. In the case of the ash sample, pH ranges from 10.88 to 11.28. However, it is important to note that these values do not increase sequentially. Rather, there is no apparent trend for this type of sample.

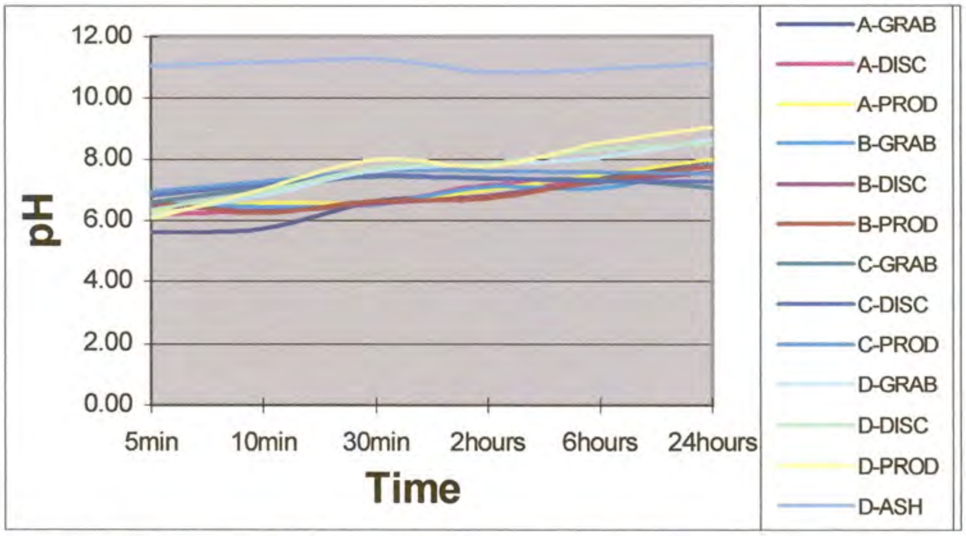


Figure 19: Summary of all samples: pH over time

- As was to be expected from South African coals, the sulphate value for all sites and all their samples was below 247 mg/l and as such is no cause for concern.

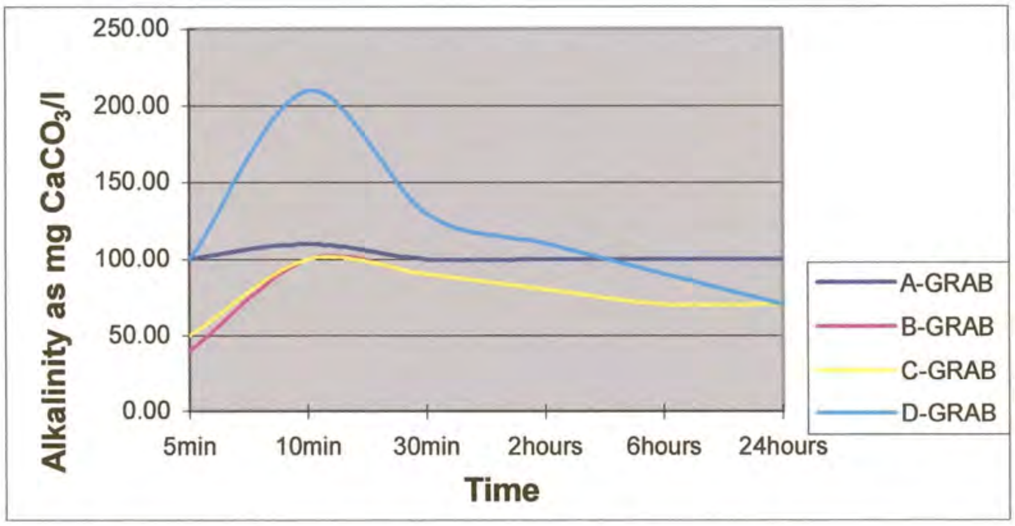


Figure 20: Summary of 'grab' samples: Alkalinity over time

- The alkalinity that was calculated for Site A shows a similar trend-line to that of its pH i.e. alkalinity increases during the first 15 minutes and then tapers off to a constant value of 100 mg $CaCO_3$/l, as can be seen in Figure 20. This is the trend that could be expected by a sample that is relatively richer in neutralising minerals that counteract the acid-producing effect of the acid-generating minerals successfully over a 24 hour period.
- The 'grab' samples from Sites B and C follow a path more similar to each other i.e. a rapid decrease in alkalinity during the first 15 minutes followed by a gradual decrease during the next 6 hour period. This is the trend that could be expected by a sample that also contains effective buffering minerals, but whose neutralising capacity may be overcome over time owing to the growing acid-generating potential of the sulphide minerals contained in the sample.
- The alkalinity trend for sample D shows the most marked variation, but follows a similar trend to that of sites B and C. Approximately 10 minutes after contact with water, all of the buffering minerals have had their effect on the solution. Thereafter, alkalinity rapidly decreases to another critical point at 30 minutes, where most of the acid-generating minerals have had their effect. However, due to relatively more or stronger acid-generating minerals in solution, alkalinity continues to decrease over the 24 hour period. This type

of sample could be expected to generate more strongly acid leachate in the longer term and therefore, long-term management strategies would have to be developed for such a site.

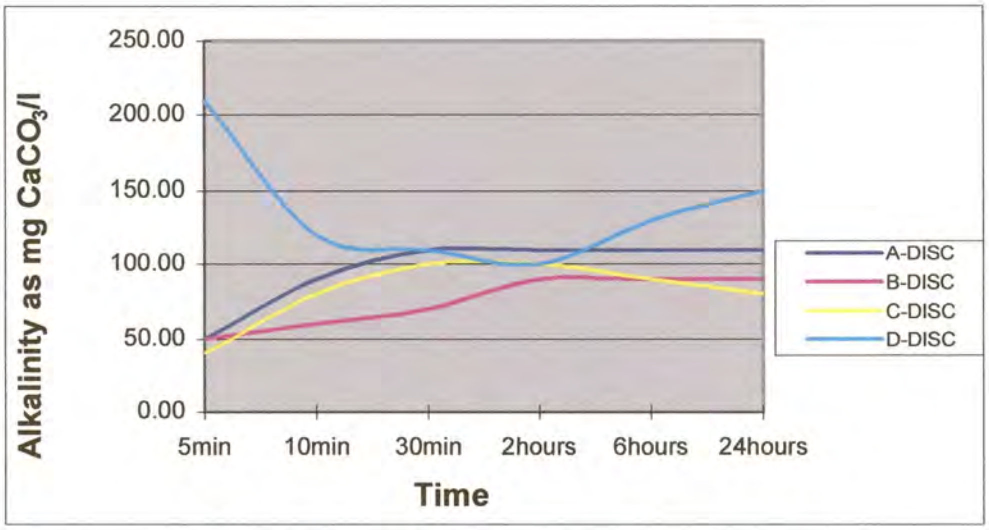


Figure 21: Summary of discard samples: Alkalinity over time

- When discussing the alkalinity trends of any discard sample relative to a grab sample from the same site, it must be remembered that all grab samples were taken in situ from a particular coal seam in each mine and the discard samples were taken randomly from a depth of 1m in the discard dump of that same mine. All discard samples have therefore been subjected to a greater intensity and variety of weathering, prior to these tests, than the grab samples.
- The alkalinity trend for the discard sample from Site A shows an increase during the first 30 minutes and then remains relatively constant for the remainder of the 24 hour period.
- The discard sample from Site B shows a slower increase in alkalinity than that of Sites A and C, only reaching maximum alkalinity after 2 hours and then remaining constant.
- The alkalinity of the discard sample from Site C increases during the first 30 minutes and then very gradually decreases over the remainder of the 24-hour period. This decrease in alkalinity was also evident in the grab sample from

Site C and is thus cause for concern when considering management options for the discard dumps at this mine.

- The discard sample from Site D is very distinct. It is interesting to note that the decrease in alkalinity of the grab sample is not followed by the discard sample, rather there is a marked increase in alkalinity over the final 19 hours of the beaker test. This indicates the increased effectiveness of the buffering minerals in this sample over an extended period of time once the sample has been allowed to weather naturally. There could thus be less cause for concern than that expressed in response to the alkalinity trend of the grab sample from this mine.

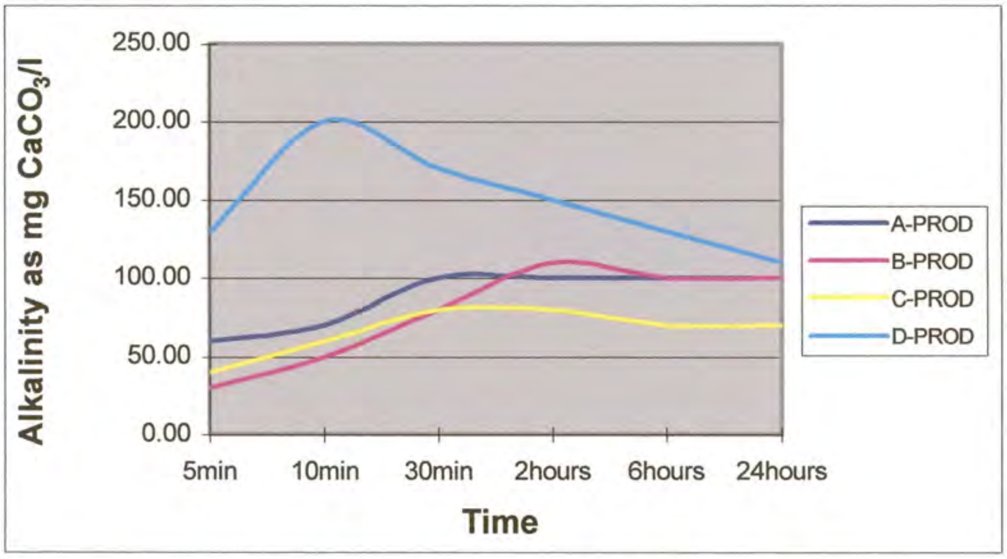


Figure 22: Summary of product samples: Alkalinity over time

- The alkalinity trend for the product sample from Site A exhibits an increase in alkalinity during the first 30 minutes and then remains constant at 100 mg $CaCO_3$/l. This trend is much the same as that for the discard sample from the same site.
- The product sample from Site B also shows an increased alkalinity, but this occurs over the first 2 hours of the test. There is then a slight decrease over the next 4 hours and then the alkalinity also remains constant at 100 mg

$CaCO_3$/l. This trend is much the same as that for the grab and discard samples from the same site.

- The alkalinity trend for the product sample from Site C shows a marked increase during the first 30 minutes, a gradual decrease over the next 5 ½ hours and is then constant for the remainder of the 24 hour period.
- The product sample from Site D shows a much higher alkalinity than that of the other sites. The trend exhibited is much the same as that of the grab sample for the same site.

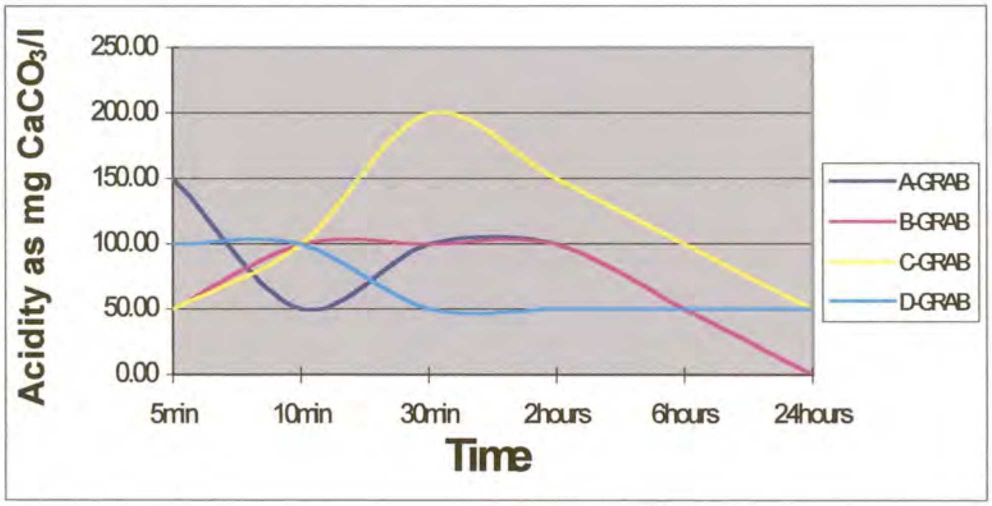


Figure 23: Summary of 'grab' samples: Acidity over time

- The acidity values calculated for the 'grab' samples for each Sample Site have only one characteristic in common i.e. they all ultimately decrease over a 24-hour period to a negligible value (Figure 23), except for the sample from Site D which shows constant acidity from 30 minutes onwards. It is important here to compare trend in acidity to trends in alkalinity in order to determine whether there is a direct correlation between the effects of acid-generating and neutralising minerals in the samples.
- It is assumed that sample A generates acidity during the first 5 minutes (due to a lack of neutralising minerals), whereas sample B only begins to generate acidity after the first 5 minutes (possibly due to the counter effects of

neutralising minerals) and sample C in turn issues a steady generation of acidity that decreases after the first 30 minutes.

- It is also assumed that sample D generates acid during the first 5 minutes. In the case of this sample, the counter effects of buffering minerals is experienced during the second 5 minutes and this buffering effect increases to a maximum at 30 minutes. After this, acidity remains constant at a value of 50 mg $CaCO_3$/l.

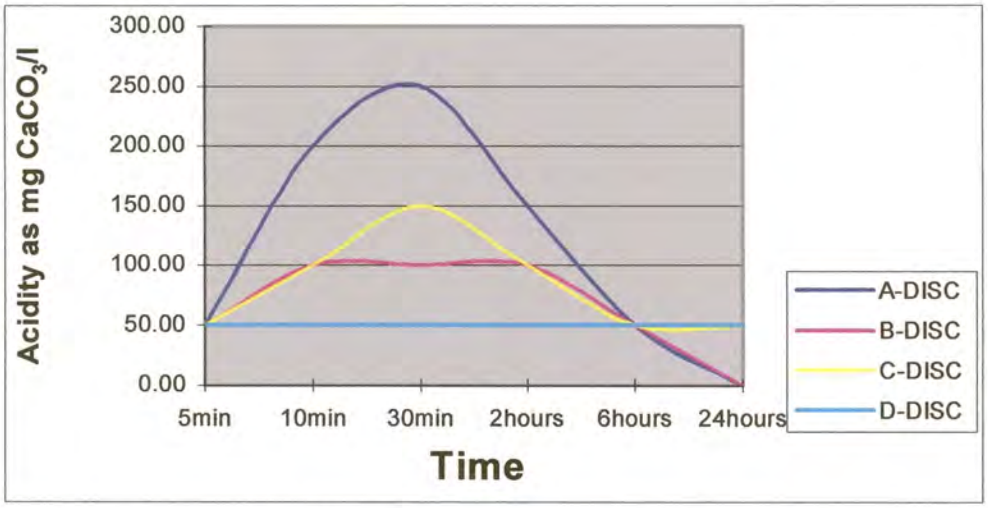


Figure 24: Summary of discard samples: Acidity over time

- The acidity values calculated for the discard samples for each Sample Site have only one characteristic in common i.e. they all ultimately decrease over a 24 hour period to a negligible value; except for the sample from Site D which maintains a constant acidity of 50 mg $CaCO_3$/l throughout the 24 hour period. The other inconsistencies in their trend must once again be explained by the relative neutralising capacity of their mineralogical make-up (Figure 24).

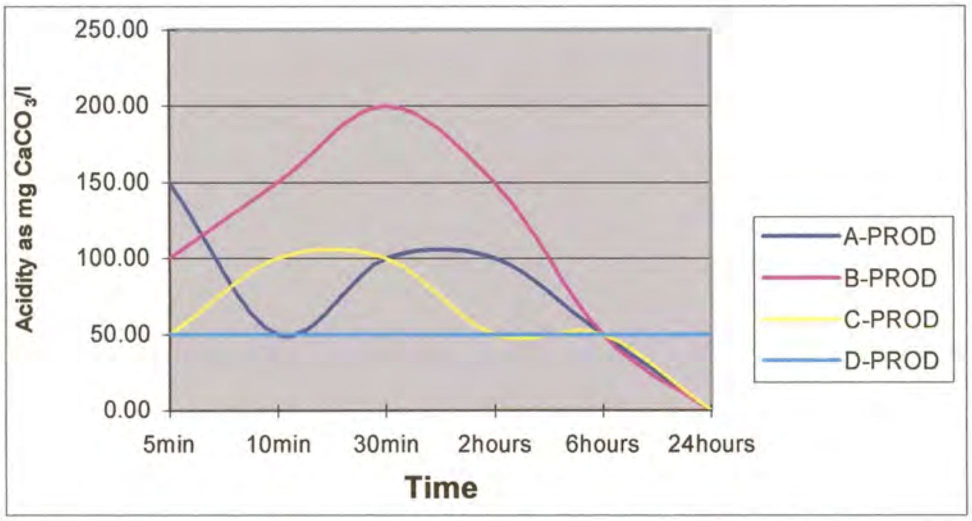


Figure 25: Summary of product samples: Acidity over time

- The acidity values calculated for the product samples for each Sample Site have only one characteristic in common i.e. they all ultimately decrease over a 24-hour period to a negligible value (Figure 25).
- Samples A and B have a high initial release of acidity i.e. during the first 5 minutes, after which they decrease only to increase again after about 2 hours. This second burst could be due to a simultaneous decrease in available neutralising agents within the product itself.
- Sample D is different in that it releases a relatively constant amount of acidity over the course of the experiment. It is assumed that this is due to the treatment process involved with producing this particular coal product.

- In general it may be stated that:
  - 'Grab' samples are likely to generate the most acid leachate;
  - Product samples are most likely to exhibit the highest alkalinity due to their processing and treatment; and
  - Ash samples, or samples with a high ash content, are most likely to produce highly alkaline leachate.

Chapter 9

PREVENTION, PREDICTION, MANAGEMENT & TREATMENT

9.1 Prevention mechanisms

The impacts of Acid Mine Drainage can be minimised by:

- Preventing water from getting to the pyrite by diverting rainwater away from workings or dumps.
- Preventing air from getting to the pyrite by compacting coal discard in thin layers.
- Removing water entering pyritic mines as soon as possible to minimise residence time.
- If acid mine drainage cannot be prevented, treating it by neutralisation with lime; in extreme cases a biocide such as bromine can be added to kill the acidifying bacteria. However, large quantities of bromine can become an additional source of pollution.
- Using passive water treatment technology where small seepage flows from abandoned workings, back-filled areas and dumps are acid and mineralised.

The potentially acid generating material should be prevented from mixing with air and water. Once the reactions begin, it is virtually impossible to completely stop AMD. The challenge is thus to isolate and contain the potentially toxic parts of the waste. The most reliable method for preventing AMD is to submerge the waste rock or tailings under water. This will prevent exposure to oxygen. The success of this method depends on keeping the water cover and dam structures intact forever.

A mitigation strategy proposed by a number of mines (including coal mines) in British Columbia is the use of blended dumps. The theory is that the combination of potentially acid and potentially neutral waste products will result in non-toxic drainage. In the case of coal mining, under certain blending criteria, projects have been successful (Kleinmann, 1990).

9.2 Prediction techniques

The science of predicting AMD is still far from conclusive. When attempting to predict AMD, the questions that need to be answered include:

- What is the acid-generating potential and neutralisation potential of the different rock types that will be exposed during the mining process?
- What potential contaminants/metals occur in the rocks that will be exposed?
- Under what conditions will exposure and transport of the contaminants take place at the mine site?

(Coastech Research Inc., 1989).

9.2.1 Statistic testing

This level of test involves the description of different characteristics of rock types at the mine site, with an eye to finding those components that are likely to generate acid and those that may buffer or neutralise the acidic potential of the mine waste. Acid Base Accounting (ABA) is one of the main preliminary tests run in assessing acid potential. A measure is made of the bulk amounts of acid-generating and acid-neutralising materials drawn from key areas in the mine site. Minerals containing sulphur, particularly sulphides such as pyrite, have the potential to generate acid when exposed to air and water. Other groups of minerals, such as carbonates e.g. calcium carbonate, can buffer or neutralise acidity. In ABA the acid-generating and –neutralising potential of multiple samples are compared, to see whether they may be expected to balance each other out. However, this is only a laboratory test and cannot account for many environmental and geochemical factors that may alter the chemical interaction between the acidic and basic components of the rock.

9.2.2 Kinetic testing

This is usually the nest step after ABA and is a more sophisticated stage of testing. Typical tests include "humidity cells" that can combine larger samples of mine waste with air, water and bacteria. This enables analysts to observe the rate at which acidification occurs over longer periods of time i.e. months. However, if kinetic testing is rushed or carried out improperly it is subject to failure and the distortion of results.

Generation of Acid Mine Drainage is more of a problem where coals have a high pyritic sulphur content e.g. 4% or more (diPretoro and Rauch, 1988).

9.3 Management strategies

Management of acid mine drainage is required by law in South Africa. There are three distinct groups of legislation applicable to water management, and therefore the associated potential problem of acid mine drainage.

Firstly, the Department of Water Affairs and Forestry (DWAF) provides legislation in the form of the new National Water Act, Act 36 of 1998. The aim of DWAF is to phase out General Effluent Standards and employ the Receiving Water Quality Objectives. It also supports the concept of managing water in terms of catchments.

Secondly, the Department of Minerals and Energy (DME) has provided legislation to which the Minerals Act is central.

Thirdly, the Department of Environment Affairs (DEA) has provided legislation in the form of the Environment Conservation Act. This Act encourages the concept of Integrated Environmental Management (Barnard, 1999).

9.3.1 *Mineral and mining management*

In order to address the environmental impacts of mining, a system for the management of these impacts was developed. This system forms a vital component of the Minerals Act 50 of 1991, section 9. In the 1990s, power was transferred from the mining houses to the structures for environmental governance existent in South Africa. Mining regulations were already in place since the 1970s, but their enforcement had not been given much attention. There was much other legislation that either anticipated or affirmed the rise of environmental rights over the previous, unchecked, right to exploit minerals. This legislation included the following:

- Environment Conservation Act 73 of 1989
- Development Facilitation Act 67 of 1995
- Mines Health and Safety Act 29 of 1996
- Bill of Rights in the Constitution of the Republic of South Africa Act 108 of 1996
- National Environmental Management Act 107 of 1998

The first application of the holder of a mineral right is for authorisation, in principle, to use mineralised land for mining. Mining authorisation is issued only once the Director of the Department of Minerals and Energy is satisfied with the "manner in and scale on which the applicant intends to mine the mineral concerned". The applicant must also satisfy the Director "with the manner in which such applicant intends to rehabilitate disturbances of the surface" and that "such applicant has the ability and can make the necessary provision...to rehabilitate such disturbances".

The Development Facilitation Act (DFA) lays down "general principles governing land development throughout the Republic". The DFA focuses on maximising the yield of land.

The Constitution of the Republic of South Africa Act protects the rights of everyone not to "...be deprived of property except in terms of law of general application". Depending on its location and management, a mine can act adversely on these rights by for example subjecting people to noise and polluted air or water.

The Environment Conservation Act contains overarching legislation. An important source of principles is the general environmental policy determined in terms of section 2. It established the following:

- The need for sustainable development
- The need for a holistic evaluation of projects
- The need to internalise external costs
- The requirement of the judicious use of land
- The need to prevent the destruction of wetlands and other environmentally sensitive areas
- The need for the application of scientific conservation principles in all land-use planning
- The undertaking of planned analyses of large-scale or high-impact development projects before embarking on them
- The involvement of the public in development planning

It is important to note that the Environment Conservation Act should be read with the National Environmental Management Act.

The National Environmental Management Act develops the principles first set out in the general environmental policy of the Environment Conservation Act.

As yet, no checklist exists to make it easier to evaluate applications in terms of section 9 of the Minerals Act. Thus the effect of the proposed activities must be evaluated against the principles set out, and in this respect DME officials are obliged to provide assistance (Barnard, 1999).

9.3.2 Water management

The White Paper *A National Water Policy for South Africa* issued by the Department of Water Affairs and Forestry in April 1997 established the basis for future water legislation. The National Water Act 36 of 1998 is structured around the following principles:

- Water is scarce
- It is unevenly distributed
- It belongs to all people
- All aspects of water must be managed in an integrated manner
- Water management must achieve sustainable use and must protect its quality

A number of underlying principles to the National Water Act deserve special mention and a brief discussion.

The ancient Roman law that water belongs to the state, which holds this resource in trust for the nation, is an internationally accepted principle. This is the basis of the Act.

In the hierarchy of water allocation the 'reserve' is regarded as priority use. The reserve is made up of two parts i.e. the basic human needs reserve and the ecological reserve. The basic human needs reserve provides for the essential needs of individuals served by the water resource and includes water for drinking, food preparation and personal hygiene. The ecological reserve relates to the water required to protect the aquatic ecosystems of the water source. The purpose of determining such reserves is to meet the requirements of sustainable use, not only of water but also of the ecosystems where it occurs.

Once the water for the reserve has been allocated, the priorities for further water allocation will depend on every applicant's circumstances and the particular characteristics of every water management area. In section 21 of the Act, lawful water uses are defined. These uses go beyond the traditional use of water for domestic, agricultural, recreational or industrial purposes. Waste disposal in a manner that may detrimentally impact on a water resource is included in the definition of water use. The sub-categories of industrial use include the use of water for cooling, steam generation, as process water, as production water and as utility water. The fitness of the water for use is determined in terms of its corrosiveness, scaling, fouling, forming of blockages, foaming, gas production, contamination, coagulation, turbidity, waste disposal and a number of other factors. The constituents analysed include alkalinity, chemical oxygen demand, pH, chloride, iron, manganese, silica, sulphates and several others.

It is essential that the quality of water should not be degraded and that water that has been polluted is purified to acceptable levels. As issues arose over the years, the integrated water quality management system evolved. In order to implement the aims of the receiving water quality objectives, water quality guidelines were compiled, based on the requirements of recognised water users; the closely aligned water quality management objectives, which recognise the water quality requirements of the water users as well as economic, social, political, legal and technological considerations were formulated; and site-specific effluent standards or other measures were set to ensure that the water quality management objectives determined for the particular water body would be met.

These are just some of the objectives that form the legal framework within which we must consider the relationship between water resources and the activities of the coal mining industry (Barnard, 1999).

9.3.3 Waste management

The Concise Oxford Dictionary defines waste as 'unwanted or unusable remains or by-products'. In the course of coal mining activities, many products for which there is no apparent use are produced. The variety of matter constituting waste is staggering. The wide variety of adverse impacts caused by waste has resulted in the development of many waste management measures.

The threat posed to human health by badly managed waste is addressed in several acts. The Health Act 63 of 1977 regulates conditions dangerous to health, such as the disposal of sludge or other waste products at a water purification works (section 37 (f)). The Hazardous Substances Act 15 of 1973 provides for the control of hazardous substances. These substances are categorised in SABS Code 0228. The depositing of waste in (or with access to) water courses is illegal as it causes pollution of that water in terms of the National Water Act 36 of 1998. Such actions may also cause the destruction of vleis, marshes and watercourses in terms of the Conservation of Agricultural Resources Act 43 of 1983.

Waste management has attained a relatively high level of sophistication. Structures have been developed that control many forms of waste. They also deal with waste in an integrated manner. Waste is primarily managed in terms of the Environment Conservation Act 73 of 1989. Mining-related waste is managed in terms of the mining-related legislation discussed above i.e. the Minerals Act 50 of 1991. Department of Water Affairs and Forestry manages the disposal of waste and has compiled a set of guidelines in the form of The Minimum Requirements for Waste Disposal; and Department of Environment And Tourism manages all other aspects of waste in South Africa (Barnard, 1999).

9.3.4 Standards and guidelines

DWAF uses the concept of fitness-for-use when giving standards with which water qualities should comply. These standards are contained in several volumes; compiled by DWAF i.e. domestic, recreational, industrial and agricultural use guidelines, respectively (Appendix A2). Environmental standards will be included after the current revision of these documents. A major knowledge gap at present is the very slow development of fitness-for-use standards for all major water users in the mining industry (Barnard, 1999).

There are at present three generally accepted approaches to the prevention or control of acid mine drainage, as follows:

- Control of the acid generating process.
- Control of acid drainage migration.
- Collection and treatment of acid mine drainage.

The three options have been listed in order of preference. The objectives of acid mine drainage monitoring are thus to:

- Detect the onset of acid generation before acid mine drainage develops to the stage where environmental impact occurs. Abatement measures, if required, need to be implemented as soon as possible.
- Monitor the effectiveness of control measures.

9.3.5 Control of acid generation

- Sulphide removal or isolation
- Exclusion of water
- Exclusion of oxygen
- Temperature control
- pH control
- Control of bacterial action

Criteria that need to be considered in the selection of control measures include:

- The degree of acid-producing potential of the mine waste. This includes the nature, quantity and reactivity of sulphide minerals present, neutralising potential of the rock etc., and would be determined using geochemical testing.
- The type and physical characteristics of the waste.
- Site criteria, such as climate, topography, surface and groundwater hydrology.
- The time period for which the control measure is required to be effective.
- The sensitivity of the receiving environment to AMD.

(Bowell, Fuge, Connelly and Sadler, 1996).

9.3.6 Control of acid migration

Water entry may be controlled by:

- Diversion of all surface water flowing towards the acid mine drainage source
- Prevention of groundwater flow into the acid mine drainage source
- Prevention of infiltration of precipitation into the acid mine drainage source
- Controlled placement of acid-generating waste.

(Broughton and Healey, 1992)

9.3.7 Management design criteria

Criteria for the design of an AMD management strategy include a large number of items. These criteria consider both bench test results and industrial experience. They include:

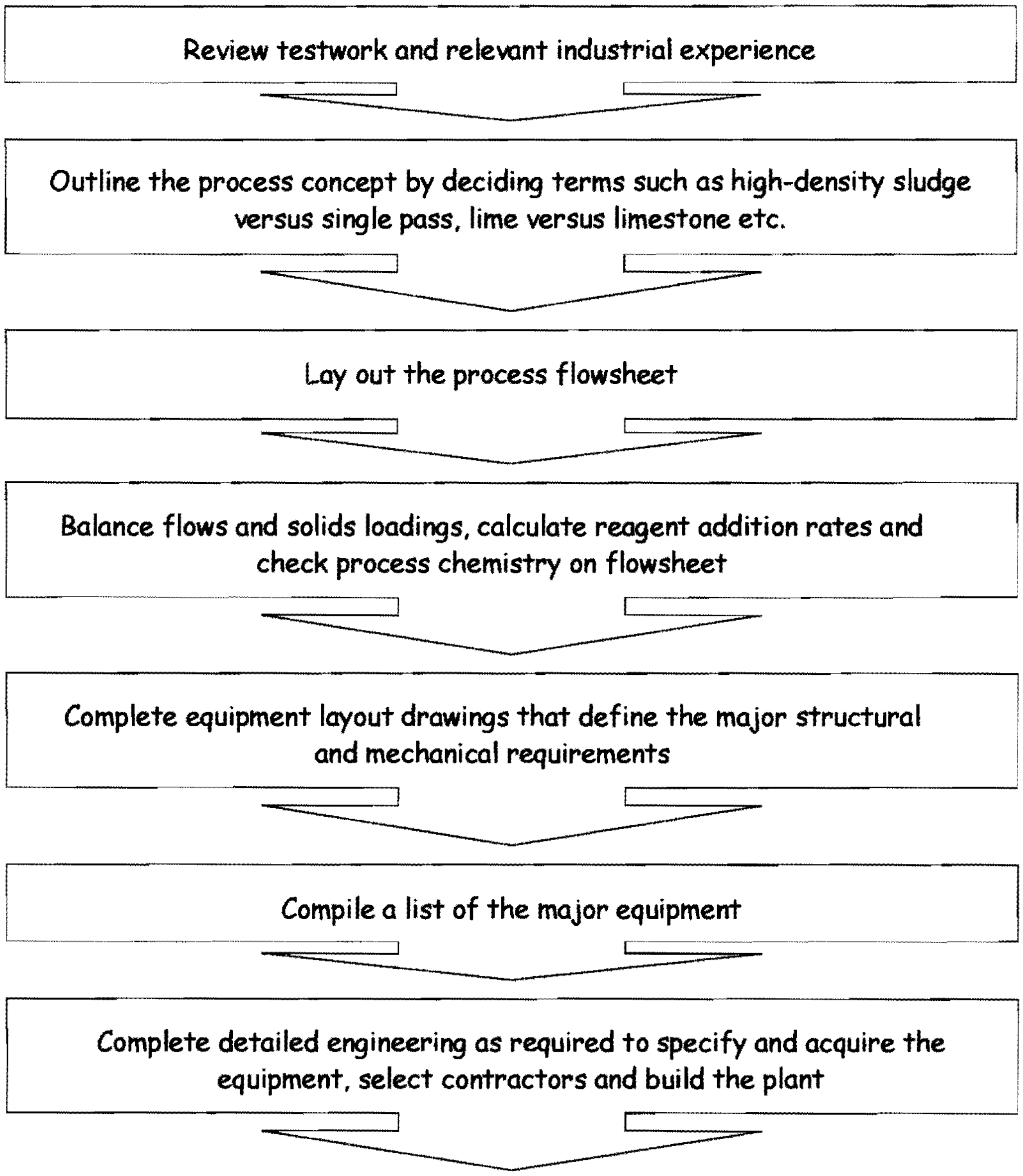
- Feed rate and hydraulic loading of coal
- pH
- Residence time

- Reagent dosages
- Clarifier loading
- Aeration and agitation
- Recirculation

(Castelli *et al*, 1992).

9.3.7.1 The design process

The design process may be outlined as follows:



<u>Figure 26:</u> The design process

9.3.7.2 Modelling

The graphics oriented system uses 3D volume modelling, geostatistics and visualisation to provide integrated capabilities for precise modelling of all aspects of the geological environment. The system can also superimpose the effects of pollution. In addition, it can simulate the results of proposed reclamation and remediation measures. It can be applied in a predictive context to forecast the effects of future mining activities, and/or in a monitoring context to determine the degree and extent of acid mine drainage (AMD) related problems. The results produced support the design of economic and effective AMD prevention or containment measures. The integrated geostatistical capabilities of the system are used to determine the distribution and extent of sub-surface contamination based on isolated observations e.g. borehole sample analysis results (Costa *et al*, 1992; Houlding, 1992).

9.3.8 Water quality management objectives

In order to develop a water quality management plan for the Witbank and Middelburg Dam Catchments, or any other catchment with similar conditions, the following protocol should be followed:

- Land use practices, mining, industrial and urban developments should be quantified in terms of a specific time frame e.g. the next 20 years.
- Initial values for soil moisture, sulphate concentration in soil moisture, groundwater level, sulphate concentration in groundwater and impoundment sulphate concentrations should be carefully estimated.
- Model simulations should be conducted using all available historical meteorological and hydrological data.
- Initial estimates for the soil moisture sulphate concentrations, groundwater sulphate concentrations and impoundment sulphate concentrations should be adjusted until a steady state situation is approached.

- Parameters describing the abstraction of water, inter-basin transfer of water, point and non-point sources of sulphate pollution should be adjustable to reflect any future water quality management approach (Harpley and Geldenhuis, 1987).

It is also necessary to do the following:

- Investigate patterns of land use and their impact on surface water quality i.e. mining, industry agriculture and urban development.
- Develop insight into pollutant mobility and future catchment scenarios by modelling water quality.
- Formulate probable future land use and development scenarios for the catchment.
- Identify and formulate water quality management options.
- Develop water quality management objectives to sustain long-term acceptable water quality to all users.
- Develop a water quality information system to allow adequate feedback to catchment water resource managers.
- Establish a management structure and provide the necessary resources to implement the Water Quality Management Plan.

The water quality management structure should be of an adequate size and consist of suitably qualified manpower to answer to the needs of their management unit. It should include representatives from mining, industry, agriculture and municipalities. It must define its spectrum of recognised water users and their water quality requirements. It must also encourage representation by the most significant player in the presence and mobilisation of primary pollutants.

In order to derive a set of water quality guidelines for the water quality management strategy the following points must be adhered to:

- Recognised water users in each catchment must be identified.
- The water quality requirements for each user should be listed in terms of the variables of concern to that particular user.
- These requirements must be analysed with respect to each water quality variable and the most sensitive user must be identified.
- The requirements of the most sensitive user then determine the water quality guideline values (Pulles *et al*, 1996).

9.3.9 Future management options for the Witbank and Middelburg Dam catchments

Requirements for the future management of water quality affected by coal mining activities in the Witbank and Middelburg Dam catchments include:

- Control of mining related non-point sources of pollution.
- Control of periodic point source discharges of effluent process water from power stations.

The proposed basis for the allocation of sulphate waste load should be based on the following criteria:

- Size of the mine, expressed in terms of production in ton ROM/annum.
- Age of the mine. Expressed in terms of total historical ton ROM produced.
- Mining technology, which distinguishes between open cast mining and underground mining.
- Sulphur content of the coal itself.

9.4 Treatment technologies

Various treatment options exist for the removal of acidity or the neutralisation of pH. Chemical addition processes involve the addition of lime, soda ash or caustic soda to the water. Although lime is the cheapest and most commonly used neutralising chemical, it suffers from two drawbacks:

- It leaves no residual buffer capacity in the water
- It adds calcium to the water, thereby increasing hardness and scaling properties.

Limestone is much cheaper than other chemicals used for the purpose of neutralising acid water. However, it suffers from a number of problems:

- Slow reaction time
- Tendency to armour with iron

For these reasons, techniques have been developed to use limestone in fluidised bed reactors. The advantage of this approach is that the agitation and scouring actions compensate for the slow reaction time and the armouring effects. However, this technology is only suitable for surface applications. This is because it requires a constant input flow rate and those to underground settling tanks have been known to change by a factor of 10 or more in less than 30 minutes (Durkin, 1995).

Anoxic Limestone Drains (ALDs) are used as a passive acidity removal technique. Appropriate pre-treatment is vital to address the problems of iron and aluminium. Design guidelines are being drafted in South Africa at present (DWAF, 1998). It is understood that these systems will be best suited to post-closure applications and the treatment of isolated seeps.

AMD pollutes thousands of kilometres of streams in the Appalachian region. Abandoned coal mines produce 90% of this acidic drainage. Most of these are deep mines. This occurs largely due to the fact that no individual is responsible for treating the water with chemicals. Wetlands and anoxic limestone drains have been installed on more than 100 sites and water quality improvements have been documented through monitoring. Iron and acid reductions were consistently greater in wetlands with limestone incorporated into the substrate. In terms of anoxic limestone drains (ALDs), the following conclusions have been presented:

- Organic matter should not be placed in the drains due to micro-organism growth on the limestone.
- Larger limestone particle size (2 cm to 6 cm) helps to maintain water flow through the drain especially in those cases where some Al, Fe and grit accumulate in the drain.
- Pipes installed in the drain must be large in diameter with large perforations to reduce the potential for plugging to occur.

(Kleinmann, 1989)

AMD can be effectively treated by passing the acidic water through underground beds of limestone. The water is neutralised by picking up alkalinity from the dissolution of limestone in these drains. Metals are also precipitated from the water. Many ALDs have failed over time due to the precipitation of metals in the drain which causes clogging of the limestone pores. On the basis of laboratory experiments, it appears that increasing the ionic strength of the water entering the drain can increase the effectiveness of ALDs. For example, when sulphate is added to acid water containing ferric iron and aluminium, much greater precipitation occurs, causing the successful removal of the metal ions from the water (Logsdon and Mudder, 1995).

Abandoned coal mines cover about 200 000 acres in West Virginia. Re-mining allows an operator to remove remaining coal reserves that were left on site and rehabilitate the entire abandoned mine site to current reclamation standards, thus affording environmental enhancement of previously affected areas.

AMD from an abandoned deep mine was eliminated by re-mining the deep workings and adding alkaline overburden material during back-filling and reclamation. The quality of the receiving stream has improved due to the results of remining.

On another site, reclaiming the discard on the site with fly ash and covering it with topsoil has reduced acid discharges by 90% (Steffen, Robertson and Kirsten, 1992).

The Cheat River Basin, West Virginia, is heavily polluted by AMD. A number of watershed projects have been initiated here and limestone filling of underground mines has been effectively employed to improve water quality in the area (Steffen, Robertson and Kirsten, 1992).

Generation of electricity by coal-fired power plants produces large quantities of bottom ash and fly ash. These ashes are alkaline in nature and are thus suitable for use in surface mine reclamation to neutralise acidity and reduce the hydraulic conductivity of disturbed overburdens. A strategy for controlling AMD on surface mines is isolating and segregating acid-producing materials with a barrier to limit their exposure to air and water. Ash generated by fluidised bed combustion (FBC) boilers could be used as an alkaline barrier material, as it has high neutralisation potential. FBC ash should be mixed with a porous material e.g. conventional bottom or fly ash, to minimise hardening and encourage continual release of alkalinity (Steffen, Robertson and Kirsten, 1992).

Treatment measures can be either active systems, which require continuous operation e.g. a chemical treatment plant; or passive systems e.g. wetlands.
Collection requires collection of both surface waters and groundwater contaminated by ARD. Collection of surface flows is usually readily achieved by means of surface ditches. The collection of groundwater flows requires the installation of collection trenches, wells, or cut-off walls to force the water to flow to the surface where it may be collected (Brown, 1995).

Chemical treatment involves the elimination of acidity by neutralisation of the acid stream with an alkali reactant or combination of alkali reactants offering the best economic implications. A number of bases may be considered for neutralisation including ground limestone, slaked lime, caustic soda, soda ash, ammonia and mill tailings. After neutralisation, most metals are precipitated as their respective hydroxides or hydrated metal oxides while the associated sulphate is precipitated as gypsum (Eggert, 1994).

A common operational concern in neutralisation systems is the formation of scale on process piping, equipment and instrumentation. This is most often associated with lime processes. The composition of scale is similar to the composition of the precipitates formed in the reactions. This may be due to a number of processes, including:

- Direct precipitation on the vessel surfaces
- Entrapment of precipitate in gypsum scale owing to gypsum supersaturation
- Absorption of CO_2 from the air by calcium-saturated solutions

Such scale is generally removed by acid treatment e.g. inhibited hydrochloric acid.

Sludges resulting from neutralisation of ARD can contain gypsum, heavy metal hydroxides, heavy metal arsenates and calcium arsenate. Instability may occur when the sludge is exposed to air or solutions of differing composition, or when changes occur over a long time period due to a slow chemical reaction (Pulles *et al*, 1996).

The treatment process is straightforward. However, there are alternative methods for accomplishing essentially the same objective. Stirred tank reactors, pipeline reactors, gravity clarifiers, circular clarifiers, reactor clarifiers, hopper clarifiers and lamella clarifiers are but a few examples which will be briefly outlined.

The advantages of stirred tank reactors are:

- Improved settling properties will result when the tank contents are close to neutralisation equilibrium. This will cause any precipitates to deposit on previously precipitated material, rather than form new nuclei.
- The tank may be constructed in a wide range of sizes. This permits any reasonable residence time to be achieved.
- More than one tank may be used, in series or parallel, to permit staging of the process.
- Where physical descaling becomes necessary, the stirred tank provides better access to reactor components than a pipeline reactor.
- Batch stirred tanks can provide very good process control, because neutralisation and reagent addition can be conducted in a stepwise manner, with pH measurements or other analyses conducted between steps or prior to discharge.

The advantages of pipeline reactors are:

- Most appropriate when neutralising with a soluble reagent.
- Short reaction times facilitate more accurate reagent dosage control.
- A caustic neutralisation scheme might reduce scaling compared to a lime system.

The main advantage of gravity clarifiers is:

- The tank provides sufficient residence time and settling area to allow solids separation and sludge densification.

Advantages of reactor clarifiers include:

- Flocculation efficiency is improved by adding polyelectrolytes to high solids concentration feed in a 'flash mix' chamber, followed by a flocculation chamber.
- Flash–mixing, flocculation and sedimentation may all be achieved in one vessel.
- Clarification efficiency is improved by allowing the mixture leaving the reaction zone to pass through a bed of flocculated solids (a 'sludge blanket') in the clarification zone, which provides a filtering action.

The advantages of hopper clarifiers are:

- Developed in South Africa, this is a simple apparatus, which is easy and inexpensive to operate.
- Requires very little operator attention.
- Virtually maintenance free.

The advantages of lamella clarifiers include:

- Settling area is multiplied through the stacking of plates. In effect clarification is increased by placing a series of clarifiers one on top of the other (Wates, 1987).

9.4.1 Process development and testwork procedures

It is essential to conduct process development and treatability testwork prior to design of a treatment system for ARD. Design failures associated with new treatment systems are commonly the result of one or more of the following:

- Non-representative samples
- Insufficient bench and pilot testing

- Inaccurate estimation of hydraulic loading
- Failure to compensate for hydraulic and chemical loading variability
- Inadequate process control instrumentation (Hutchison *et al*, 1995).

9.4.1.1 Characterisation of feed

The ore and waste rock can be characterised by examining the following features:

- Physical characteristics i.e. hardness, pore water pH etc.
- Mineralogical characteristics i.e. pyrite, pyrrhotite, calcite, arsenopyrite, galena etc.
- Metal composition
- Composition of major anions

9.4.1.2 Testing

Testing for design purposes should involve analysis of the following:

- Full set of analyses on the feed sample
- Generation of a neutralisation curve
- Determination of the neutralisation reaction rate
- Small scale batch precipitation and coagulation tests
- Flocculation tests and polyelectrolyte screening
- Settling tests
- Sludge characterisation and stability tests including physical and leaching characteristics
- Batch oxidation testing (where there is a need to oxidise ferrous iron or arsenite)

9.4.1.3 Case studies

Studies that simply consider the wetland as a "black-box" and only investigate the quantity and quality of influent and effluent cannot provide information on individual processes occurring in the wetland. A better option is to use a synthetically prepared acid drainage that contains only one contaminant at a time (Kleinmann and Hedin, 1993).

Substantial improvements in water quality can be effected by maximising the residence time of the water in the wetland. Optimum treatment of acid mine drainage may be obtained by co-disposal with another effluent which has a high pH (Hedin, Narin and Kleinmann, 1994).

The U.S. Bureau of Mines has developed porous polymeric beads (i.e. resin) containing immobilised biological materials for extracting metal contaminants from wastewaters. These beads have distinct advantages over traditional methods and can be used in conventional processing equipment or low maintenance systems. The beads have removed toxic metals such as Cd, Pb and Cu from a number of different wastewaters, including acid mine drainage waters from active and abandoned mining operations. Adsorbed metals are removed from the beads using dilute mineral acids (Robinson, Carrington, Fitch, Shupe, Herrmann and Worcester, 1992).

Chapter 10

CONCLUSION

Water is the lifeblood of any nation. It becomes an even more precious resource when it is scarce and in high demand. Thus we see the need to protect this resource from the impacts of man's development. This thesis is an attempt to discuss the issues surrounding the impact of coal mining on water resources with a few focal points taken from an extremely broad and complex subject.

Although this study did not reveal any significant pollution at the given sample sites in the Witbank and Middelburg Dam catchments, a number of conclusions may be made:

1. Grab samples are most likely to produce the most acid leachate.
2. Coal product samples are most likely to exhibit the highest alkalinity.
3. Ash samples, or samples with a high ash content are likely to produce highly alkaline leachate.
4. GIS maps are a very good method of correlating information contained in a series of databases and provide a user-friendly, interactive means to access a wide range of data at once.

Mining, by its nature, consumes, diverts and can seriously pollute water. These impacts depend on a variety of factors including the sensitivity of the terrain, the composition of minerals being mined, the type of technology employed, the skill, knowledge and environmental commitment of the mining company and our ability to monitor and enforce compliance with environmental legislation. For the sake of current and future generations we need to safeguard the purity and quantity of our water against irresponsible mineral development. We need to ensure the best pollution prevention strategies are employed in cases where the risks can be managed. We should also recognise that in some places mining should not be allowed to proceed because the identified risks to other resources are too great. In the right place and with conscientious companies, innovative technologies and good planning many of the potential impacts of mining on the aqueous environment are avoidable. In fact, most mine pollution arises from negligence and not necessity, as some would have us believe. Once a mine is in operation water protection must remain the highest goal of the company, even if it means reduced mineral productivity. Adopting this ethic is the only way we can ensure that the golden dreams of mining do not turn into the nightmare of poisoned streams.

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APPENDIX A

A.1 Water Quality Databases

Each water sample taken from the sample sites has been compared to the South African Water Quality Guidelines, to assess their respective fitness-for-use. In the following tables, all samples that do not fall within the water quality guidelines for a specific use, have been highlighted. For each set of guidelines, only those parameters for which standards have been set are indicated for means of comparison.

Please note that as the database used for this exercise was not compiled by the author, data has been omitted on the basis of unacceptable ionic balances.

PARAMETER	SO_4	pH	TDS	Na	Cl	Ca	Mg	Fe	Al	Mn
UNITS	mg/l		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
DOMESTIC	200	6-9	450	100	100	32-80	30	0.3	0.12-0.5	0.05
GOEDEHOOP	355	8	-	-	-	-	-	-	-	-
ARNOT	249	8	-	74	50	-	-	-	-	-
WOESTALLEEN	1866	8	-	100	-	33	21	-	0.1	-
KRIEL	165	9	482	113	28	22	18	0.02	0.28	0.01
KLEINKOPJE	1904	8	-	-	-	-	-	-	-	-
SYFERFONTEIN	334	8	707	208	12	23	20	0.24	0.15	0.08
MMS	1371	7	1985	41	13	-	-	0.16	0.13	0.93
MATLA	436	9	860	2	54	46	-	-	-	-
KOORNFONTEIN	352	8	-	107	36	-	33	0.88	-	0.32
GREENSIDE	1912	9	2321	73	53	36	-	-	-	-
EIKEBOOM	62	8	-	34	-	-	21	-	-	-

NOTE: '-' indicates no data available

Water from all sites, except for Eikeboom, is unsuitable for domestic use, based on the limited data available

PARAMETER	pH
UNITS	
RECREATIONAL	6.5-8.5
GOEDEHOOP	8
ARNOT	8
WOESTALLEEN	8
KRIEL	9
KLEINKOPJE	8
SYFERFONTEIN	8
MMS	7
MATLA	9
KOORNFONTEIN	8
GREENSIDE	9
EIKEBOOM	8

NOTE: '-' indicates no data available

Water from Kriel, Matla and Greenside is not suitable for recreational use, based on the limited data available.

PARAMETER	SO_4	pH	TDS	Cl	TOTAL ALKALINITY	Fe	Mn
UNITS	mg/l		mg/l	mg/l	mg/l	mg/l	mg/l
INDUSTRIAL	200	6.5-8	450	100	300	0.3	0.2
GOEDEHOOP	355	8	-	-	-	-	-
ARNOT	249	8	-	50	-	-	-
WOESTALLEEN	1866	8	-	-	21	-	-
KRIEL	165	9	482	28	18	0.02	0.01
KLEINKOPJE	1904	8	-	-	-	-	-
SYFERFONTEIN	334	8	707	12	20	0.24	0.08
MMS	1371	7	1985	13	-	0.16	0.93
MATLA	436	9	860	54	-	-	-
KOORNFONTEIN	352	8	-	36	33	0.88	0.32
GREENSIDE	1912	9	2321	53	-	-	-
EIKEBOOM	62	8	-	-	21	-	-

NOTE: '-' indicates no data available

Water from all sites is not suitable for Class 3 industrial use, based on the limited data available.

PARAMETER	SO_4	pH	TDS	Na	Cl	Fe	Al	Mn
UNITS	mg/l		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
AGRICULTURE: IRRIGATION	40	6.5-8.4	280	70	140	5	5	10
GOEDEHOOP	355	8	-	-	-	-	-	-
ARNOT	249	8	-	74	50	-	-	-
WOESTALLEEN	1866	8	-	100	-	-	0.1	-
KRIEL	165	9	482	113	28	0.02	0.28	0.01
KLEINKOPJE	1904	8	-	-	-	-	-	-
SYFERFONTEIN	334	8	707	208	12	0.24	0.15	0.08
MMS	1371	7	1985	41	13	0.16	0.13	0.93
MATLA	436	9	860	2	54	-	-	-
KOORNFONTEIN	352	8	-	107	36	0.88	-	0.32
GREENSIDE	1912	9	2321	73	53	-	-	-
EIKEBOOM	62	8	-	34	-	-	-	-

NOTE: '-' indicates no data available

Water from all sites is unsuitable for irrigation, based on the limited data available

PARAMETER	SO_4	TDS	Na	Cl	Ca	Mg	Fe	Al	Mn
UNITS	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
AGRICULTURE: LIVESTOCK WATERING	**1000**	**1000**	**2000**	**3000**	**1000**	**500**	**10**	**5**	**10**
GOEDEHOOP	355	-	-	-	-	-	-	-	-
ARNOT	249	-	74	50	-	-	-	-	-
WOESTALLEEN	1866	-	100	-	33	21	-	0.1	-
KRIEL	165	482	113	28	22	18	0.02	0.28	0.01
KLEINKOPJE	1904	-	-	-	-	-	-	-	-
SYFERFONTEIN	334	707	208	12	23	20	0.24	0.15	0.08
MMS	1371	1985	41	13	-	-	0.16	0.13	0.93
MATLA	436	860	2	54	46	-	-	-	-
KOORNFONTEIN	352	-	107	36	-	33	0.88	-	0.32
GREENSIDE	1912	2321	73	53	36	-	-	-	-
EIKEBOOM	62	-	34	-	-	21	-	-	-

NOTE: '-' indicates no data available

Water from Woestalleen, Kleinkopje, Middelburg (MMS) and Greenside is unsuitable for livestock watering, based on the limited data available

PARAMETER	pH	TDS	Cl	Fe	Al	Mn
UNITS		mg/l	mg/l	mg/l	mg/l	mg/l
AQUACULTURE	6.5-9	2000	600	0.01	0.01	0.1
GOEDEHOOP	8	-	-	-	-	-
ARNOT	8	-	50	-	-	-
WOESTALLEEN	8	-	-	-	0.1	-
KRIEL	9	482	28	0.02	0.28	0.01
KLEINKOPJE	8	-	-	-	-	-
SYFERFONTEIN	8	707	12	0.24	0.15	0.08
MMS	7	1985	13	0.16	0.13	0.93
MATLA	9	860	54	-	-	-
KOORNFONTEIN	8	-	36	0.88	-	0.32
GREENSIDE	9	2321	53	-	-	-
EIKEBOOM	8	-	-	-	-	-

NOTE: '-' indicates no data available

Only the water from Goedehoop, Arnot, Kleinkopje, Matla and Eikeboom, is suitable for aquaculture, based on the limited data available

PARAMETER	Cl	Al
UNITS	mg/l	mg/l
AQUATIC ECOSYSTEMS	200	5-10
GOEDEHOOP	-	-
ARNOT	50	-
WOESTALLEEN	-	0.1
KRIEL	28	0.28
KLEINKOPJE	-	-
SYFERFONTEIN	12	0.15
MMS	13	0.13
MATLA	54	-
KOORNFONTEIN	36	-
GREENSIDE	53	-
EIKEBOOM	-	-

NOTE: '-' indicates no data available

Water from all sites is suitable for aquatic ecosystems, based on the limited data available

A.2 South African Water Quality Guidelines

A.2.1 Domestic use: Volume 1

	ELEMENT	VALUE	UNITS	MEASUREMENT
1	**ALGAE**			
	Chlorophyll *a*	1-15	*µg/l chl a*	Algal cell/colony counts
	Blue-green algae	50-1400	*cells/ml*	Algal cell/colony counts
	Microsystins	0.8-1	*µg/l*	Algal cell/colony counts
2	**ALUMINIUM**	0.15-0.5	*mg/l*	Dissolved Al concentration I.e. Al which passes through a 0.45 µm membrane filter.
3	**AMMONIA**	1.0-2.0	*mg/l N*	Free ammonia nitrogen concentration I.e. sum of NH3 and NH4 nitrogen concentrations.
4	**ARSENIC**	10-200	*µg/l*	Atomic absorption spectrometry (AAS) with hydride generation. Various forms of arsenic are converted to As(V) and then reduced to As(III).
5	**ASBESTOS**	$1x10^{7}$	*fibres/l*	Total asbestos fibre counts/l.
6	**ATRAZINE**	2-20	*µg/l*	Total extractable atrazine concentration
7	**CADMIUM**	10-20	*µg/l*	Total cadmium concentrations
8	**CALCIUM**	32-80	*mg (Ca)/l*	Dissolved calcium concentration
9	**CHLORIDE**	100	*mg / l*	Dissolved chloride concentration
10	**CHROMIUM (VI)**	0.05	*mg / l*	Diphenyl carbazide spectrophotometry
11	**COLOUR**		dominant wavelength, luminance (%), purity (%), colour	Pt-Co colour units or spectrophotometric methods
12	**COPPER**	1.00	*mg / l*	Total copper concentration
13	**CORROSION**	positive = scale-forming tendency		Langlier index = (actual pH of water) - (hypothetical pH of water if it were in eq. With solid CaCO3)
		<6.5 = scale-forming >6.5 = corrosive		Ryznar index (RI) = 2x(saturation pH) - (actual pH)
		>0.1		Corrosion ratio: >0.1 = progressive corrosion I.e. aggressive waters
		10.00		Aggressiveness index: >10 = aggressive waters

14	**DISSOLVED ORGANIC CARBON**	5	*mg C / l*	DOC = persulphate-ultraviolet oxidation; TOC = combustion-infrared; COD = dichromate sulphuric acid digestion; BOD = five-day water sample
15	**FLUORIDE**	1	*mg / l*	Dissolved fluoride concentration
16	**INDICATOR ORGANISMS**			
	E. coli			Faecal coliforms which test indole-positive at 44.5C and generally consists only of E.coli which is definitely of faecal origin.
	Enterococci			Bacteria which produce typical reddish colonies on m-Enterococcus agar after 48hrs incubation at 35C. Faecal streptococci (sub-group) of proven faecal origin.
	Somatic coliphages			Indicate faecal pollution.
	F-RNA coliphages			Highly specific indicators of faecal pollution.
	Heterotrophic bacteria	100	*(number of colonies) / ml*	Heterotrophic plate counts: pour plates, spread plates and membrane filtration methods.
	Total coliforms	5	*counts / 100ml water*	Membrane filtration, pour plates and multiple tube fermentation techniques. Note: **some bacteria classified as coliforms are NOT of faecal origin!** All bacteria which produce colonies with a metallic sheen within 24hrs of incubation at 35C on m-Endo agar. Indicates general sanitary quality of water.
	Faecal coliforms	0	*counts / 100ml water*	All bacteria which produce typical blue colonies on m-FC agar within 24hrs of incubation at 44.5C. Indicates faecal pollution of wastewater, raw water supplies and recreational water bodies. Membrane filtration, pour plates and multiple tube fermentation techniques.
	Coliphages	10	*counts / 100ml water*	Bacterial viruses which infect and replicate in E. coli. Indicators of faecal pollution and may indicate the presence of pathogenic viruses.
	Enteric viruses	1	*TCID50/10 l*	Cool 100 l water samples to 4-10C immediately. Adsorption-elution techniques.

	Protozoan parasites	>1	*(cysts or oocysts / 10 l)*	Fluorescent-conjugated antibody staining. No standard monitoring practices, concentration procedures or detection methods. *Giardia lambia* and *Cryptosporidium parvum* infect humans.
17	**IRON**	0.3	*mg / l*	Total iron concentration, which requires acidification prior to filtration before AAS analysis.
18	**LEAD**	10	*µg/l*	Total lead concentration, measured using dithizone or AAS.
19	**MAGNESIUM**	30	*mg / l as Mg*	AAS using a phosphate interference inhibitor and an ionisation suppressant
20	**MANGANESE**	0.05	*mg / l*	Total Mn measured using AAS with an air-acetylene flame.
21	**MERCURY**	1	*µg / l*	Total mercury concentrations (both dissolved and particulate forms must be measured).
22	**NITRATE**	6	*mg / l N*	Concentration of nitrate plus nitrite nitrogen, determined by cadmium reduction followed by diazotisation.
23	**ODOUR**	1	*TON*	Threshold odour number (TON) I.e. greatest dilution of a sample with odour-free water that yields a final water with an odour which is just detectable by a panel of judges under carefully controlled test conditions.
24	**pH**	6.0-9.0	*pH units*	Measured electrometrically using a calibrated pH meter and temperature should always be recorded.
25	**PHENOLS**	1	*µg / l*	Total concentration of phenols.
26	**POTASSIUM**	50	*mg / l*	Dissolved potassium concentration.
27	**RADIOACTIVITY (Gross alpha activity)**	0.5	*Bq / l*	Radioactive nuclides are measured by the detection of emissions from alpha and beta particles or gamma rays. They are presented as disintegrations per second.
	Uranium	0.89	*Bq / l*	U238
	Thorium	0.228	*Bq / l*	Th232
	Radium	>0.42	*Bq / l*	Rd226
	Radon	11	*Bq / l*	Rd222
	Gross Beta activity	1.38	*Bq / l*	Gross Beta activity
	Radium	0.42	*Bq / l*	Rd228
28	**SELENIUM**	20	*µg / l*	Total selenium concentration
29	**SETTLEABLE MATTER**	Qualitative		Settleable solids concentration determined by the volumetric and/or gravimetric method. Responsible for erosion, corrosion etc.
30	**SODIUM**	100	*mg / l*	Dissolved sodium concentration

31	**SULPHATE**	200	*mg / l*	Dissolved sulphate concentration
32	**TRIHALO-METHANES**	100	*µg / l*	Total THM concentration
33	**TDS**	450	*mg / l*	TDS concentration and/or EC (mS/m)
34	**TOTAL HARDNESS**	100	*mg CaCO3 / l*	Calculated from Ca and Mg concentrations
35	**TURBIDITY**	5	*NTU*	Turbidity should be measured in nephelometric turbidity units on the day of sample collection.
36	**VANADIUM**	0.1	*mg / l*	Total vanadium concentration.
37	**ZINC**	3	*mg / l*	Total zinc concentration

A.2.2 Recreational use: Volume 2

	ELEMENT	VALUE	UNITS	MEASUREMENT
1	**ALGAE**	15	*µg/l chl a*	Measurement of the chlorophyll *a* concentration
2	**CHEMICAL IRRITANTS**	Qualitative		Depends on chemical type.
3	**CLARITY**	3	*Secchi disc depth, metres*	Secchi disk visibility in metres
4	**FLOATING MATTER & REFUSE**	Qualitative		Presence, amount and type determined qualitatively
5	**INDICATOR ORGANISMS**	Qualitative	*counts*	Depends on organism
	Faecal Coliforms	130	*counts/ 100 ml*	
	E. coli	130	*counts/ 100 ml*	
	Enterococci: Faecal Streptococci	30	*counts/ 100 ml*	
	Coliphages	20	*counts/ 100 ml*	
	Enteric viruses	1	*$TCID_{50}$/10l*	
	Schistosoma / Bilharzia	Qualitative		
6	**NUISANCE PLANTS**	Qualitative		
7	**ODOUR**	Qualitative		
8	**pH**	6.5-8.5	*pH units*	Measured electrometrically using a pH meter

A.2.3 Industrial use: Volume 3

		CATEGORY				
	ELEMENT	1	2	3	4	MEASUREMENT
1	ALKALINITY	50	120	300	1 200	Total alkalinity concentration
2	C.O.D.	10	15	30	75	Oxygen equivalent of the oxidisable matter in a sample following oxidation with a strong chemical oxidant
3	CHLORIDE	20	40	100	500	Dissolved chloride concentration
4	IRON	0.1	0.2	0.3	10	Total iron concentration, which requires acidification prior to filtration before AAS analysis.
5	MANGANESE	0.05	0.1	0.2	10	Total Mn measured using AAS with an air-acetylene flame.
6	pH	7 - 8	6.5 - 8	6.5 - 8	5 - 10	Measured electrometrically using a calibrated pH meter and temperature should always be recorded.
7	SILICA	5	10	20	##	Dissolved silica concentration
8	SULPHATE	30	80	200	##	Dissolved sulphate concentration
9	SUSPENDED SOLIDS	3	5	5	25	Measured as the mass of material retained on a glass fibre filter after drying at 103 - 105C
10	TDS	100	200	450	##	TDS concentration and/or EC (mS/m)
11	TOTAL HARDNESS	50	100	250	1 000	Calculated from Ca and Mg concentrations

A.2.4 Agricultural use - Irrigation: Volume 4

	ELEMENT	VALUE	UNITS	MEASUREMENT
1	**ALUMINIUM**	5	*mg / l*	Dissolved Al concentration
2	**ARSENIC**	0.1	*mg / l*	Total As concentration
3	**BERYLLIUM**	0.1	*mg / l*	Total beryllium concentration
4	**BORON**	0.5	*mg / l*	Total dissolved boron concentration.
5	**CADMIUM**	0.05	*mg / l*	Total cadmium concentration
6	**CHLORIDE**	140	*mg / l*	Dissolved chloride concentration
7	**CHROMIUM (VI)**	1	*mg / l*	Total chromium concentration
8	**COBALT**	5	*mg / l*	Total cobalt concentration
9	**COLIFORMS (Faecal)**	10 000	*counts / 100ml water*	All bacteria which produce typical blue colonies on M-FC agar within 24hrs of incubation at 44.5C.
	E. coli	1	*E. coli counts / 100ml water*	
10	**COPPER**	5	*mg / l*	Total copper concentration
11	**FLUORIDE**	15	*mg / l*	Dissolved fluoride concentration
12	**IRON (crop yield)**	5	*mg / l*	Total iron concentration
	IRON (equipment)	0.2	*mg / l*	Total iron concentration
13	**LEAD**	0.2	*mg / l*	Total lead concentration
14	**LITHIUM**	2.5	*mg / l*	Measured by flame emission photometry
15	**MANGANESE (crop yield)**	10	*mg / l*	Total manganese
	MANGANESE (equipment)	0.1	*mg / l*	Total manganese
16	**MOLYBDENUM**	0.05	*mg / l*	Total molybdenum concentrations
17	**NICKEL**	0.2	*mg / l*	Total nickel concentration
18	**NITROGEN (inorganic)**	5	*mg / l*	Concentration of inorganic nitrogen in water determined by adding concentrations of ammonia, nitrite and nitrate.
	NITROGEN (equipment)	0.5	*mg / l*	As above.
19	**pH**	6.5-8.4	pH units	Measured electrometrically using a pH meter

20	**SCALING / CORROSION**	-0.2 - +0.2	*Langlier Index Range*	Langlier Index
		>12	*AI*	Aggressiveness Index
		<6.5	*Ryznar index*	Scale-forming
		>6.5	*Ryznar index*	Corrosive
21	**SELENIUM**	0.05	*µg / l*	Total selenium concentration
22	**SODIUM ADSORPTION RATIO**	2	*SAR Range*	SAR=[sodium] / ([calcium] + [magnesium]) *0.5
23	**SODIUM**	70	*mg / l*	Dissolved sodium concentration
24	**SUSPENDED SOLIDS**	50	*mg / l*	Suspended solids are measured as the mass of material retained on a glass fibre filter after drying at 103-105C.
25	**TOTAL DISSOLVED SOLIDS**	40	*mS/m*	The TDS concentration can be measured as: an estimate based on the EC value; the dry weight of the salts after evaporation of a known volume of filtered water; and the sum of the concentrations of the constituent cations and anions.
26	**URANIUM**	0.1	*mg / l*	Can be chemically measured as mg / l or radiologically measured as Bq / l.
27	**VANADIUM**	1	*mg / l*	Total vanadium concentration
28	**ZINC**	5	*mg / l*	Total zinc concentration

A.2.5 Agricultural use - Livestock watering: Volume 5

	ELEMENT	VALUE	UNITS	MEASUREMENT
1	**ALGAE**	<6 colonies of blue-green algae / 0.5 ml	*cells / ml*	Blue-green cells are measured in the top meter of water
2	**ALUMINIUM**	5	*mg/l*	Dissolved Al concentration I.e. Al which passes through a 0.45 μm membrane filter.
3	**ARSENIC**	1	*mg/l*	Atomic absorption spectrometry (AAS) with hydride generation. Various forms of arsenic are converted to As(V) and then reduced to As(III).
4	**BORON**	5	*mg/l*	Total dissolved boron concentration
5	**CADMIUM**	0.01	*mg/l*	Total cadmium concentrations
6	**CALCIUM**	1 000	*mg/l*	Dissolved calcium concentration
7	**CHLORIDE**	3 000	*mg / l*	Dissolved chloride concentration
8	**CHROMIUM (VI)**	1	*mg / l*	Total chromium concentration
9	**COBALT**	1.00	*mg / l*	Total cobalt concentration
10	**COPPER**	1.00	*mg / l*	Total copper concentration
11	**FLUORIDE**	2	*mg / l*	Dissolved fluoride concentration
12	**IRON**	10	*mg / l*	Total iron concentration, which requires acidification prior to filtration before AAS analysis.
13	**LEAD**	0.2	*mg / l*	Total lead concentration, measured using dithizone or AAS.
14	**MAGNESIUM**	500	*mg / l*	Total magnesium concentration
15	**MANGANESE**	10	*mg / l*	Total Mn measured using AAS with an air-acetylene flame.
16	**MERCURY**	1	*μg / l*	Total mercury concentrations (both dissolved and particulate forms must be measured).
17	**MOLYBDENUM**	0.01	*mg / l*	Total molybdenum concentrations
18	**NICKEL**	5	*mg / l*	Total nickel concentration
19	**NITRATE / NITRITE**	200	*mg / l*	Concentration of nitrate plus nitrite nitrogen, determined by cadmium reduction followed by diazotisation.
20	**PATHOGENS**	1000	*counts / 100ml water*	Faecal coliforms are used as indicator bacteria to test for the possible presence of pathogens.
21	**PESTICIDES**	0.1 (wide range)	*μg / l*	Concentration determined by chromatographic methods
22	**SELENIUM**	50	*μg / l*	Total selenium concentration

23	**SODIUM**	2000	*mg / l*	Dissolved sodium concentration
24	**SULPHATE**	1000	*mg / l*	Dissolved sulphate concentration
25	**TDS**	1000	*mg / l*	TDS concentration and/or EC (mS/m)
26	**VANADIUM**	1	*mg / l*	Total vanadium concentration.
27	**ZINC**	20	*mg / l*	Total zinc concentration

A.2.6 Agricultural use - Aquaculture: Volume 6

	ELEMENT	VALUE	UNITS	MEASUREMENT
1	ALGAE	Qualitative		Blooms of single-celled algae are estimated from the concentration of chlorophyll a
2	ALKALINITY	20 - 100	*mg CaCO3/l*	Measured by titration of the water sample with a strong acid (usually HCl), of known concentration to an end point pH of between 8 - 10.
3	ALUMINIUM	0.03	*mg* Al^{3+}/l	Dissolved Al concentration I.e. Al which passes through a 0.45 µm membrane filter.
4	AMMONIA	0.025 or 0.3	*mg* NH_3/l	Based on the un-ionised ammonia fraction. Values given for cold-water and warm-water fish respectively.
5	ARSENIC	0.05	*mg/l*	Atomic absorption spectrometry (AAS) with hydride generation. Various forms of arsenic are converted to As(V) and then reduced to As(III).
6	BACTERIA			Bacterial diagnosis: fish surface is disinfected, samples taken from blood and kidney, streaked and incubated for 24 - 48 hours at 28C. Isolated types of bacteria can then be characterised.
	E. coli	*10 E. coli /g of fish flesh*	*counts/ 100ml water*	Counted from cultures on agar plates
7	CADMIUM	0.2	*µg/l*	Soluble cadmium concentration. (Value given depends on water hardness values)
8	CARBON DIOXIDE	12	*mg/l*	Concentrations of individual dissolved gases expressed in mg/l, ml/l or as a %saturation or partial pressure
9	CHLORIDE	600	*mg / l*	Dissolved chloride concentration. (Value given is a tentative guideline).
10	CHLORINE	1	*µg HOCL/l*	Total chlorine concentration
11	CHROMIUM (VI)	20	*µg/l*	Necessary to assume all chromium present is chromium VI
12	COPPER	0.01	*mg / l*	Total copper concentration
13	CYANIDE	0.02	*mg/l*	Acid distillation followed by colorimetry.
14	DISSOLVED OXYGEN	5 - 9	*mg / l*	Use Winkler method to give DO concentration

15	**HERBICIDES**	0.1 - 3	*mg/kg*	Wet weight. (Values have a wide range depending on particular herbicide. Value for Benomyl has been given as it is lowest).
16	**IRON**	0.01	*mg / l*	Soluble iron concentration
17	**LEAD**	0.01	*mg Pb/l*	Total lead concentration
18	**MANGANESE**	0.1	*mg / l*	Total manganese
19	**MERCURY**	1	*µg Hg / l*	Total mercury concentrations (both dissolved and particulate forms must be measured).
20	**NITRATE**	300	*mg* NO_3^- *N/ l*	Concentration of nitrate-nitrogen
16	**NITRITE**	0.05	*mg* NO_2^- *N/ l*	Concentration of nitrate-nitrogen
17	**NUISANCE PLANTS**	<10%		Estimate of the proportion of the water body covered.
18	**PARASITES**			Microscopic examination of gills, skin and internal organs of the fish.
19	**PCBs**	Qualitative		Measured by gas chromatography after solvent extraction.
20	**PESTICIDES**	0.05	*mg wet weight / kg*	Wet weight. (Value given is the smallest value and depends on particular pesticide).
21	pH	6.5-9	*pH units*	
22	**PHENOLS**	1	*mg / l*	Total concentration of phenols.
23	**PHOSPHOROUS**	0.1	*mg/l*	Soluble orthophosphate concentration
24	**SELENIUM**	0.3	*mg Se(VI)/l*	Total selenium concentration
25	**SULPHIDE**	0.001	*mg* H_2S*/l*	Un-ionised hydrogen sulphide
26	**TEMPERATURE**	12/25/28	*°C*	Degrees Celsius. (Values given are those for cold -, intermediate- and warm-water species respectively).
27	**TOTAL DISSOVED GASES**	100	*%TGP*	Saturation level I.e. % Total Gas Pressure
28	**TDS**	2	*g/l*	TDS concentration and/or EC (mS/m)
29	**TOTAL HARDNESS**	20-100	*mg* $CaCO_3$ */ l*	Calculated from Ca and Mg concentrations

30	**TOTAL SUSPENDED MATTER**	20 000	*mg/l*	Measured by weighing the residue collected on a 0.2-0.5 µm filter from a known volume evaporated to dryness at a temperature below 70C.
26	**VIRUSES**	Qualitative		Serum neutralisation
27	**ZINC**	0.03	*mg / l*	Soluble zinc concentrations. (Dependent on water hardness).

A.2.7 Aquatic ecosystems: Volume 7

	ELEMENT	VALUE	UNITS	MEASUREMENT
1	ALUMINIUM	5 (pH<6) - 10 (pH>6.5	μg / l	Acid-soluble aluminium concentration
2	AMMONIA	7	μg N / l	Total ammonia concentration I.e. sum of ammonia and ammonium concentrations
3	ARSENIC	10	μg / l	Dissolved arsenic
4	ATRAZINE	10	μg / l	Gas chromatography after solvent extraction and clarification
5	CADMIUM	0.25	μg / l	Total cadmium concentration I.e. dissolved + particulate forms
6	CHLORINE	0.2	μg Cl_2 / l	Total residual chlorine concentration
7	CHROMIUM	7-12	μg / l	Dissolved concentration of chromium III and chromium VI
8	COPPER	0.8	μg / l	Dissolved copper
9	CYANIDE	1	μg / l	Free cyanide concentration
10	DISSOLVED OXYGEN	80% - 100% of saturation		The lowest instantaneous concentration recorded in a 24-hour period.
11	ENDOSULFAN	0.01	μg / l	Gas chromatography after solvent extraction and clarification
12	FLUORIDE	750	μg / l	Dissolved fluoride concentration
13	IRON (crop yield)	<10% variation from background dissolved Fe concentration	μg / l	Dissolved iron concentrations
14	LEAD	0.5	μg / l	Dissolved lead concentration
17	NITROGEN (inorganic)	0.5	mg / l	Concentration of inorganic nitrogen in water determined by adding concentrations of ammonia, nitrite and nitrate.
18	pH	<5% variation from background pH values	pH units	Calculated from the mean hydrogen ion concentration
19	PHENOL	30	μg / l	Gas chromatography
20	PHOSPHORUS (inorganic)	5-25	μg / l	Orthophosphates, total inorganic phosphate or total dissolved phosphorous
21	SELENIUM	2	μg / l	Dissolved selenium concentration

22	**TEMPERATURE**	<2°C variation from background average daily water temperature	°C	Celsius value recorded over 24hr period
24	**TOTAL DISSOLVED SOLIDS**	<15% variation from normal cycles of water body	*mS/m*	The TDS concentration can be measured as: an estimate based on the EC value; the dry weight of the salts after evaporation of a known volume of filtered water; and the sum of the concentrations of the constituent cations and anions.
25	**TOTAL SUSPENDED SOLIDS**	<10% increase relative to background TSS concentrations	*mg / l*	Measured gravimetrically
26	**ZINC**	5	*mg / l*	Total zinc concentration

APPENDIX B

B.1 pH

TEST: **pH**			DATE: **08-10-99**				
	TIME	**5min**	**10min**	**30min**	**2hours**	**6hours**	**24hours**
A	**GRAB**	5.60	5.73	6.64	6.79	7.36	8.00
	DISC	6.19	6.31	6.56	7.16	7.25	7.86
	PROD	6.30	6.58	6.57	7.00	7.48	8.00
B	**GRAB**	6.59	6.45	6.52	7.10	7.05	7.84
	DISC	6.51	6.31	6.56	6.79	7.25	7.57
	PROD	6.61	6.26	6.64	6.72	7.29	7.76
C	**GRAB**	6.58	7.05	7.43	7.36	7.32	7.06
	DISC	6.79	7.15	7.47	7.39	7.28	7.27
	PROD	6.95	7.28	7.64	7.6	7.58	7.53
D	**GRAB**	6.16	6.83	7.63	7.83	8.05	8.66
	DISC	6.36	6.94	7.71	7.84	8.32	8.50
	PROD	6.05	7.01	7.99	7.77	8.52	9.03
	ASH	11.07	11.16	11.28	10.88	10.96	11.14

B.2 Sulphates

TEST: **Sulphate**						DATE: **08-10-99**							
	TIME	**5min**		**10min**		**30min**		**2hours**		**6hours**		**24hours**	
		Vol	**Turbidity**	**Vol**	**Turbidity**	**Vol**	**Turbidity**	**Vol**	**Turbidity**	**Vol**	**Turbidity**	**Vol**	**Turbidity**
A	**GRAB**	2ml	2	2ml	2	2ml	2	2ml	3	2ml	3	2ml	3
	DISC	2ml	2	2ml	2	2ml	2	2ml	2	2ml	3	2ml	3
	PROD	2ml	2	2ml	2	2ml	3	2ml	3	2ml	4	2ml	7
B	**GRAB**	2ml	2	2ml	2	2ml	3	2ml	4	2ml	4	2ml	5
	DISC	2ml	2	2ml	2	2ml	3	2ml	4	2ml	4	2ml	5
	PROD	2ml	2	2ml	3	2ml	3	2ml	3	2ml	4	2ml	7
C	**GRAB**	2ml	2	2ml	2	2ml	3	2ml	5	2ml	4	2ml	5
	DISC	2ml	2	2ml	2	2ml	3	2ml	4	2ml	4	2ml	4
	PROD	2ml	2	2ml	2	2ml	3	2ml	3	2ml	3	2ml	2
D	**GRAB**	2ml	2	2ml	2	2ml	3	2ml	3	2ml	4	2ml	4
	DISC	2ml	2	2ml	2	2ml	3	2ml	3	2ml	4	2ml	4
	PROD	2ml	2	2ml	2	2ml	2	2ml	3	2ml	3	2ml	3
	ASH	2ml	1	2ml	1	2ml	2	2ml	2	2ml	3	2ml	3

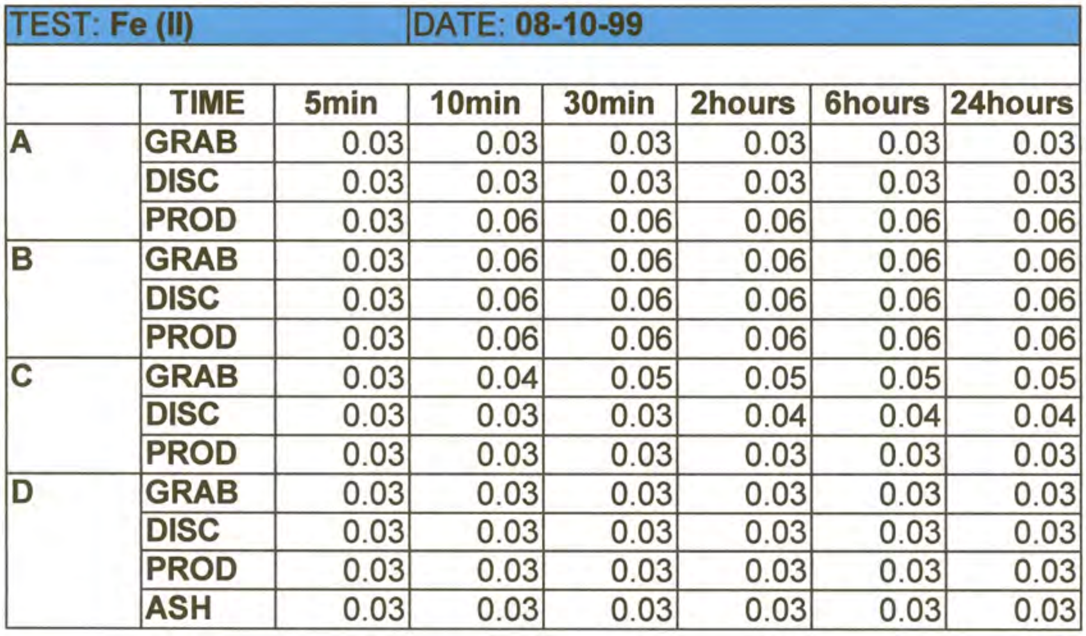
B.3 Alkalinity

TEST: **ALKALINITY**			DATE: **09-10-99**				
	TIME	**5min**	**10min**	**30min**	**2hours**	**6hours**	**24hours**
A	**GRAB**	100.00	110.00	100.00	100.00	100.00	100.00
	DISC	50.00	90.00	110.00	110.00	110.00	110.00
	PROD	60.00	70.00	100.00	100.00	100.00	100.00
B	**GRAB**	40.00	100.00	90.00	80.00	70.00	70.00
	DISC	50.00	60.00	70.00	90.00	90.00	90.00
	PROD	30.00	50.00	80.00	110.00	100.00	100.00
C	**GRAB**	50.00	100.00	90.00	80.00	70.00	70.00
	DISC	40.00	80.00	100.00	100.00	90.00	80.00
	PROD	40.00	60.00	80.00	80.00	70.00	70.00
D	**GRAB**	100.00	210.00	130.00	110.00	90.00	70.00
	DISC	210.00	120.00	110.00	100.00	130.00	150.00
	PROD	130.00	200.00	170.00	150.00	130.00	110.00
	ASH	100.00	100.00	100.00	100.00	100.00	100.00

B.4 Acidity

TEST: **ACIDITY**			DATE: **09-10-99**				
	TIME	**5min**	**10min**	**30min**	**2hours**	**6hours**	**24hours**
A	**GRAB**	150.00	50.00	100.00	100.00	50.00	<50.00
	DISC	50.00	200.00	250.00	150.00	50.00	<50.00
	PROD	150.00	50.00	100.00	100.00	50.00	<50.00
B	**GRAB**	50.00	100.00	100.00	100.00	50.00	<50.00
	DISC	50.00	100.00	100.00	100.00	50.00	<50.00
	PROD	100.00	150.00	200.00	150.00	50.00	<50.00
C	**GRAB**	50.00	100.00	200.00	150.00	100.00	50.00
	DISC	50.00	100.00	150.00	100.00	50.00	50.00
	PROD	50.00	100.00	100.00	50.00	50.00	<50.00
D	**GRAB**	100.00	100.00	50.00	50.00	50.00	50.00
	DISC	50.00	50.00	50.00	50.00	50.00	50.00
	PROD	50.00	50.00	50.00	50.00	50.00	50.00
	ASH	<50.00	<50.00	<50.00	<50.00	<50.00	<50.00

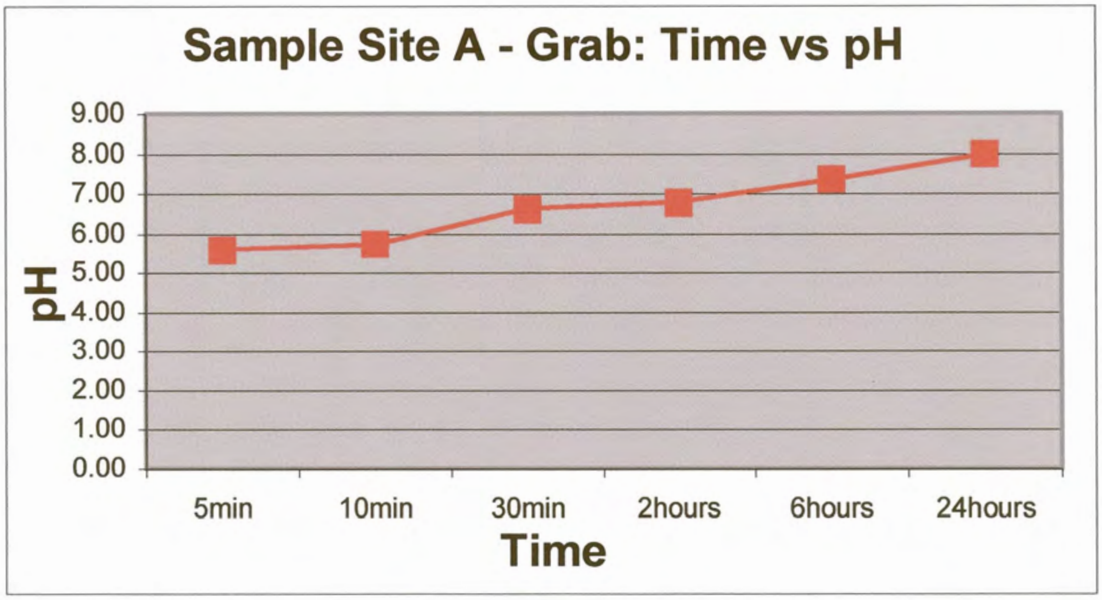
B.5 Iron (II)

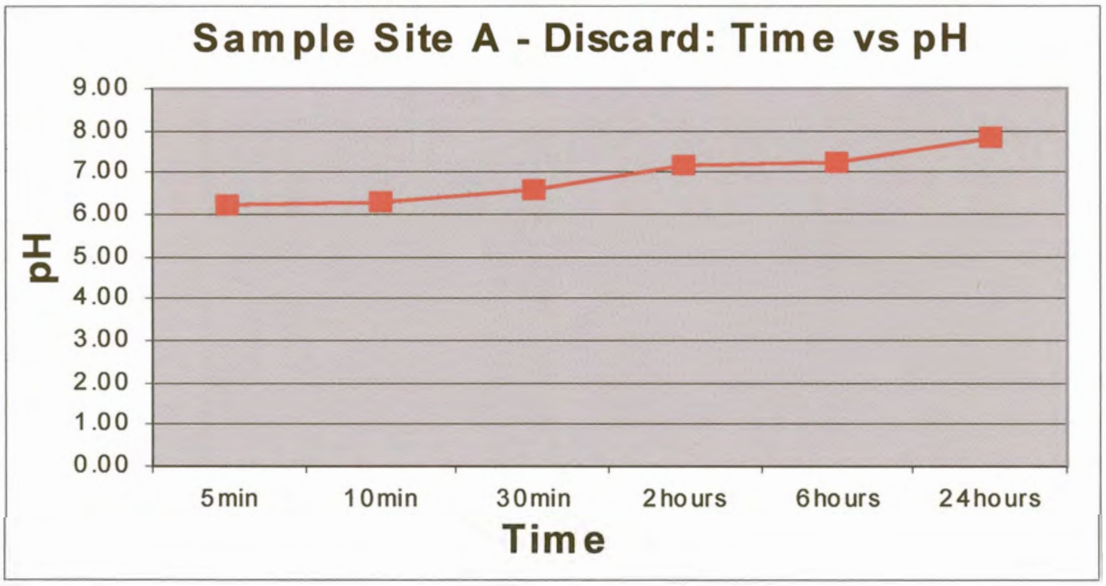


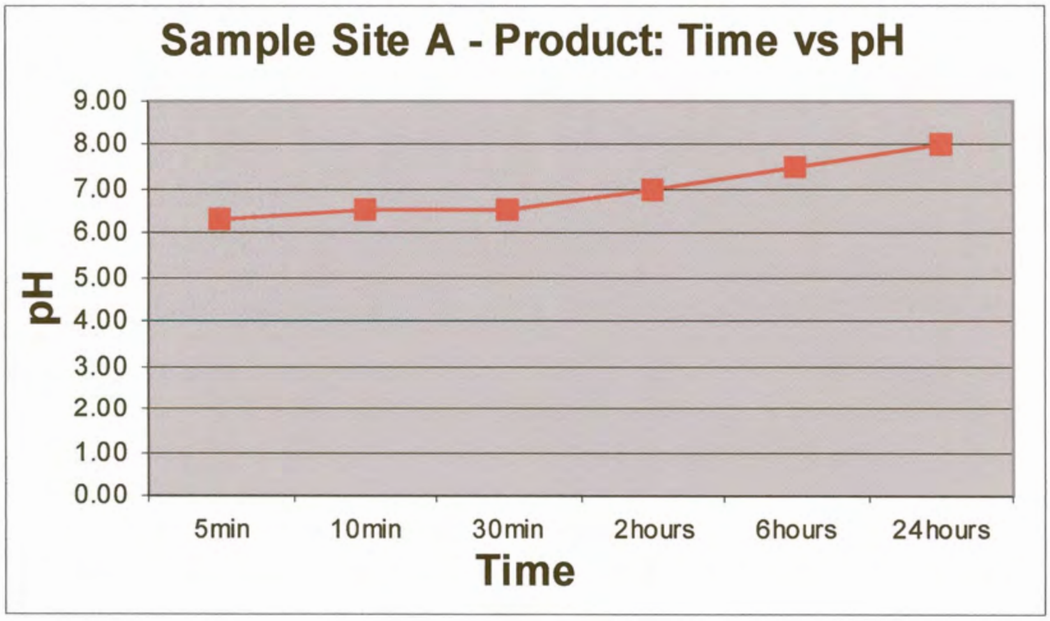
TEST: **Fe (II)**			DATE: **08-10-99**				
	TIME	**5min**	**10min**	**30min**	**2hours**	**6hours**	**24hours**
A	**GRAB**	0.03	0.03	0.03	0.03	0.03	0.03
	DISC	0.03	0.03	0.03	0.03	0.03	0.03
	PROD	0.03	0.06	0.06	0.06	0.06	0.06
B	**GRAB**	0.03	0.06	0.06	0.06	0.06	0.06
	DISC	0.03	0.06	0.06	0.06	0.06	0.06
	PROD	0.03	0.06	0.06	0.06	0.06	0.06
C	**GRAB**	0.03	0.04	0.05	0.05	0.05	0.05
	DISC	0.03	0.03	0.03	0.04	0.04	0.04
	PROD	0.03	0.03	0.03	0.03	0.03	0.03
D	**GRAB**	0.03	0.03	0.03	0.03	0.03	0.03
	DISC	0.03	0.03	0.03	0.03	0.03	0.03
	PROD	0.03	0.03	0.03	0.03	0.03	0.03
	ASH	0.03	0.03	0.03	0.03	0.03	0.03

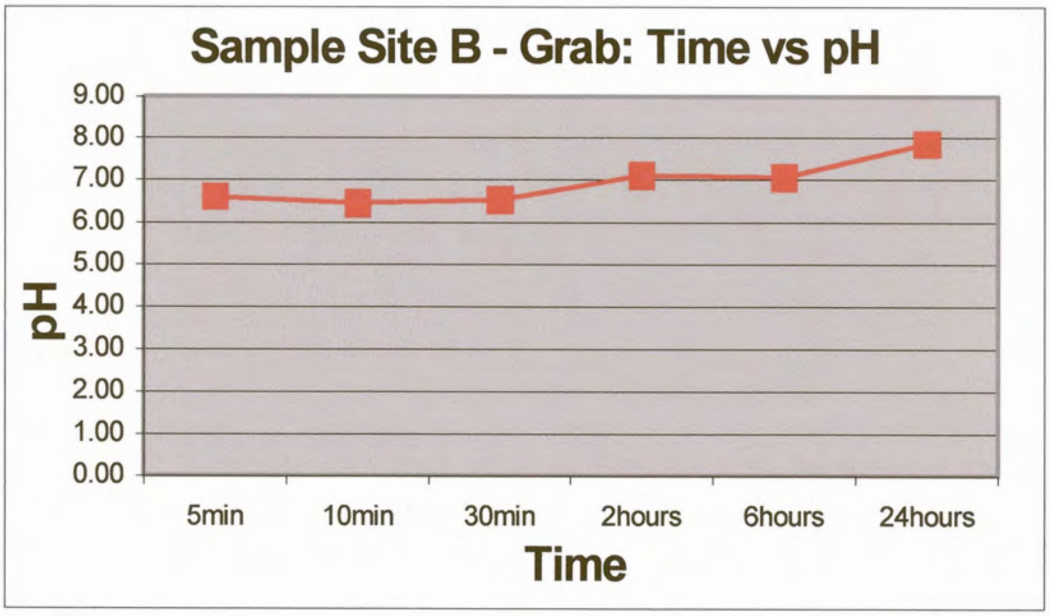
APPENDIX C

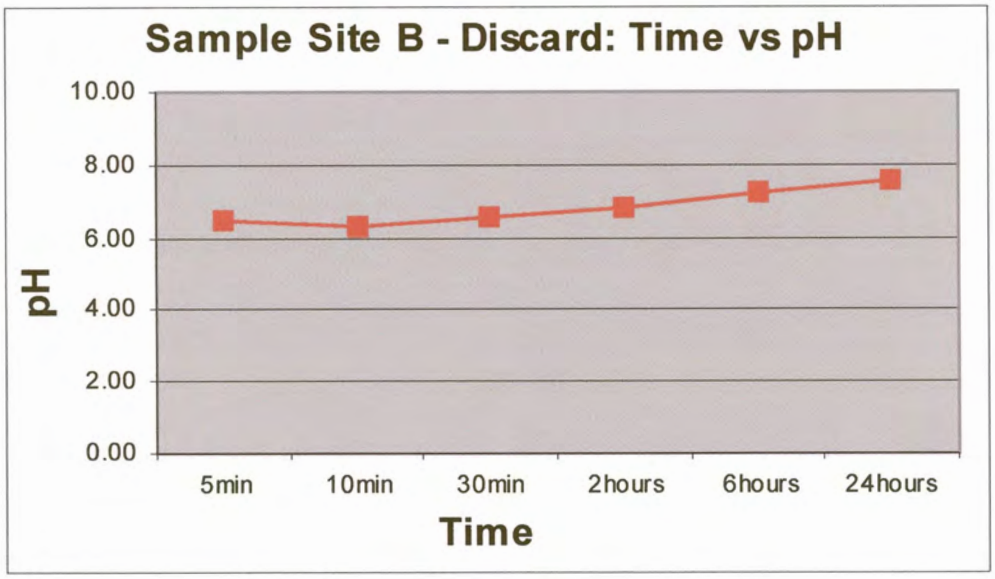
C.1 pH

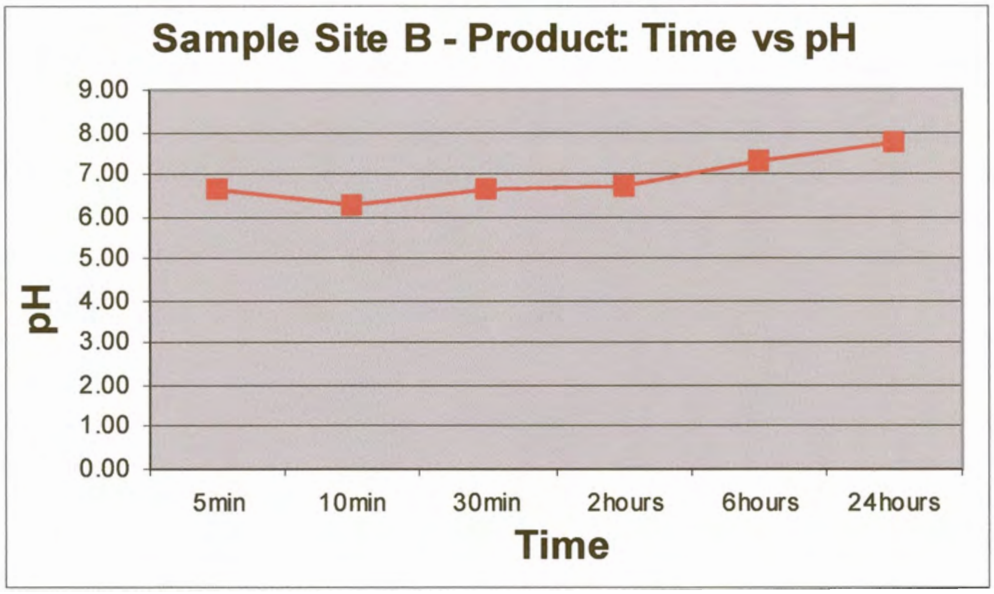


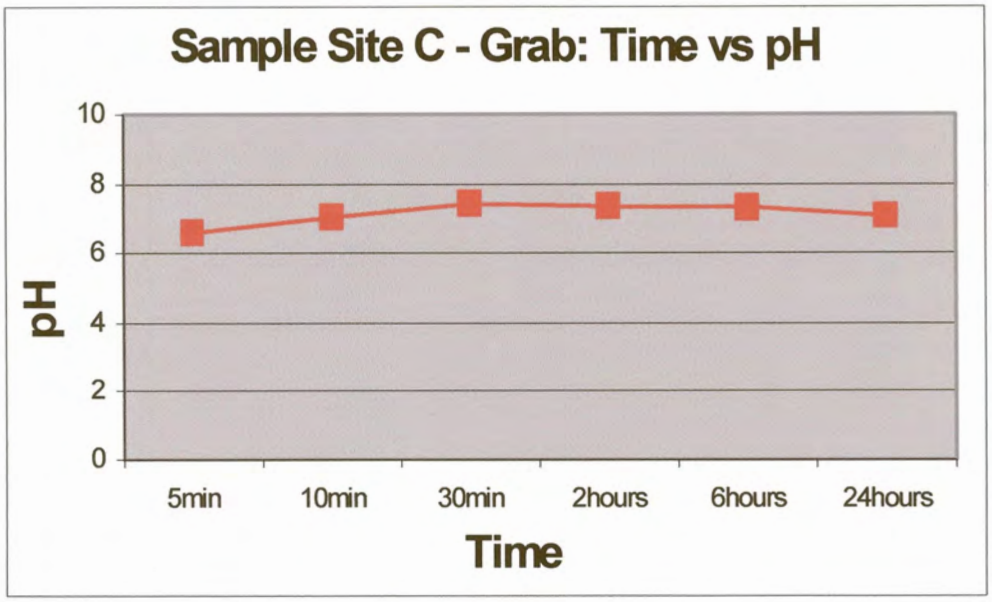


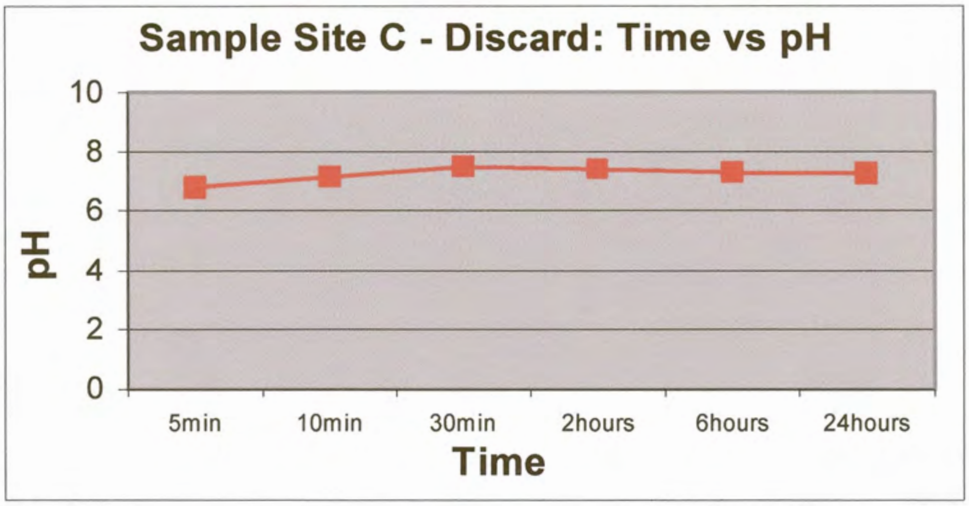

Sample Site A - Product: Time vs pH
pH
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
5min
10min
30min
2hours
6hours
24hours
Time

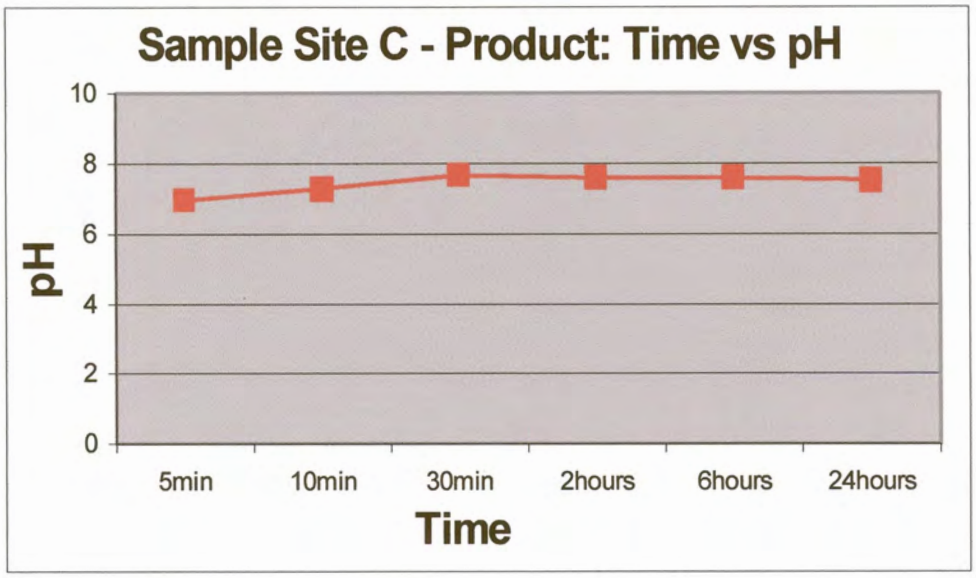

Sample Site B - Grab: Time vs pH
pH
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
5min
10min
30min
2hours
6hours
24hours
Time

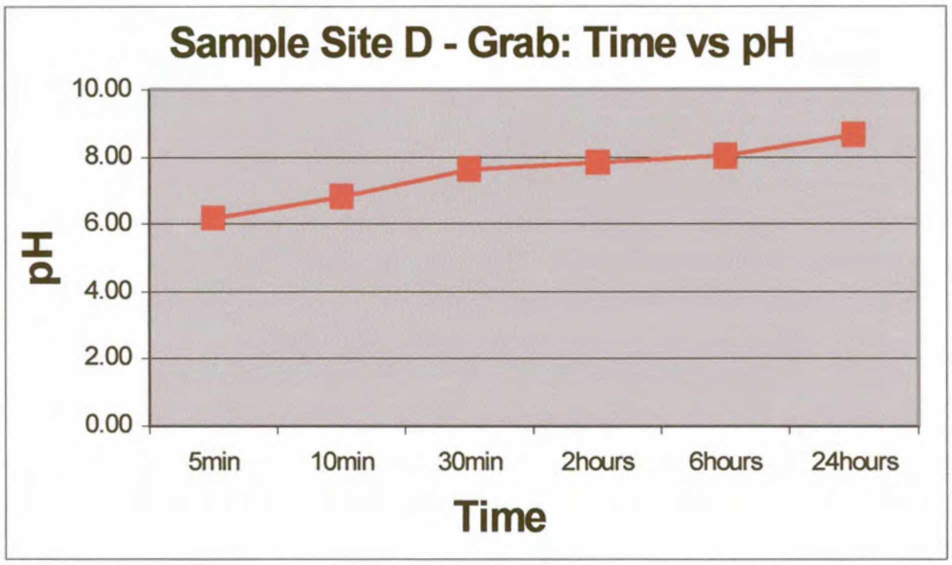

Sample Site B - Discard: Time vs pH
10.00
8.00
6.00
4.00
2.00
0.00
pH
5min
10min
30min
2hours
6hours
24hours
Time

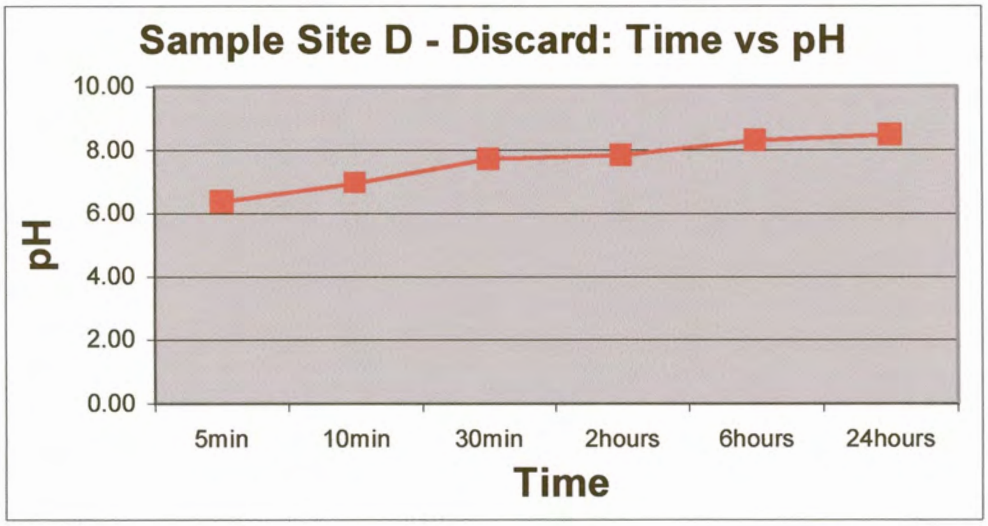

Sample Site B - Product: Time vs pH
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
pH
5min
10min
30min
2hours
6hours
24hours
Time

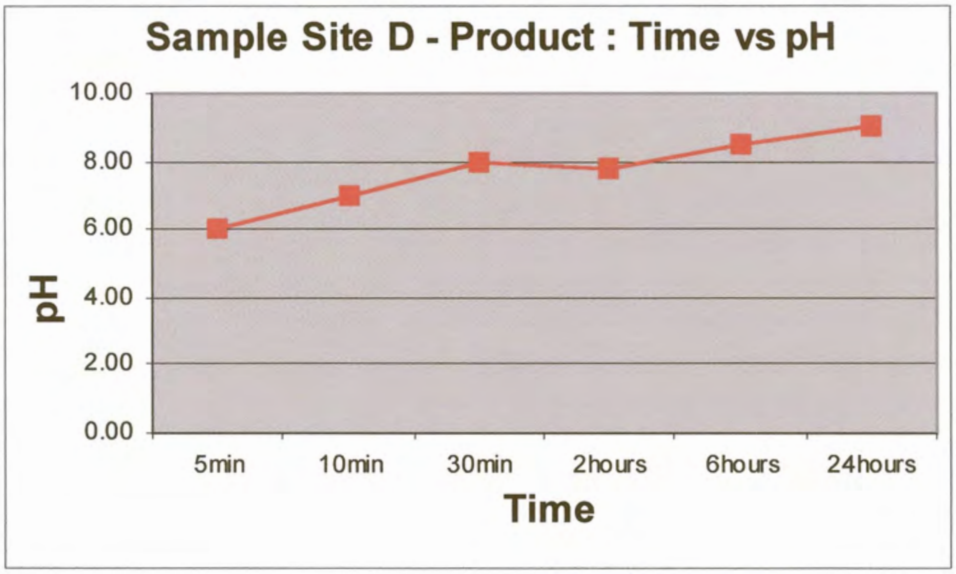

Sample Site C - Grab: Time vs pH
pH
10
8
6
4
2
0
5min
10min
30min
2hours
6hours
24hours
Time

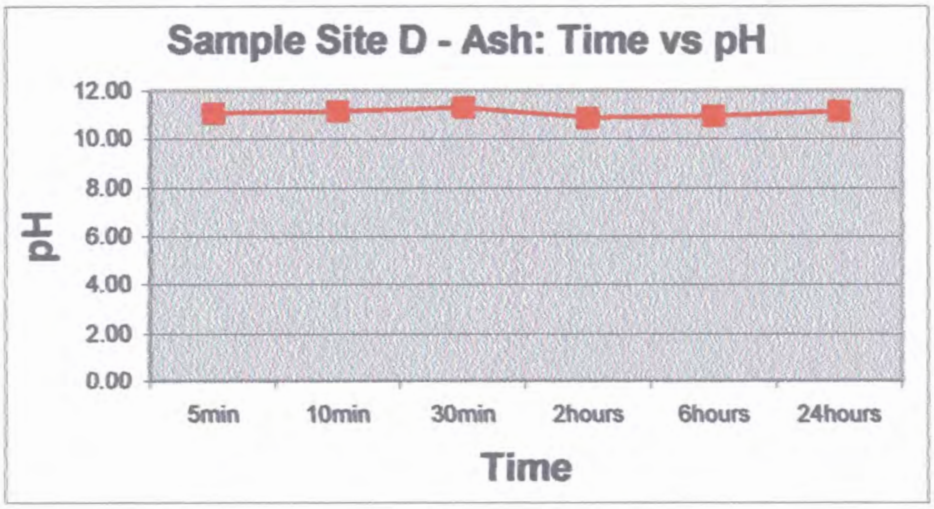

Sample Site C - Discard: Time vs pH
pH
10
8
6
4
2
0
5min
10min
30min
2hours
6hours
24hours
Time


Sample Site C - Product: Time vs pH
10
8
6
4
2
0
pH
5min
10min
30min
2hours
6hours
24hours
Time


Sample Site D - Grab: Time vs pH
10.00
8.00
6.00
4.00
2.00
0.00
pH
5min
10min
30min
2hours
6hours
24hours
Time


Sample Site D - Discard: Time vs pH
10.00
8.00
6.00
4.00
2.00
0.00
pH
5min
10min
30min
2hours
6hours
24hours
Time

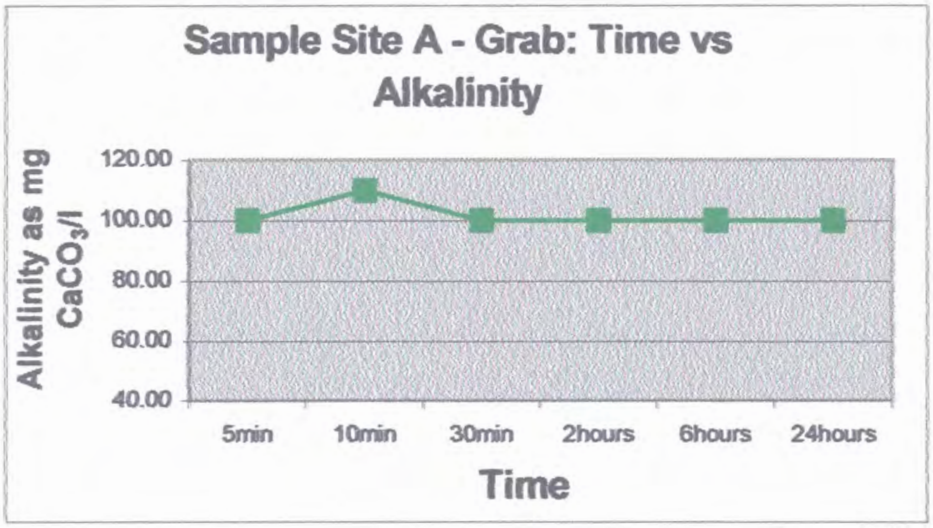

Sample Site D - Product : Time vs pH
10.00
8.00
6.00
4.00
2.00
0.00
pH
5min
10min
30min
2hours
6hours
24hours
Time

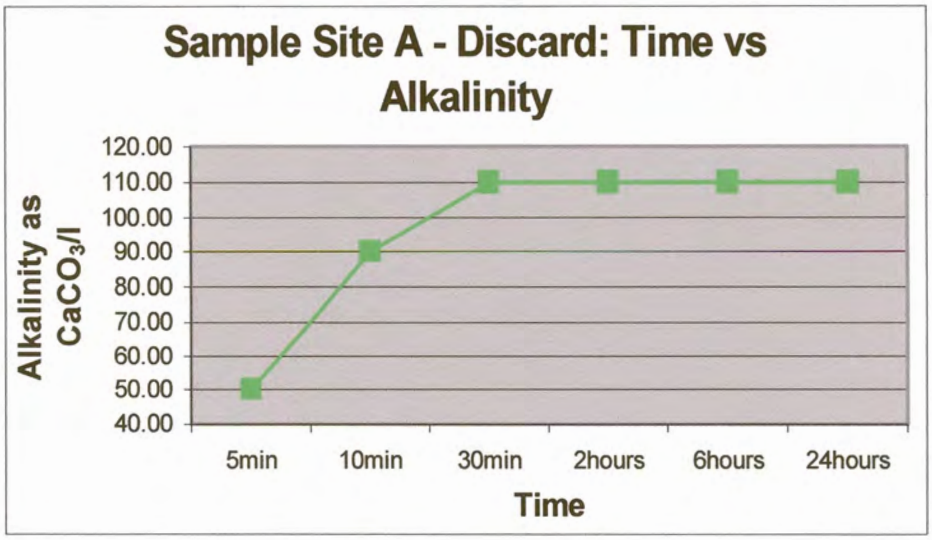


C.2 Sulphates

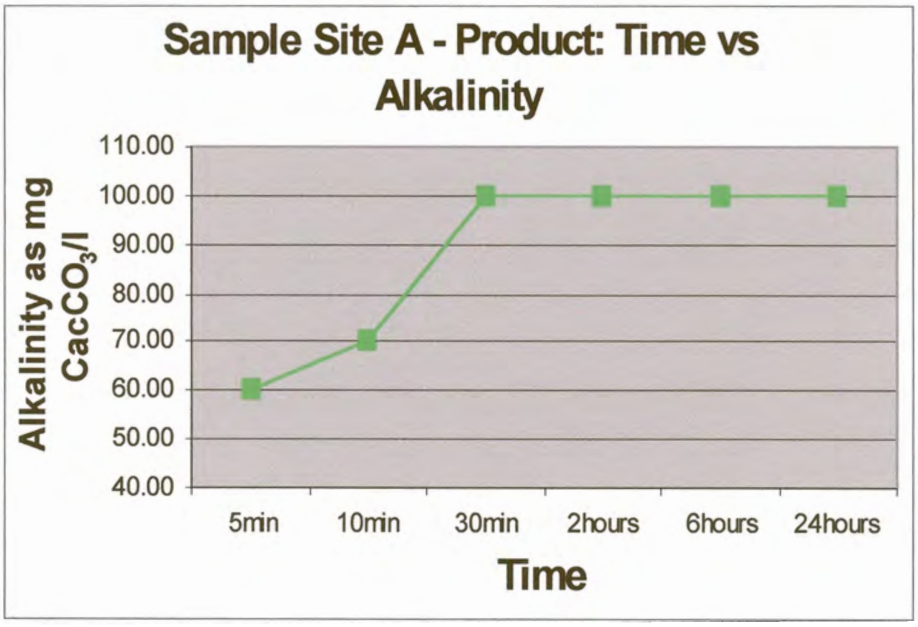
Sulphate concentration was <247 mg/l for all samples, at all time intervals.

C.3 Alkalinity

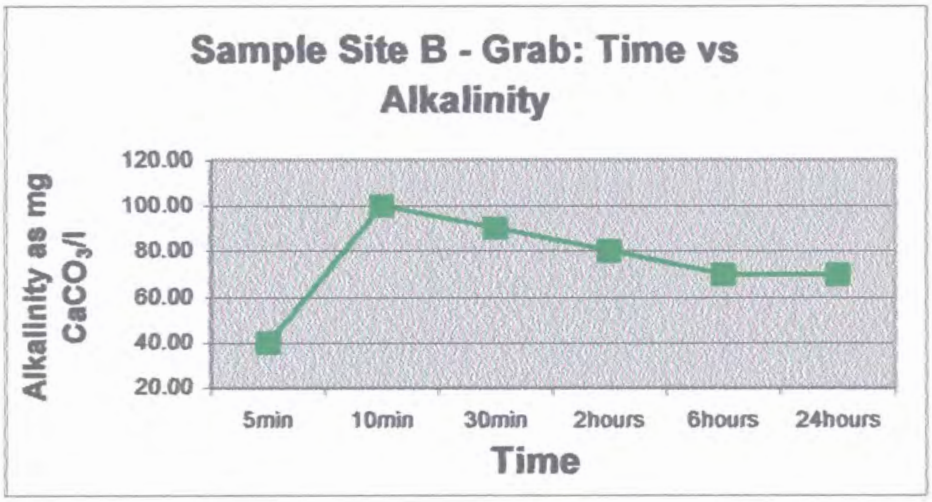


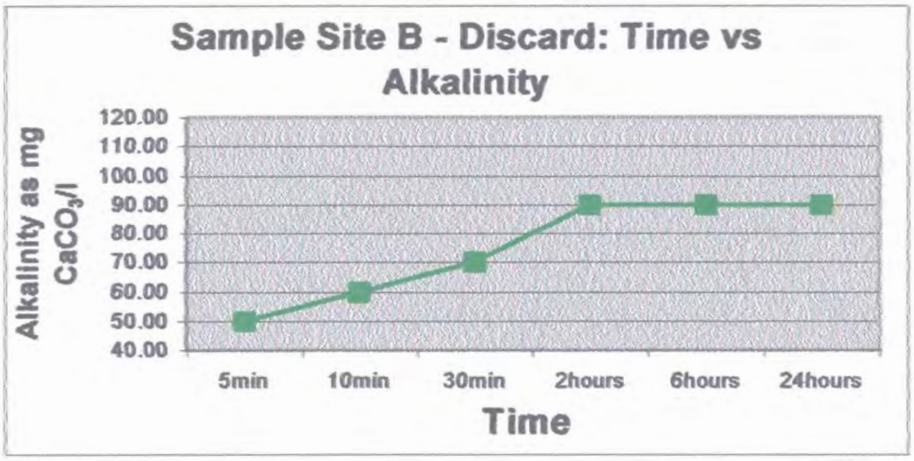


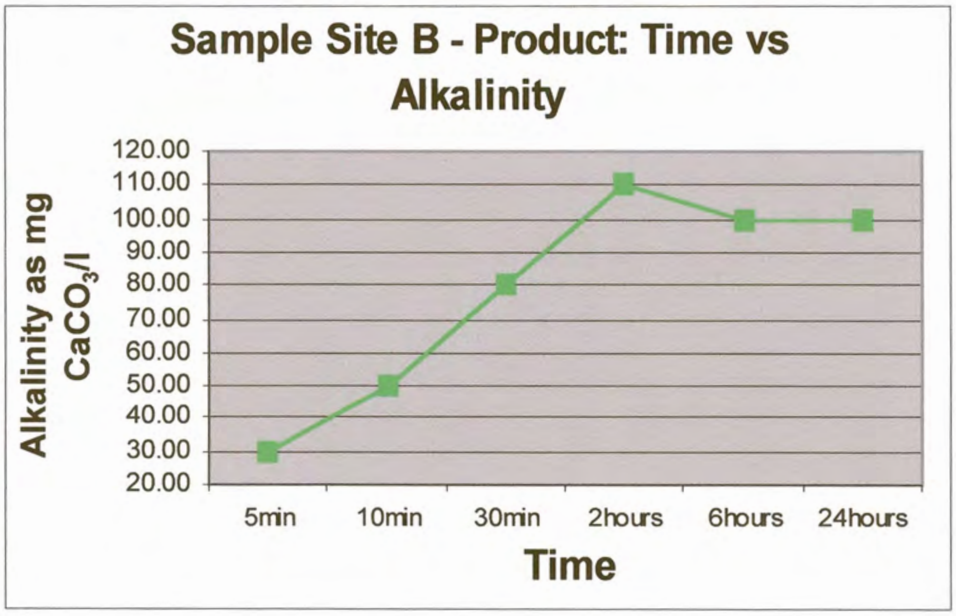
Sample Site A - Discard: Time vs Alkalinity

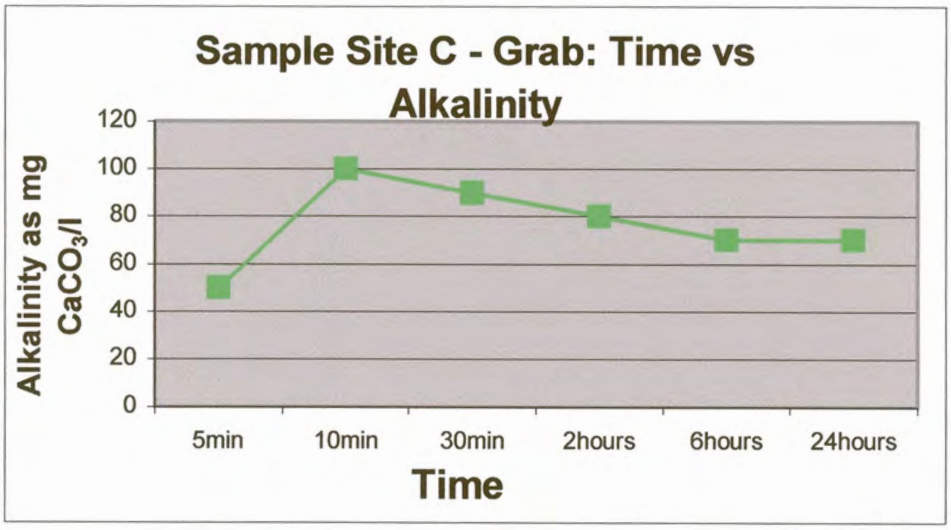


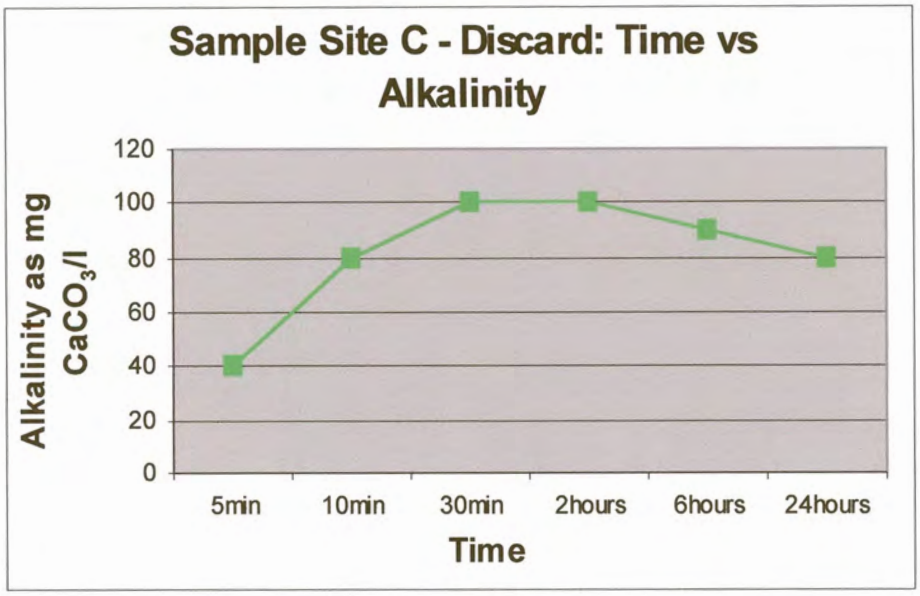
Sample Site A - Product: Time vs Alkalinity

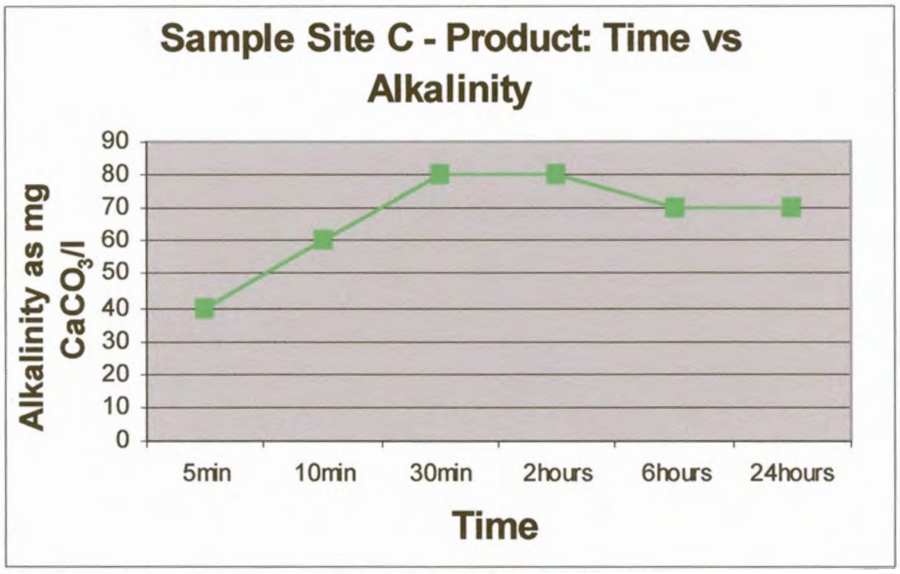

Sample Site B - Grab: Time vs Alkalinity
Alkalinity as mg CaCO$_3$/l
120.00
100.00
80.00
60.00
40.00
20.00
5min
10min
30min
2hours
6hours
24hours
Time

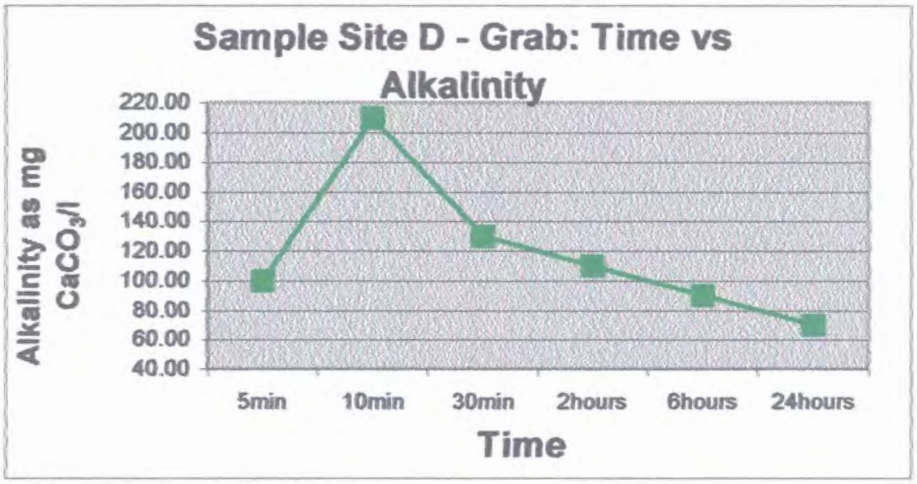

Sample Site B - Discard: Time vs Alkalinity
Alkalinity as mg CaCO$_3$/l
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
5min
10min
30min
2hours
6hours
24hours
Time

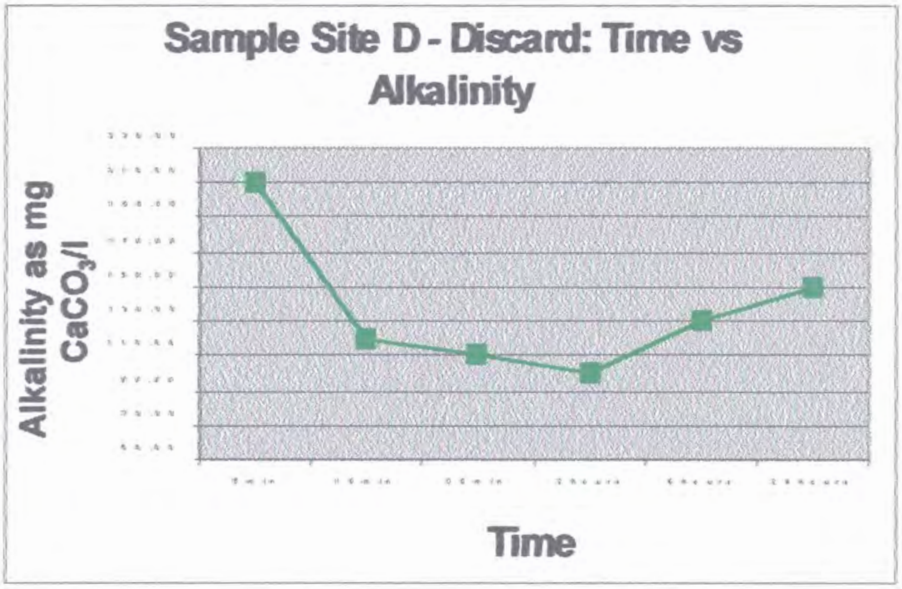

Sample Site B - Product: Time vs Alkalinity
Alkalinity as mg $CaCO_3$/l
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
5min
10min
30min
2hours
6hours
24hours
Time

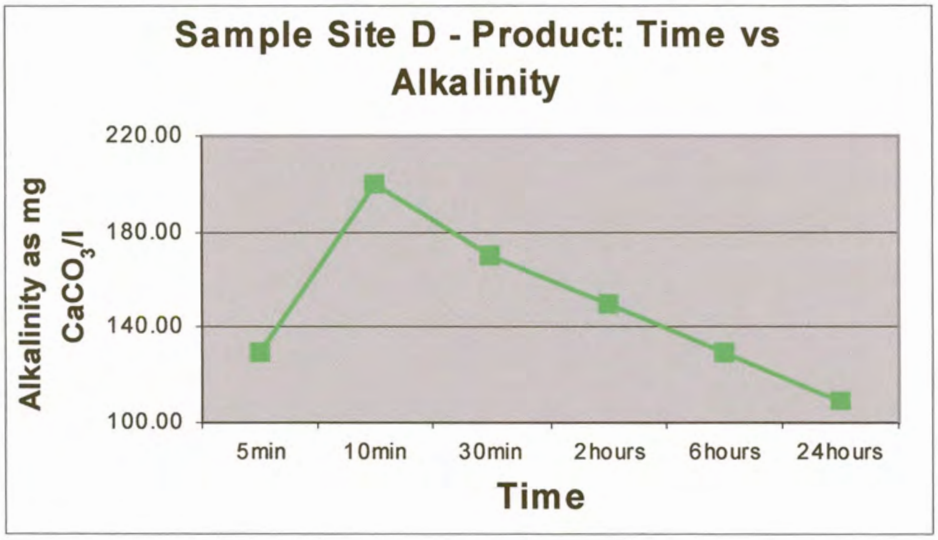

Sample Site C - Grab: Time vs Alkalinity
Alkalinity as mg $CaCO_3$/l
120
100
80
60
40
20
0
5min
10min
30min
2hours
6hours
24hours
Time

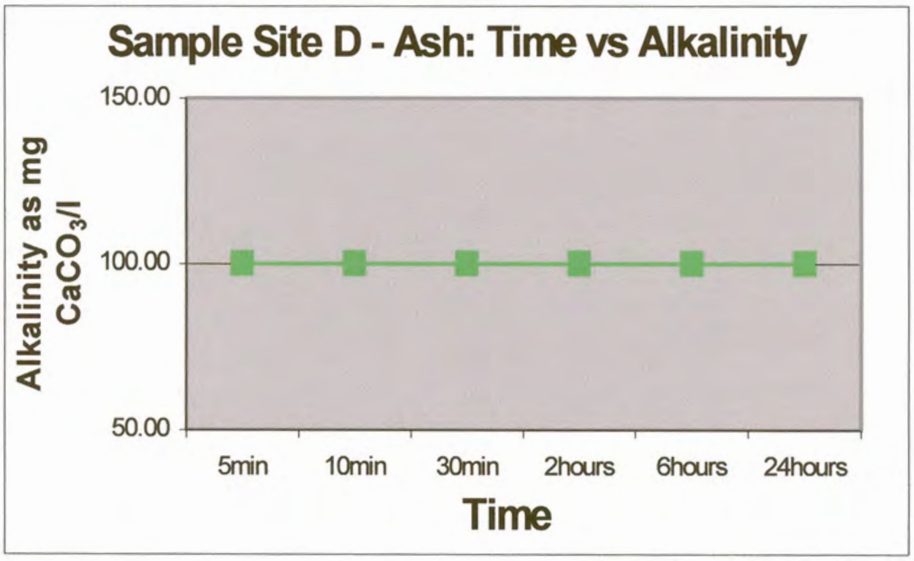

Sample Site C - Discard: Time vs Alkalinity
Alkalinity as mg CaCO3/l
120
100
80
60
40
20
0
5min
10min
30min
2hours
6hours
24hours
Time


Sample Site C - Product: Time vs Alkalinity
Alkalinity as mg CaCO3/l
90
80
70
60
50
40
30
20
10
0
5min
10min
30min
2hours
6hours
24hours
Time

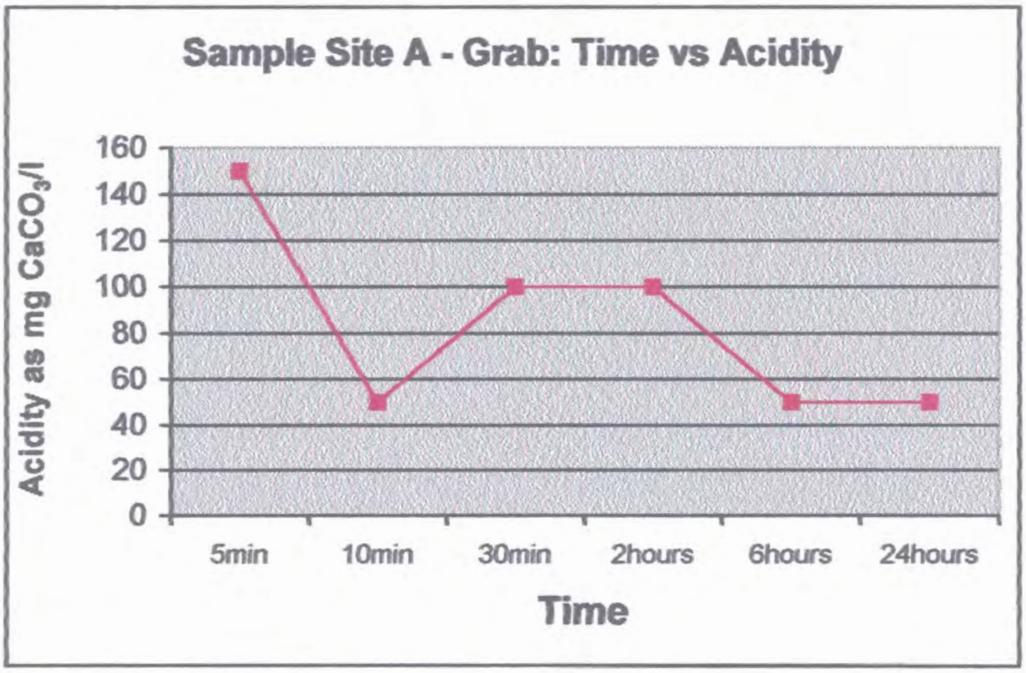

Sample Site D - Grab: Time vs Alkalinity

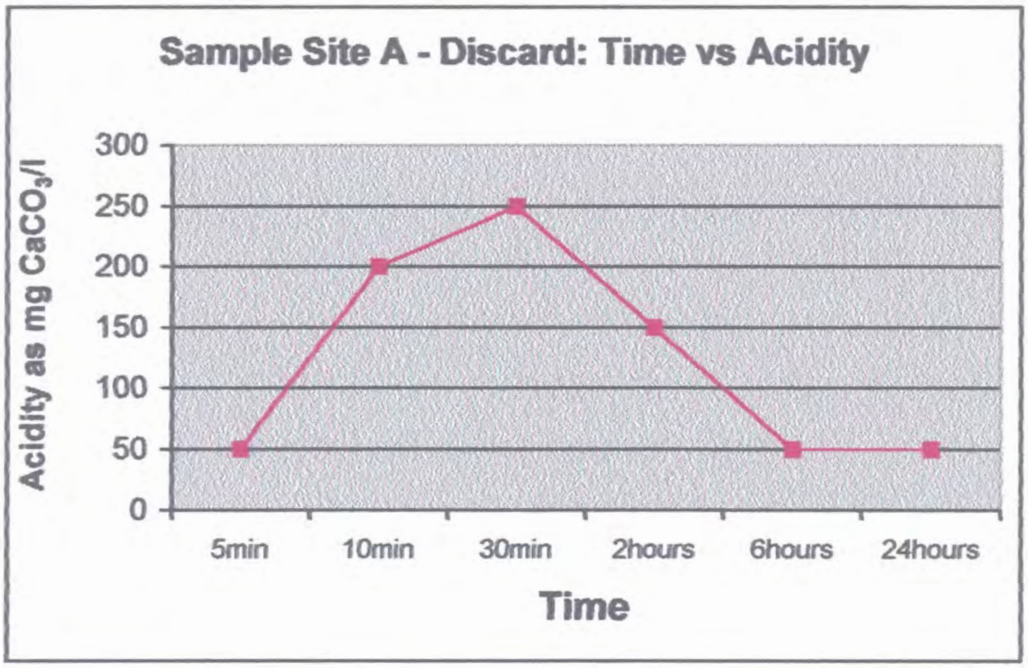

Sample Site D - Discard: Time vs Alkalinity

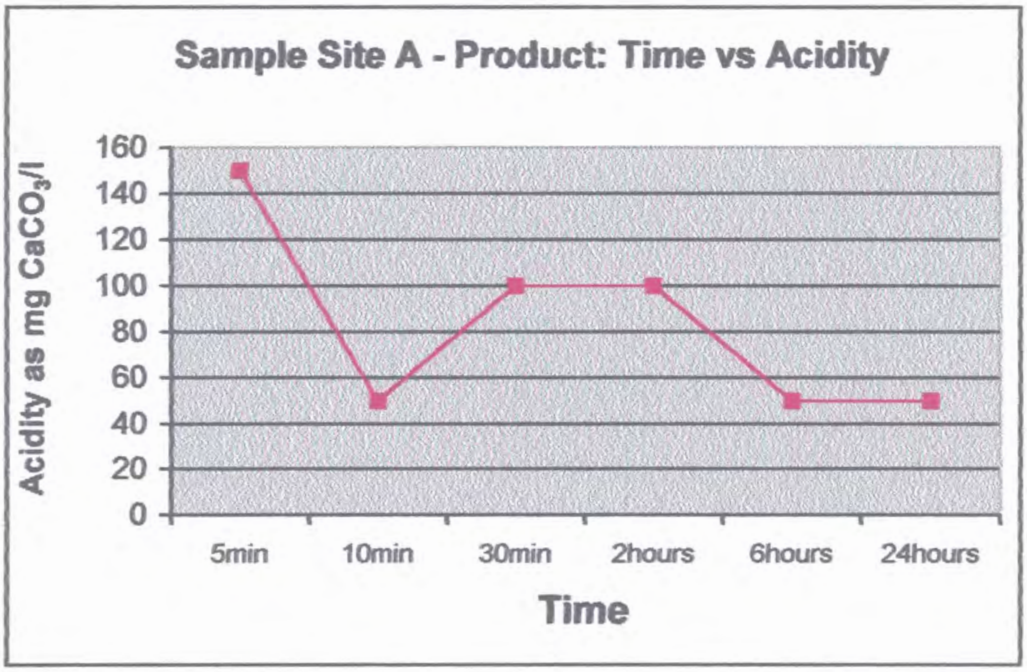

Sample Site D - Product: Time vs Alkalinity
220.00
180.00
140.00
100.00
Alkalinity as mg CaCO$_3$/l
5min
10min
30min
2hours
6hours
24hours
Time

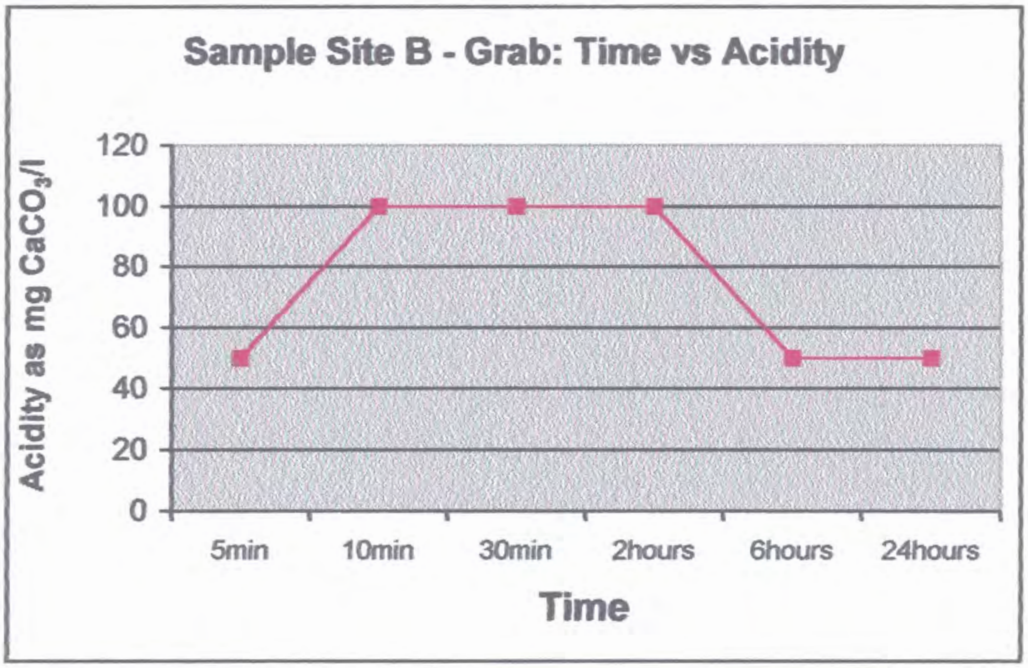

Sample Site D - Ash: Time vs Alkalinity
150.00
100.00
50.00
Alkalinity as mg CaCO$_3$/l
5min
10min
30min
2hours
6hours
24hours
Time

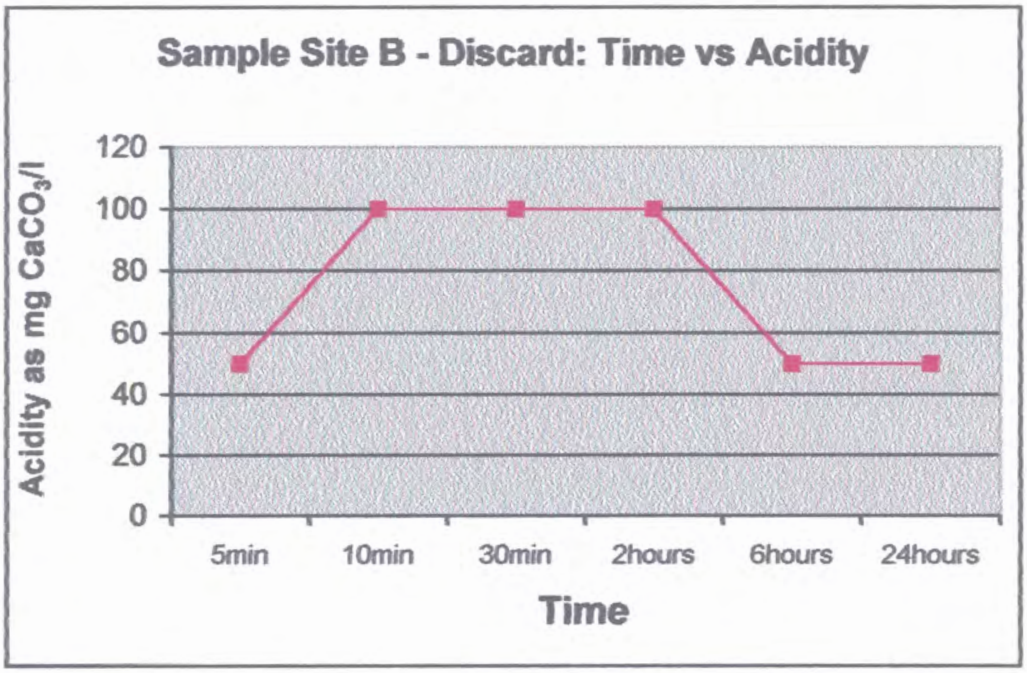
C.4 Acidity

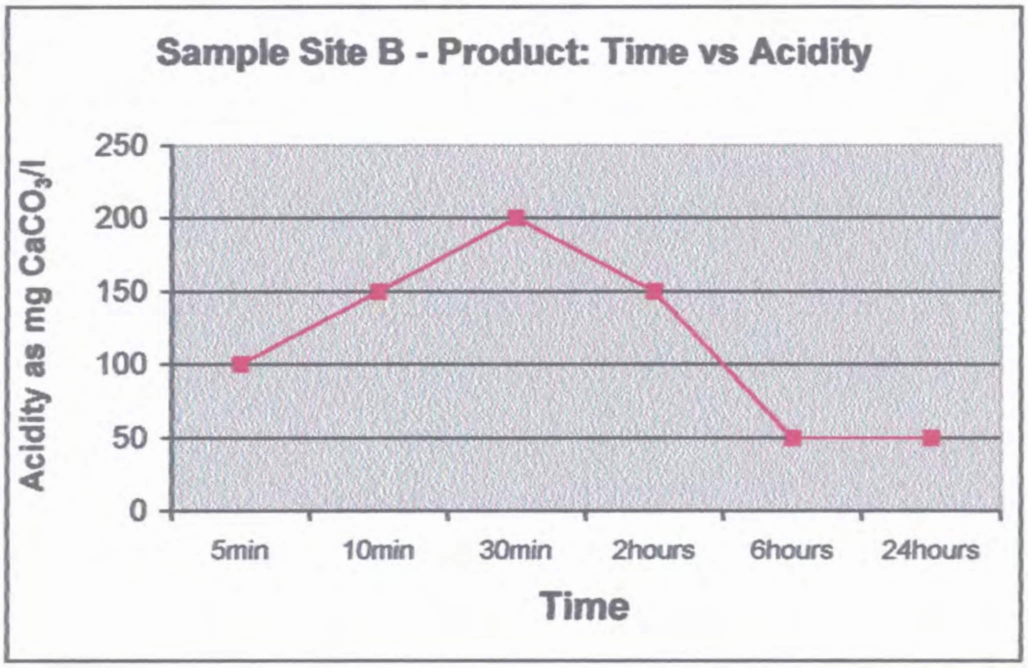

Sample Site A - Grab: Time vs Acidity
Acidity as mg CaCO₃/l
160
140
120
100
80
60
40
20
0
5min
10min
30min
2hours
6hours
24hours
Time

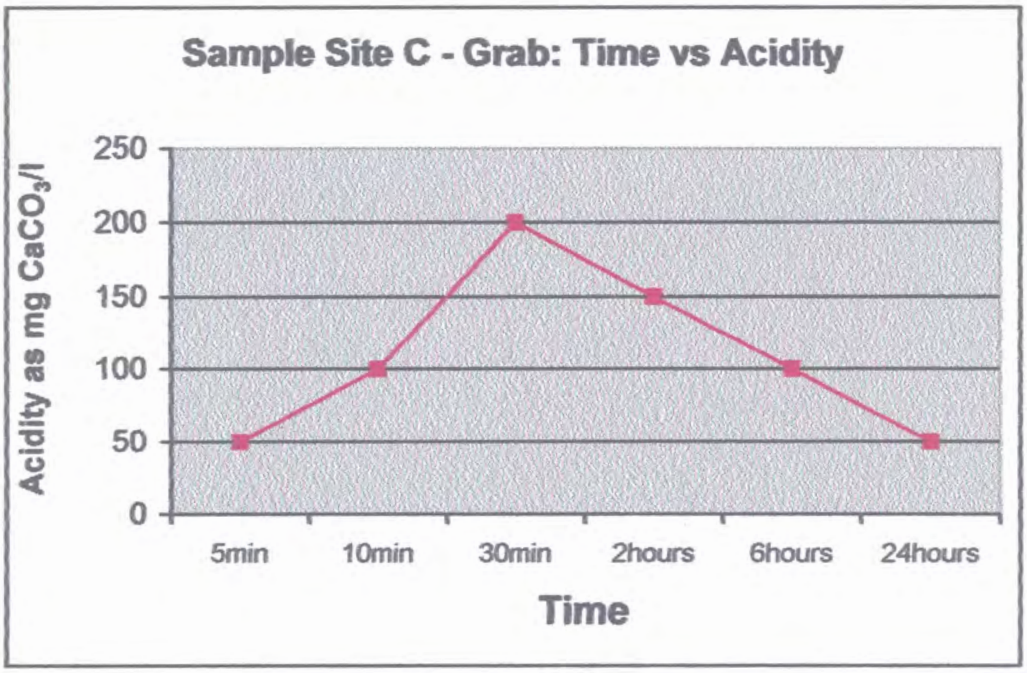

Sample Site A - Discard: Time vs Acidity
Acidity as mg CaCO₃/l
300
250
200
150
100
50
0
5min
10min
30min
2hours
6hours
24hours
Time

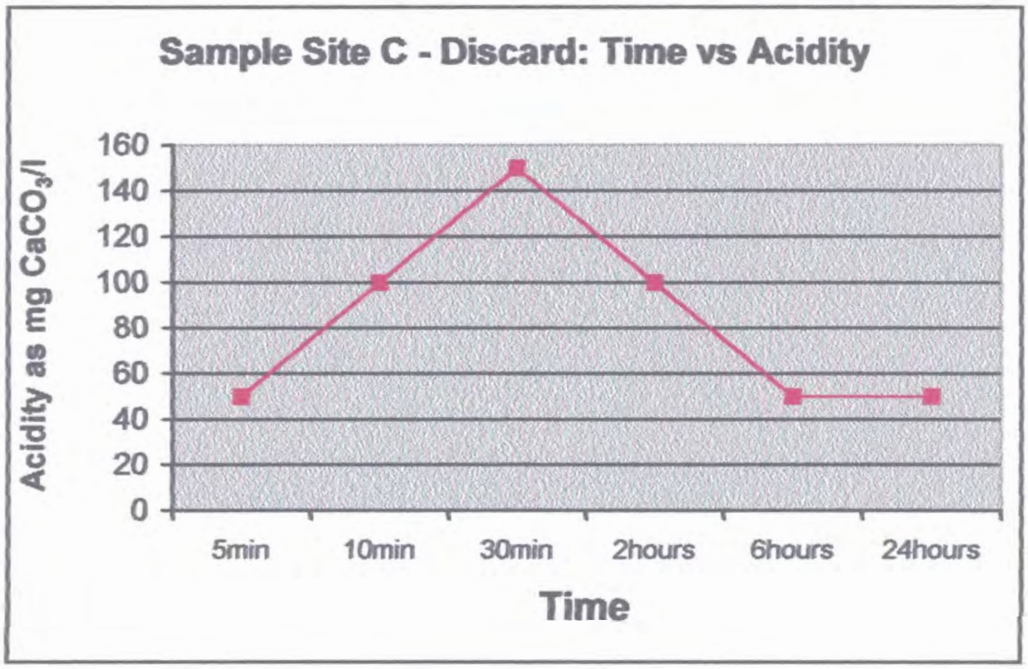

Sample Site A - Product: Time vs Acidity
Acidity as mg CaCO3/l
160
140
120
100
80
60
40
20
0
5min
10min
30min
2hours
6hours
24hours
Time

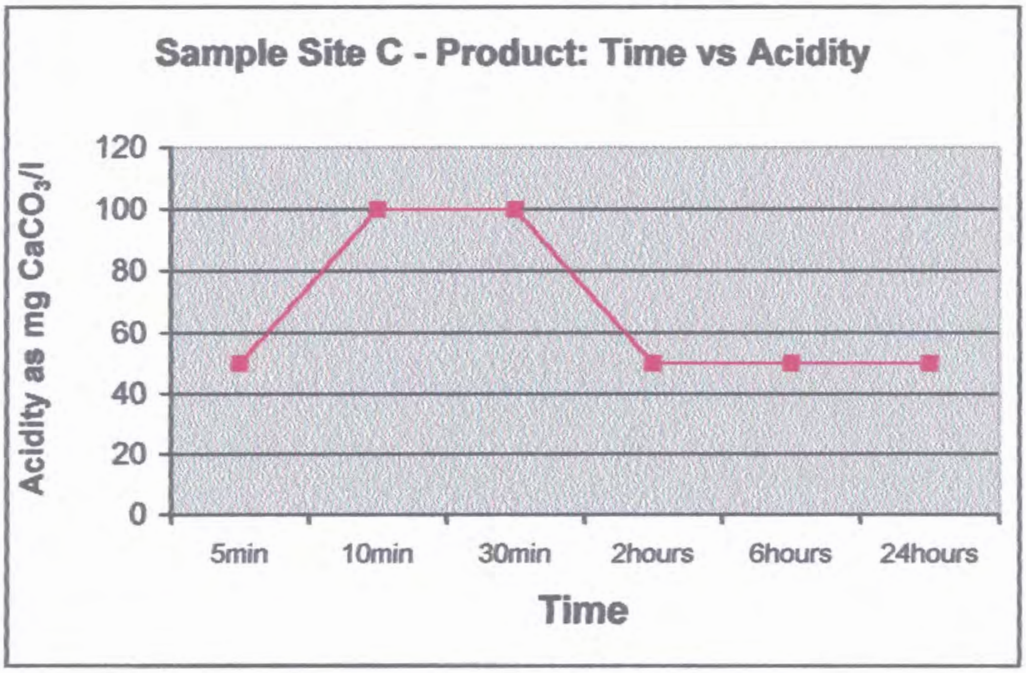

Sample Site B - Grab: Time vs Acidity
Acidity as mg CaCO3/l
120
100
80
60
40
20
0
5min
10min
30min
2hours
6hours
24hours
Time

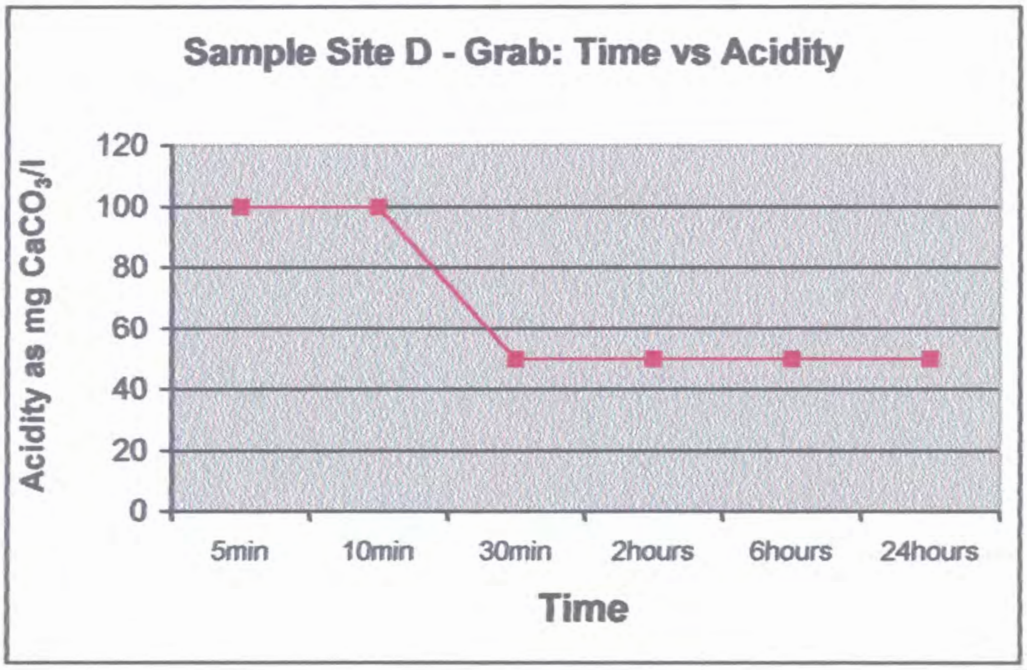

Sample Site B - Discard: Time vs Acidity
Acidity as mg CaCO3/l
120
100
80
60
40
20
0
5min
10min
30min
2hours
6hours
24hours
Time

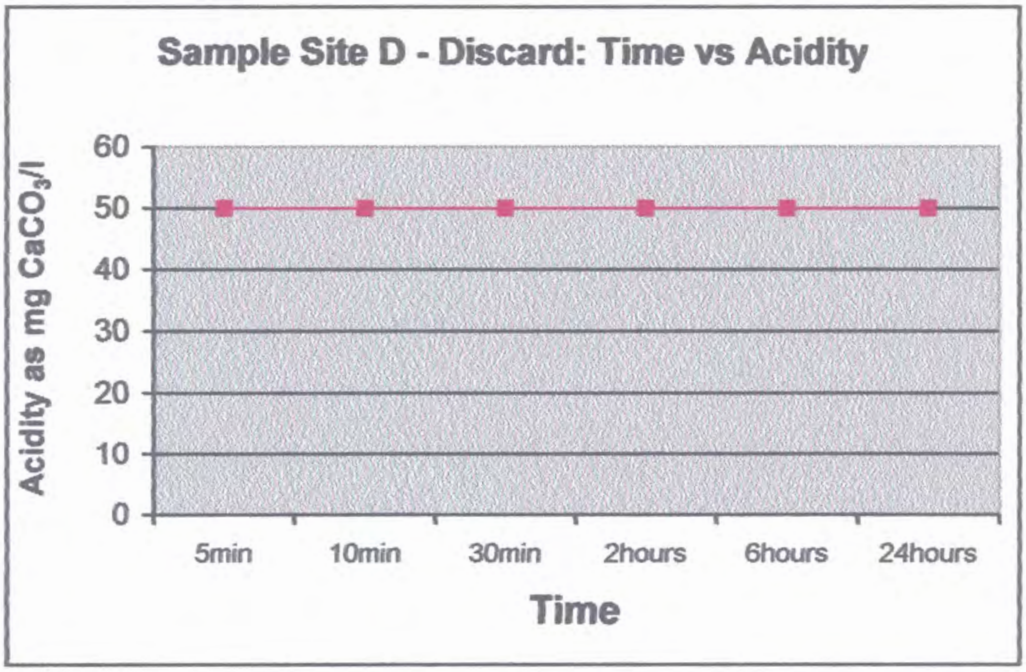

Sample Site B - Product: Time vs Acidity
Acidity as mg CaCO3/l
250
200
150
100
50
0
5min
10min
30min
2hours
6hours
24hours
Time

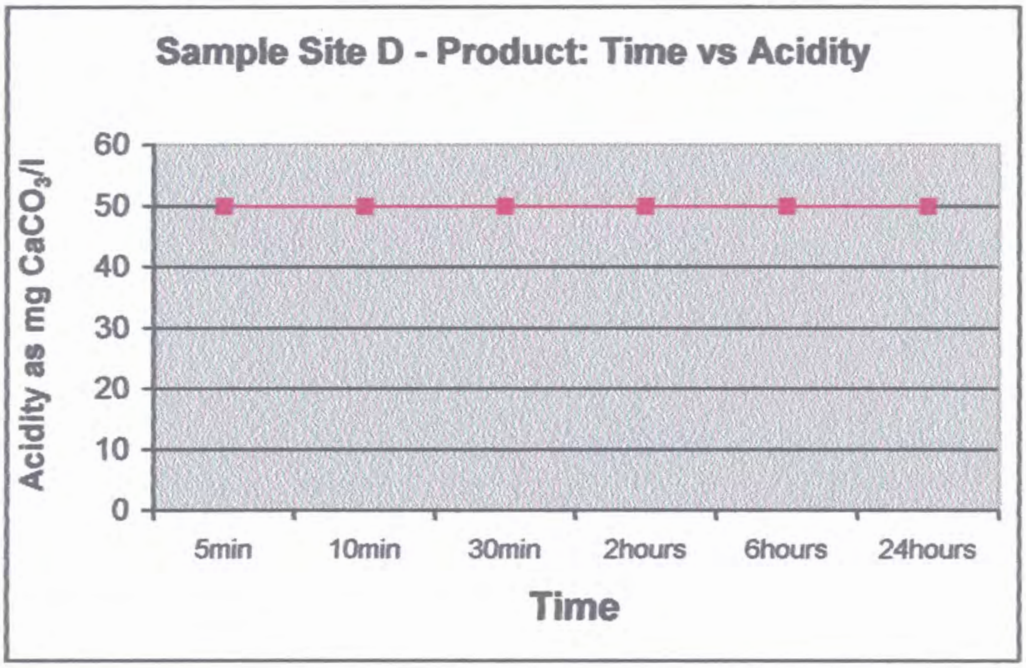

Sample Site C - Grab: Time vs Acidity
Acidity as mg CaCO3/l
250
200
150
100
50
0
5min
10min
30min
2hours
6hours
24hours
Time

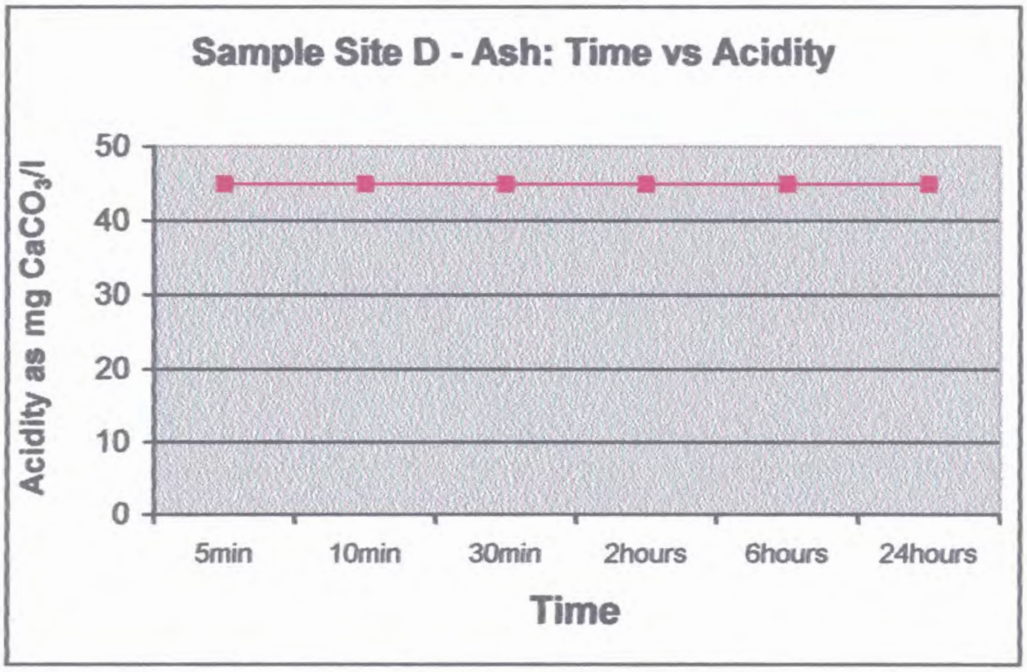

Sample Site C - Discard: Time vs Acidity
Acidity as mg CaCO3/l
160
140
120
100
80
60
40
20
0
5min
10min
30min
2hours
6hours
24hours
Time


Sample Site C - Product: Time vs Acidity
Acidity as mg CaCO$_3$/l
120
100
80
60
40
20
0
5min
10min
30min
2hours
6hours
24hours
Time


Sample Site D - Grab: Time vs Acidity
Acidity as mg CaCO$_3$/l
120
100
80
60
40
20
0
5min
10min
30min
2hours
6hours
24hours
Time


Sample Site D - Discard: Time vs Acidity
Acidity as mg CaCO3/l
60
50
40
30
20
10
0
5min
10min
30min
2hours
6hours
24hours
Time


Sample Site D - Product: Time vs Acidity
Acidity as mg CaCO3/l
60
50
40
30
20
10
0
5min
10min
30min
2hours
6hours
24hours
Time



C.5 Iron (II)

All Fe(II) trends show minimal variation and concentrations of this ion are minimal in all samples. Thus, the graphical representation for this variable has been excluded.