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IMPACTS OF ACID MINE DRAINAGE ON THE KROMDRAAISPRUIT SYSTEM

S. K. Kyeyune

MSc

2000

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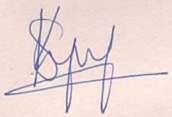
Silvia Kataliwa Kyeyune

A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2000

Declaration

I declare that this dissertation is my own unaided work. It is being submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.



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This 24th day of July 2000

Abstract

The area of study, the Kromdraaispruit system, is located in the Mpumalanga Province of South Africa. The system consists of both a stream and a wetland, which are receiving environments of treated acid mine drainage emanating from the flooded underground coal workings. The mine management noted that, even after the water from the underground workings had passed through the liming plant, acidic seeps 200m downstream were polluting it.

Sampling of the Kromdraaispruit system was done over a 12-month period. Different parameters including pH, EC, Total Dissolved Solids (TDS), Suspended Solids, Total Alkalinity (TAlk), Acidity, Chloride, Sulphate, Calcium, Magnesium, Sodium, Potassium, Iron, Manganese and Aluminium were analysed. The analysis revealed an acid mine drainage problem with maximum measured concentrations of >2000 mg/l SO_4^{2-}, 15.84 mg/l Mn^{2+}, 580.90 mg/l Ca^{2+}, 49.14 mg/l Mg^{2+}, 13.41 mg/l K^+ and 98.25 mg/l Fe^{2+}. The lowest pH in the region was pH 2.97 from the seeps around the liming plant area.

Using different modelling packages like ILWIS and STASOFT, it was found that, compared to the acidic seep, the groundwater intercepting the stream at four points, one point along the liming plant stream and three in the wetland, did not have as big an impact on the concentration of some determinants like pH.

In the Kromdraaispruit wetland, the wetland sediments act as a sink for contaminants, generally improving the quality of the water flowing through it. The concentration of some determinants passing through the wetland, such as SO_4^{2-}, Mn^{2+}, Ca^{2+}, Mg^{2+}, K^+ and TDS, decreased. It was also noted that the efficiency of the wetland was greatly reduced by the high discharge of accumulated salts that simply flushed through it. In most cases, determinants like SO_4^{2-}, Mn^{2+}, Al^{3+}, Ca^{2+}, TDS, EC and pH decreased, but not to concentrations complying with the permissible levels stipulated by the Department of Water Affairs and Forestry. Due to the addition of lime downstream of the liming plant, a suspension of "yellow buoy" formed in the wetland. This decreased the potential of the wetland to reduce pollution.

Soils were collected at different sites around the study area during the rainy and dry seasons. Laboratory analysis involved determination of total anions and cations, Sodium Adsorption Ratio (SAR), saturation, pH, electrical conductivity (EC) and the concentrations of Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, SO_4^{2-}, F^{-}, Cl^{-}, NO_2^{-}, NO_3^{-} and available PO_4. From the results obtained it was noted that the soils did not contribute to nor ameliorate acid mine drainage in the Kromdraaispruit system. This is because South Africa is an arid region and migration of ions in the soil to cause any siginificant impacts is slow.

This study discusses the implications of these observations for the monitoring and management of the polluted system.

To my beloved parents Mr & Mrs. R. N. Kyeyune

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CHAPTER 1

MINING AND WATER IN SOUTH AFRICA

1.1 INTRODUCTION

The Republic of South Africa (SA) has severely limited water resources. A burgeoning population, which is predicted to increase from 38 million to 60 million by the year 2010 (Fourie *et al.*, 1992), coupled with an expanding industrial demand, are increasingly putting water resources under pressure. These are indications of the short-term demands, likely to be exerted on water resources.

Coupled with this increasing demand, the large volume of dissolved salts, derived primarily from the mining industry, further strain the water resources. While mining is essential for continued development, it generates serious impacts on the environment. Mining activities are one of the major sources of pollution of surface water in South Africa. These activities discharge more than 300 000 m^3/day of contaminated water and approximately 330 000 tonnes of salt load annually to the limited water resources (Fourie *et al.*, 1996). In recent years increasing production and the disposal of wastewater have caused an accelerated destruction of the receiving environment. In mineral processing the need for higher mineral recoveries has led to more elaborate recovery methods, most of which involve the extensive use and recycling of water (Tedder, 1989).

The management and control of water in mining operations has been a neglected area in comparison to the control exercised over the air used in the ventilation of deep mining operations (Tedder, 1989). It is noted that there is a need to exercise careful control over water quality.

1.2 LEGISLATION GOVERNING MINING IN SA

Faced with the gradual deterioration of water quality and the economic, political, social and demographic changes taking place in South Africa, the Department of Water Affairs and Forestry (DWAF) adopted an approach to water quality management that would ensure that it could continue to meet its obligations. Its main objective was to ensure that water of an acceptable quality for recognised water uses such as urban, industrial, agricultural, recreational and environmental conservation continues to be available (Bervoets *et al.*, 1996).

The growing concern about public health and the progressive deterioration of the aquatic environment has resulted in the promulgation of legislation to control the quality of effluents and receiving waters (Hellawell, 1989 in Bervoets *et al.*, 1996). All mining in South Africa is governed by the legislation below, which regulates the impacts that mining activities may have on the environment.

1.2.1 National Environmental Management Act 107 of 1998 (Dalton *et al.*, 1998a)

This act stipulates that everyone has the right to an environment that is not harmful to his or her health or well–being. This act provides for cooperative environmental governance by establishing principles for decision making on matters affecting the environment, institutions that will promote cooperative governance and procedures for coordinating environmental functions exercised by organs of state.

1.2.2 The Water Amendment Act 58 of 1997 (Dalton *et al.*, 1998b)

The Water Act came into effect in 1956. It protects water and limits effluent discharge by the industry. Before promulgation of the Water Act 54 of 1956, many mines were abandoned without implementation of adequate pollution control measures. Regarding the provision of pollution control measures at abandoned collieries and the responsibility for costs to institute measures in terms of the Water Act 54 of 1956, an agreement was reached between the Ministry of Water Affairs and the Chamber of Mines in 1976. This act, in summary, states that:

- Pollution control measures, the maintenance of such measures and all costs pertaining thereto in respect of mines and works abandoned before July 1956, would be the responsibility of the State.
- In respect of mines or works abandoned subsequent to July 1956, where measures had been instituted to the satisfaction of the State, the State will take responsibility for the maintenance and betterment of the pollution control measures taken.
- Should mining or works at any stage be resumed at a previously abandoned mine, the company resuming the operations will be responsible for any existing pollution control measures on the portion which is to be reworked, and for any additional pollution control measures required in respect to the resumed operations.

The Water Amendment Act 96 of 1984, sections 22 replaced sections 21 and 23 of the Water Act 54 of 1956.

1.2.3 Mines and Works Act 67 of 1956 (Dalton *et al.*, 1998a)

Currently, regulations in the Minerals Act are concerned with opencast mining rehabilitation as well as water and air pollution and environmental degradation.

1.2.4 Environment Conservation Act 73 of 1989 (Dalton *et al.*, 1998b)

This Act encompasses:

a) Protection of the natural environment; i.e. preservation of specific ecological processes, natural systems, natural beauty, species of indigenous wildlife and the preservation of biotic diversity in general.

b) Control of environmental pollution.

c) Control of activities that may have detrimental effects on the environment. e.g., water use and disposal, resource removal, including natural living resources, industrial processes, waste and sewage disposal and chemical treatment.

1.2.5 Minerals Act 50 of 1991 (soon to be replaced) (Dalton *et al.*, 1998a, p. 1-151)

The Act requires a mandatory rehabilitation and layout plan to be completed for all new prospecting operations. It states that:
"An environmental management programme in respect of the surface of land concerned in any prospecting or mining operations or such intended operations, shall be submitted by the holder of the prospecting permit or mining authorisation concerned to the Director: Minerals Development concerned for this approval and, subject to subsection (4), no such operations shall be commenced without/before obtaining any such approval."

1.3 COAL MINING IN SOUTH AFRICA

Historically coal mining has played a major role in the economy and development of South Africa (Batchelor, 1994). As an earner of foreign exchange it is second only to gold mining and is regarded as a mainstay of the South African economy. South Africa has nineteen coalfields spread over an area of some 700 km from North to South and 500 km from West to East. One of the nineteen coalfields is the Witbank coalfield, the centre of the country's modern coal mining industry, where the area under study (Kromdraai Coal field) is situated (Fig 1.1).

Mining of the Witbank Coalfield started in 1896 (Long, 1986) in areas near the present-day town of Witbank. The shallow coal seams were exploited by underground bord and pillar mining methods until their abandonment in the late 1940's and early 1950's (Wates *et al.*, 1992). To date, all underground mining in the Kromdraai study area has ceased and has been replaced by opencast operations.

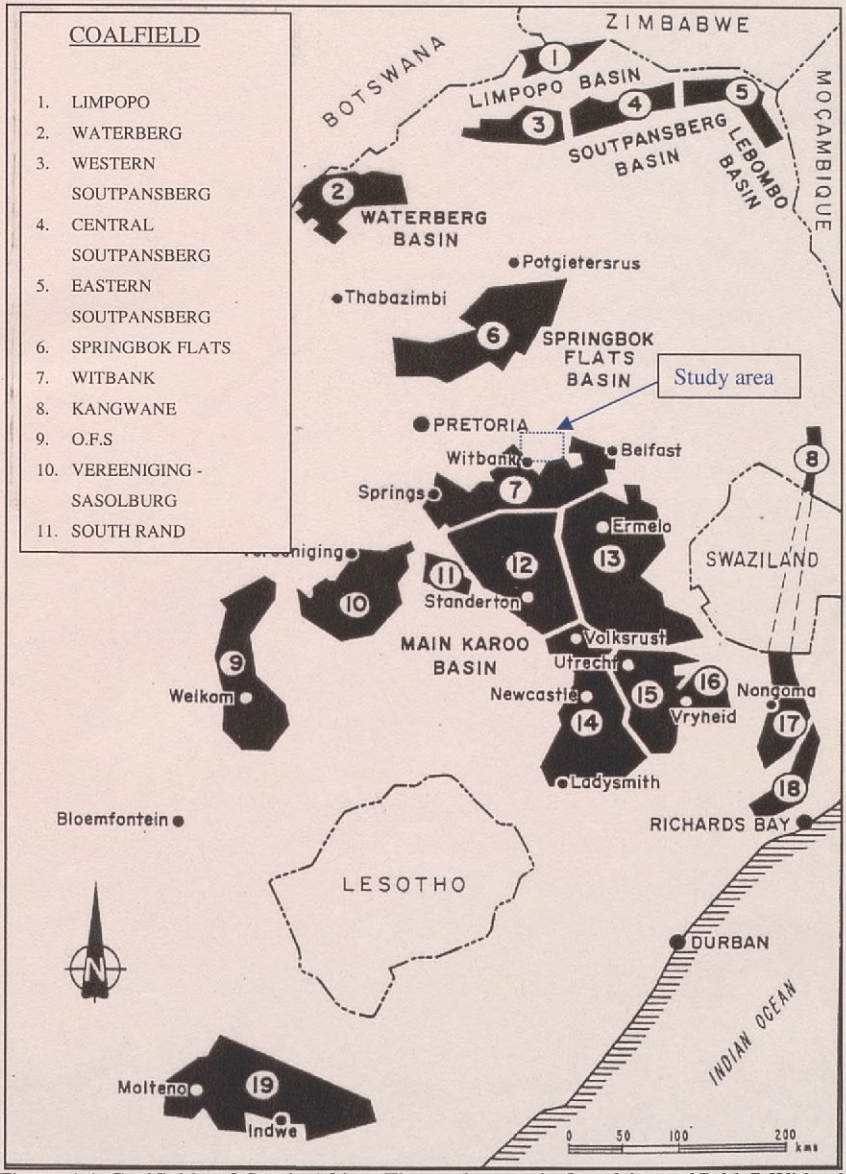


Figure 1.1 Coalfields of South Africa. The study area is found in coalfield 7-Witbank (Mehliss, 1990).

South African coal started forming in the Permo-Carboniferous and Triassic ages (Long, 1986), from plants that grew in swamps, in a temperate climate some 250 million years ago, as Gondwanaland was emerging from an extensive ice age. Glacial melt water, carrying suspended rock flour, poured into the peat swamps lying in the basin that is today known as the Karoo basin. Iron and sulphur compounds were included in the detritus flowing into these swamps (Wells *et al.*, 1992).

Peat formation was followed by a depositional phase during which the peat was buried by sediments. Further peat formation and another depositional phase followed. As the deposits accumulated in depth, the lower ones were subjected to elevated pressures and temperatures, bringing about the onset of coalification. A final phase of deposition covered the last peat layer and formed that, too, into coal (Wells *et al.*, 1992).

Typical of peat swamps, the underwater environment was anaerobic. The iron and sulphur compounds therefore reacted to form an iron sulphur compound (FeS_2), also known as pyrite, as well as sulphur compounds in the coal itself. These inherent characteristics give coal a quality that can have significant potential environmental impacts. On exposure to both oxygen and water, the pyrites oxidise to form sulphuric acid, which can lead to water pollution.

South Africa is the fourth largest producer of black coal in the world and second largest exporter after Australia. In 1999, run of mine (ROM) coal production for South Africa was 287.97 million tonnes compared to 289.48 million tonnes in 1998. The 287.97 million tonnes of ROM coal in 1999 yielded 220.44 million tonnes of saleable coal, a yield of 76.5% (South African Coal Report cc, 2000).

1.4 ENVIRONMENTAL IMPACTS OF COAL MINING

The coal mining industry has committed itself to the concept of sustainable development and recognises the equal and inter-dependent relationship between economic growth on

the one hand and the protection of human health and the natural environment on the other. It is noted that, as with gold mining, most of the environmental problems associated with coal mining are a legacy of the past. The defunct mines are the culprits, but fortunately few of these remain (Russell, 1990).

Detailed research on the waste products from old mines, the re-evaluation of existing mining operations, predictions of acid rock drainage from proposed mines and the development and improvement of waste management plans are essential for the future success of the mining industry and the safety of the environment. Acid mine drainage has become of significant concern because of the potential long-term environmental implications and the accompanying liabilities.

The cost of using chemical treatment techniques to ensure that mine water meets the required standards can be prohibitive. Chemical treatment also generates waste, which may be hazardous and requires disposal (Fourie *et al.*, 1996). The mining industry spends more than R50 million annually on environmental rehabilitation and even more on research into more efficient and effective ways of ensuring that the mining industry co-exists in harmony with the South African environment (Russell, 1990). Programmes developed for the environment require that the environmental implications of mining be considered at every stage of the life of a project. i.e. feasibility study stage, planning stage and operational stage, up to and beyond closure of the mine.

When mining was originally started, the water pollution potential of coal mining was not realised. The impact of coal mining on the environment has only become apparent in recent decades. Mining of the coal reserves in the areas affected in South Africa started as early as 1860 (Vorster, 1994).

1.5 SUMMARY

- Coal mining is a very old industry in South Africa. It commenced in the latter half of the 19th century. Coal mining impacts on different types of environmental media, of which the main ones are surface, air and water. This industry is one of the major contributors to the pollution of surface and ground water resources in South Africa.

- Even if coal mining is an old industry, its impacts on the water resources have only become apparent in recent decades. If these resources continue to be polluted, there will not be enough to cater for the rapidly expanding population in SA.

- Given these environmental problems, the government has ensured that legislation is in place to regulate the usage of water resources and control their pollution. New legislation is also in the pipeline and it will have significant impacts on the mining industry and the conservation of the water resources.

CHAPTER 2
ACID MINE DRAINAGE AND TREATMENT

2.1 INTRODUCTION

Coal mining impacts on three systems; water, land and atmospheric environments. Surface pollution is the most visible impact, especially in open cast mining operations, which expose the underlying layers of coal. The surface pollution effects of underground coal mining are less visible (Russell, 1990). The most critical surface pollution aspects of coal mining are waste dumps and surface subsidence. Forty percent of South Africa's coal production is mined by open cast methods. The extraction of large quantities of coal creates large pits that have the potential to cause severe environmental degradation.

Open cast mining also has the potential to damage the atmospheric environment. There is a high probability of dust production, which can causes lung diseases. It also impacts on the soil and water resources by promoting acidic environments that are not conducive to most flora and fauna survival.

This study focuses on the third main area of impact of coal mining; water pollution in the Kromdraai study area as a result of acid mine drainage.

2.2 PROBLEM IDENTIFICATION

Specific streams in the Witbank area are of particular concern to the Department of Water Affairs and Forestry (DWAF) because the water quality in some streams has deteriorated to a level that is unacceptable to downstream users. The pollutant load exported by these streams also impacts on receiving water bodies further downstream, in particular Loskop Dam (Wates *et al.*, 1992).

The Kromdraai opencast mine is part of the South African Coal Estates (S.A.C.E) situated in the Witbank area. Presently mining is proceeding in areas which were

previously exploited underground. Underground bord and pillar workings previously existed in large portions of the planned operations. Following closure of the previous mining activities, the underground workings have become flooded and water seeps out of these workings into the nearby streams. When this water comes into contact with the pyrite (FeS_2) in the coal seams in the presence of air, an environment which promotes the production of acid is created. Before it flows into the Kromdraaispruit system, which consists of a stream and a wetland, the acidified water is treated at the HDS liming plant situated to the north-west of the old workings.

It was been noted that the water being discharged from the liming plant had a high, alkaline pH (> 9) but by the time the water reached the Kromdraai weir, located approximately 5 km downstream, it had attained low, acidic pH (< 4). The area from the liming plant to the Kromdraaispruit weir was studied in order to permit remediation of this problem.

2.3 AIMS AND OBJECTIVES OF THE STUDY

The main objective of this study was to find sustainable solutions for mine management to maintain water resources of a quality fit for use by all recognised downstream users. To achieve this objective, the study aims to:

1. Locate all the pollution sources, i.e. the acidic seepages, along the Kromdraaispruit from the liming plant up to the end of the wetland which is 5 km downstream.

2. Determine the impacts of acidic seepages, wetlands, evaporation pans and ground water on the different properties of the water in the Kromdraaispruit.

3. Investigate the impacts of seasonal fluctuations on all the abovementioned properties.

4. Use geochemical and geospatial modelling to quantify the extent of the impacts of acid mine drainage on the Kromdraaispruit stream and wetland.

5. Suggest, from observations, solutions to ameliorate the effects of acidic drainage.

2.4 KROMDRAAI STUDY AREA

2.4.1 Location of the Study Area

The study area is found near Witbank in the Mpumalanga Province in the north–eastern region of South Africa (Fig 1.1). It is situated 18 km north-west of the town of Witbank (Fig. 2.1) which is 90 km NE of Pretoria and 105 km NNE of Johannesburg, both major cities. Geographically the study area lies between 28^0 E and 29^0 E (longitude) and 25^0 S and 26^0S (latitude). It is relatively high lying ground with elevation ranging from 1400m to 1520m above sea level. The mining area is situated on a watershed, giving rise to the Kromdraaispruit, Suikerboskopspruit and Brugspruit to the west and the Grootspruit to the north-east.

Witbank and its environs are characterised by a wide spectrum of land uses - agriculture, residential and commercial development, industry and coal mining (Wates *et al.*, 1992). These are the dominant sectors contributing to regional economic growth. The region has experienced rapid growth over the past three decades. The mine is situated in a mixed farming area, typical of the Witbank highveld region, with a mixture of arable, grazing and wilderness land use.

2.4.2 Climatic Conditions

The long-term mean annual rainfall as measured in Witbank over the last sixteen years ending August 1999 is 59.64 mm (App. D, Table D3). The prevailing wind is north-easterly with an average speed of 2.9 m/s. The temperatures in the area are shown in table 2.1.

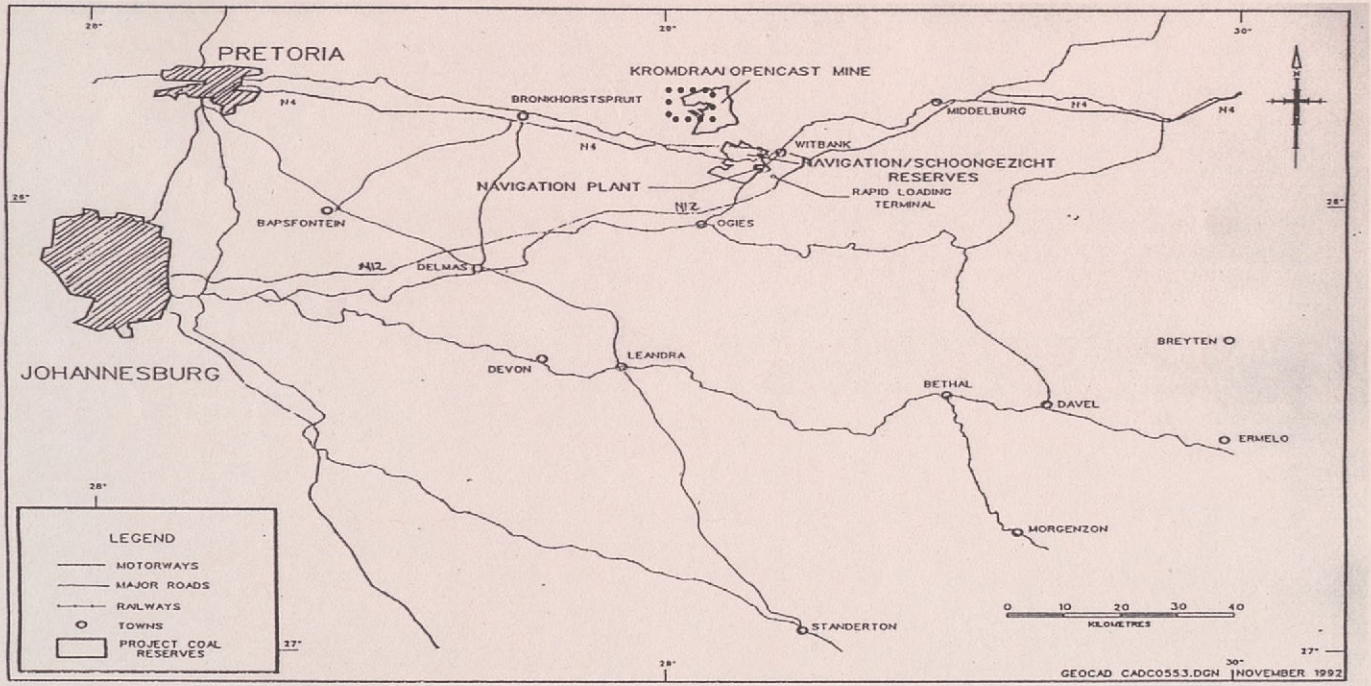


Figure 2.1 : Locality plan of the study area (Kromdraai). Dashed square shows the study area (Amcoal Colliery & Industrial Operations Ltd., 1993)

Table 2. 1 Average temperatures of the Witbank Area (De Villiers, 1991).

	Summer (Oct –Mar)	Winter (April–Sep)
Mean	20^0C	9^0C
Maximum	29^0C	20^0C
Minimum	12^0C	3^0C

2.4.3 Geology

This area occupies a nearly level residual of what was formerly a very extensive, old erosion surface that has been termed the "African" surface. This is believed to have occupied most of Southern Africa 50 or 60 million years ago, but has subsequently been dissected, leaving relatively few perfect residuals. Although the study area has been subject to some erosion (commonly referred to as "lowering"), it nevertheless has some deep soils and weathering residues which are characteristics of the African surface (de Villiers & Heathman, 1991).

The underlying geology of the survey area is dominantly the coal-bearing Vryheid Formation (±200 ma.) sandstone with minor interbedded shale units. These sediments belong to the Ecca Group of the Carboniferous System (230-345 ma) and were deposited on a scoured, shallow paleovalley floor comprising older sediments and volcanic rocks of the Waterberg and Rooiberg Groups respectively. This is seen on a digitised regional geological map (Fig 2.2) extracted from the 1:250000 geological series Map 2528 of Pretoria. A white square marks the study area. Pre-Karoo diabase intrusions also form part of the paleo-valley floor in places.

A few Karoo-age dolerite dykes and sills have intruded into the Ecca sediments and are commonly responsible for minor vertical displacements of coal seams underground. Structurally, the sediments are generally unaffected by faulting, and the regional dip

mostly mimics the topography of the paleo-valley floor (Wates *et al.*, 1992). The Ecca series overlies a thin layer of Dwyka shales and tillites (Fig 2.3).

2.4.4 Surrounding Aquifers

Witbank and environs are located upstream, in the southern part of the Olifants River catchment. The Olifants River Catchment is situated in the north east of South Africa spanning the Northern Province and Mpumalanga. Its upper streams drain the Witbank and Middleburg Highveld regions, then passes over the Springbok Flats and ends up meadering through the Lowveld to the Kruger National Park and onwards to Mozambique (DWAF, 1996). The catchment has a surface area of 54 570 km^2 (Moolman *et al.*, 1999). Figure 2.4 shows the regional perspective of the Witbank area in relation to the total drainage basin of the Olifants River.

The Waterberg Sandstone underlies the area surrounding the Kromdraai Coalfield. These sandstones are weathered to shallow depths, generally less than 4 metres. Below this depth, the sandstone is generally impermeable to ground water movement except in the odd fracture (Hodgson, 1992).

The hydrology of the area is complicated by the presence of water bodies in the underground workings (Fig 2.5). Underground bord and pillar coal mining has previously been done in large portions of the planned operations. After closure of the previous mining activities, portions of the underground mine filled up with water (Fig 2.5). This water has an acidic character. Seepage of acid water from the old mine workings forced South African Coal Estates (S.A.C.E) to establish a water liming plant to the north-west of the old workings. The liming plant was to improve quality of water being drained into the stream.

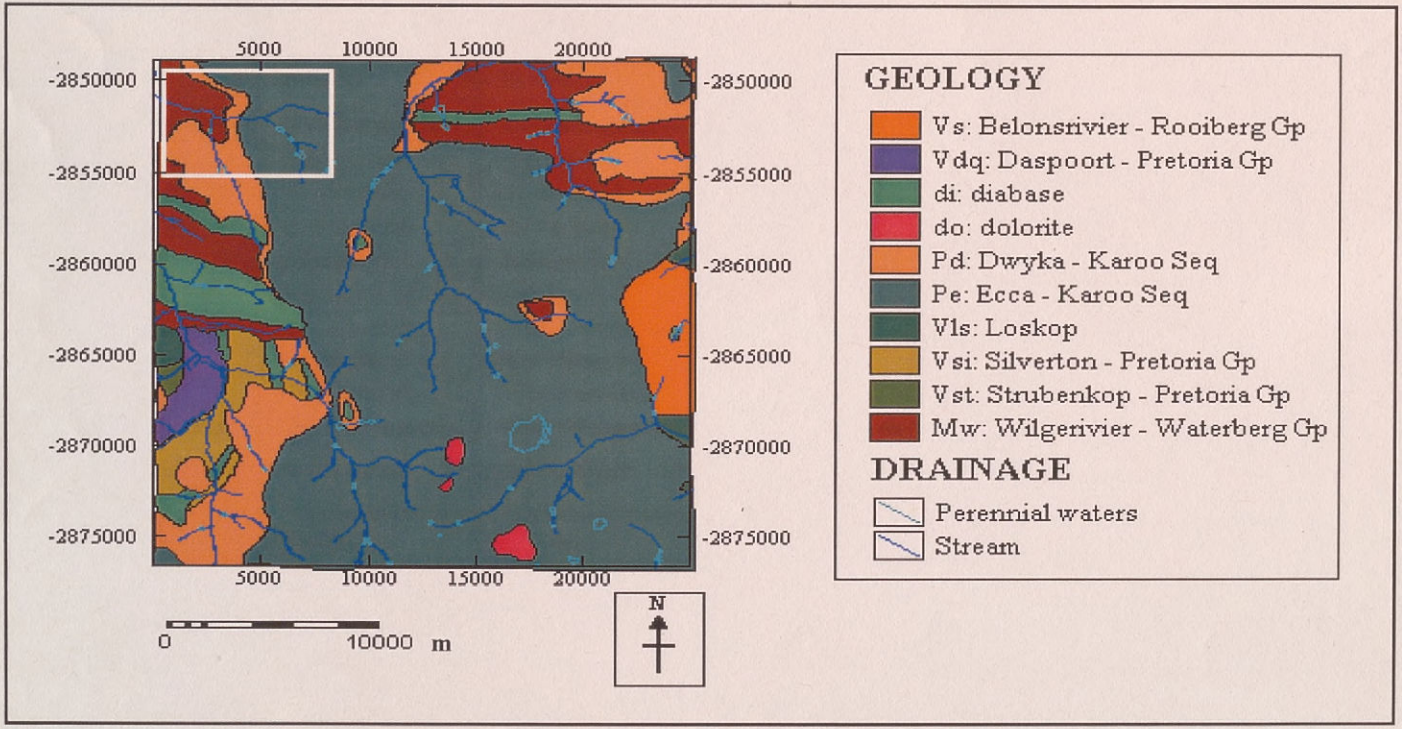


Figure 2. 2 : Regional Geology of the Witbank area. The white square shows the Kromdraaispruit study area (Geological Series, 2528 PRETORIA)

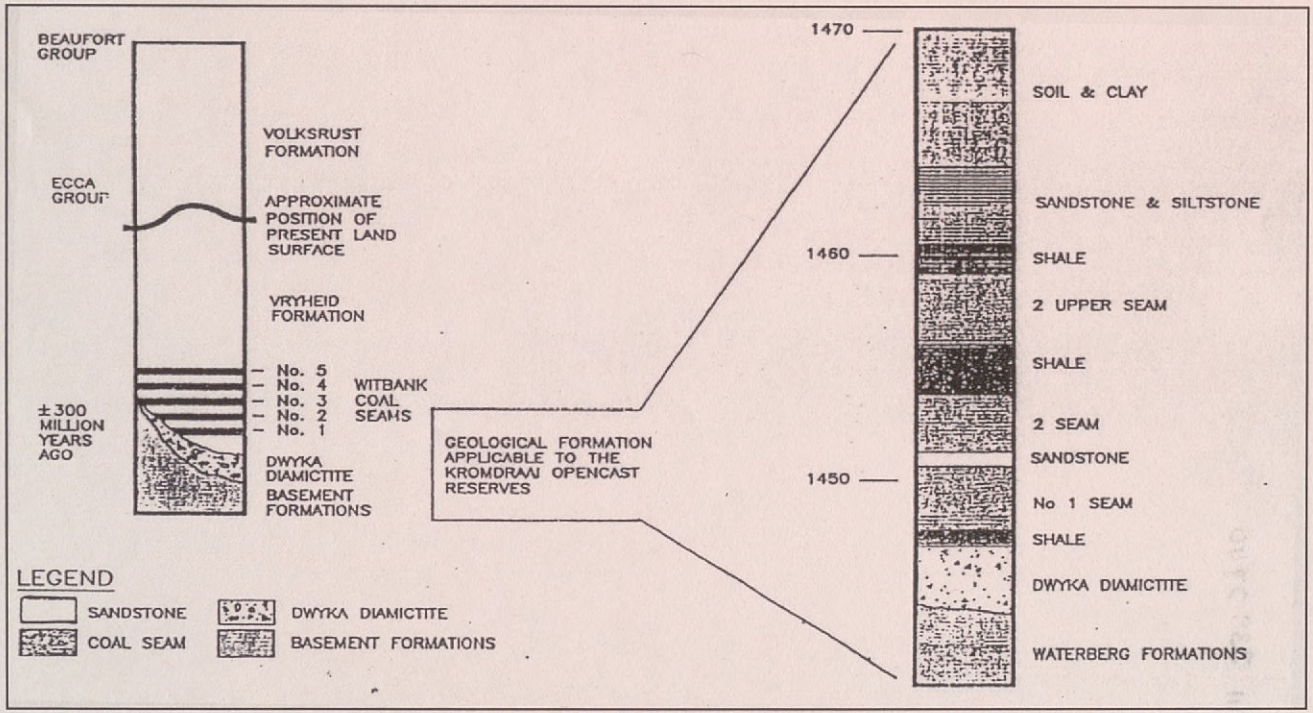


Figure 2.3 : General geological profile of the Witbank area (Amcoal Colliery & Industrial Operations Ltd., 1993)

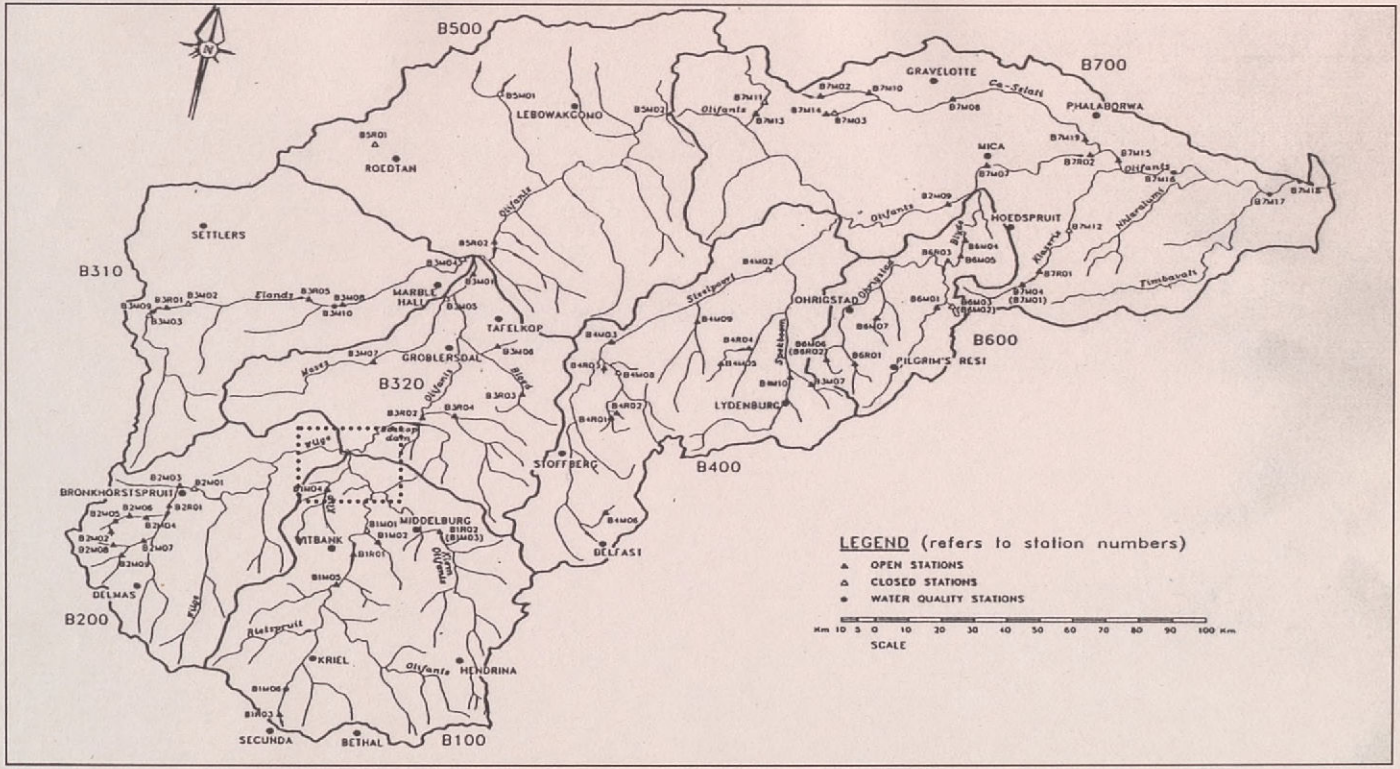


Figure 2.4: Regional perspective of the Olifants river catchment. Dashed square shows area of study (Wates *et al*, 1992)

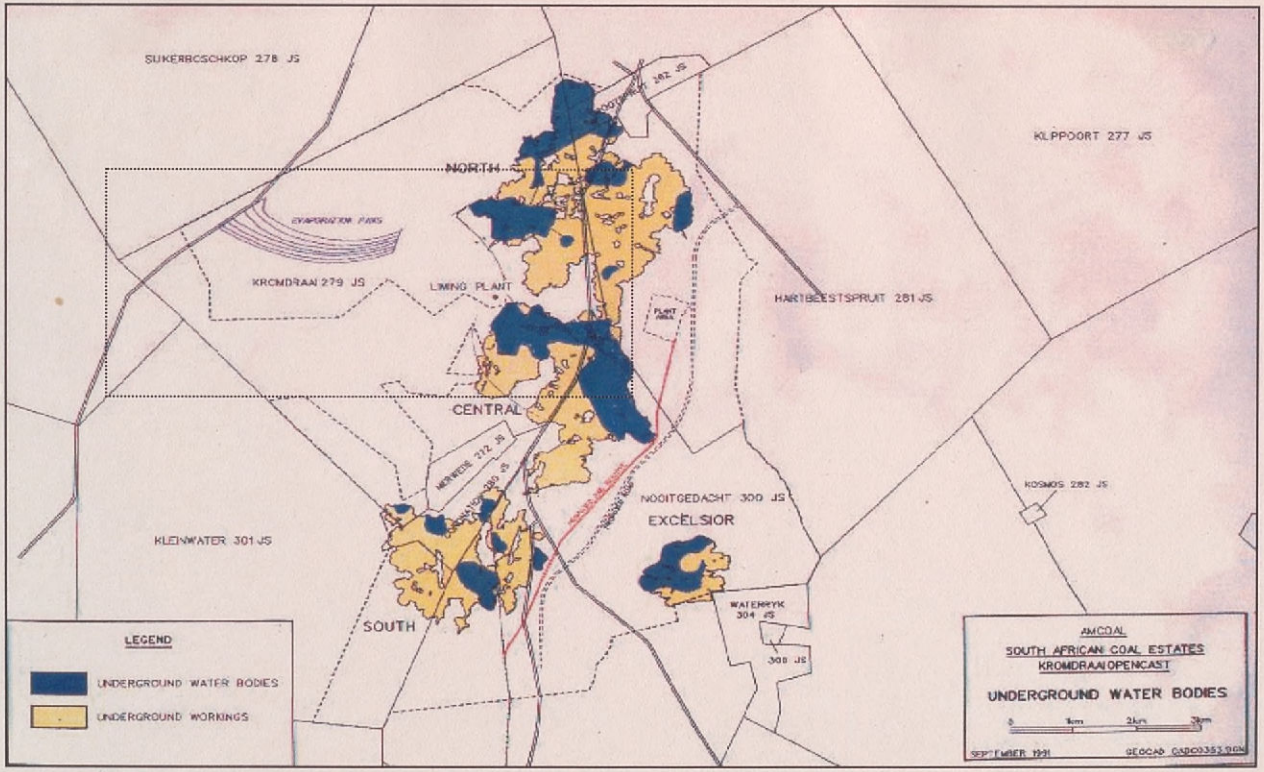


Figure 2.5 : Waterbodies in the Kromdraai region. Dashed box demarcates the study area (De Villiers, 1991)

2.5 ACID MINE DRAINAGE

Acid mine drainage (AMD) is the mining industry's greatest environmental problem and its greatest liability, especially to the waterways. AMD occurs when sulphide minerals in rocks (most commonly pyrite but also pyrrohotite, marcasite, galena, sphalerite, and chalcopyrite) in water permeable strata or waste heaps become exposed to air (Boult *et al.*, 1994). When pyrite-bearing rocks become exposed to air and water, e.g. during mining operations, oxidation of the pyrite leads to the generation of acid mine drainage (AMD) (Fourie *et al.*, 1996).

Commonly mined ore bodies that pose a risk of AMD are gold, silver, copper, iron, zinc, lead, (or multi-metal combinations) and coal (Miningwatch, 1999). The sulphuric acid generated has the potential to dissolve heavy metals such as lead, zinc, copper, arsenic, selenium, mercury and cadmium into ground and surface water (USGS; Mine Drainage, 1999). AMD and heavy metal pollution can poison ground and drinking water. It also destroys aquatic life and habitats.

AMD from coal mining activities occurs through a series of complex geochemical and microbial reactions. It most commonly occurs when rainwater seeps through coal discard dumps and in the presence of oxygen comes into contact with iron pyrites in the coal dumps. With the assistance of micro-organisms a weak solution of sulphuric acid is formed (Russell, 1990). This process also occurs underground, where groundwater that seeps into the underground workings and water pumped underground (for dust suppression purposes) comes into contact with exposed coal seams.

Coal mining affects water quality by increasing its acidity and burdening it with salts and suspended solid. The level of acidity and the concentration of heavy metal pollutants in the mine drainage can be directly correlated to the amount of pyrite in the area around the mine. Combined with the geochemical and microbial reactions below, physical weathering of the pyrite is also essential in reducing the grain size of the mineral which is catalyst in the AMD forming process. The chemical oxidation of pyrite after physical weathering is described in the reactions below: (AMD Chemistry, 1999).

$$4FeS_{2(s)} + 14O_{2(g)} + 4H_2O_{(l)} \rightarrow 4Fe^{2+}{}_{(aq)} + 8SO_4{}^{2-}{}_{(aq)} + 8H^+{}_{(aq)} \quad (1)$$

Iron II and acidic hydrogen ions are released into the waters that form runoff from the mine drainage tunnels or tailings piles. When the runoff reaches the surface where there is an abundant supply of oxygen, Iron II ions are oxidised to form iron III ions as shown in reaction equation 2 (AMD Chemistry, 1999).

$$4Fe^{2+}{}_{(aq)} + O_{2\,(g)} + 4H^+{}_{(aq)} \rightarrow 4Fe^{3+}{}_{(aq)} + 2H_2O_{(l)} \quad (2)$$

The iron III ions now hydrolyse in water to form iron III hydroxide (Equation 3). This process releases even more hydrogen ions into the aquatic environment and continues to reduce the pH. The iron III hydroxide formed in this reaction, called "yellow buoy", is a yellowish-orange precipitate that turns the acidic runoff in the streams an orange or red colour and covers the streambed with a slimy coating. This is the most visible impact of AMD and a warning sign to regulators and the community. With this precipitate covering the streambed, the aquatic life that dwells at the bottom is smothered.

$$4Fe^{3+}{}_{(aq)} + 12\,H_2O_{(l)} \rightarrow 4Fe\,(OH)_{3(s)} + 12H^+{}_{(aq)} \quad (3)$$

Equations 1 - 3 show that the pyrite is oxidised, releasing acidic hydrogen ions into the water and coating the streambed with "yellow buoy". The sum of equations 1 - 3 is shown in reaction equation 4 (AMD Chemistry, 1999).

$$4FeS_{2\,(s)} + 15O_{2\,(g)} + 14H_2O_{(l)} \rightarrow 4Fe(OH)_{3\,(s)} + 8SO_4{}^{2-}{}_{(aq)} + 16H^+{}_{(aq)} \quad (4)$$

Complex systems in nature, such as mine tailings impoundments and mine drainage tunnels cannot be described by a few equations. Other chemical reactions also occur, as shown in equation 5. Factors such as the presence of acidic tolerant bacteria (*Thiobacillus ferroxidans*) can also speed up the process of sulphide oxidation.

$$FeS_{2\,(aq)} + 14Fe^{3+}{}_{(aq)} + 8H_2O_{(l)} \rightarrow 15Fe^{2+}{}_{(aq)} + 2SO_4{}^{2-}{}_{(aq)} + 16H^+{}_{(aq)} \quad (5)$$

The impacts of AMD include the drainage of contaminated, low pH water into waterways, resulting in the death of aquatic ecosystems, soil contamination, the disruption of the food chain and contaminated groundwater. Another serious consequence of acid drainage is the accelerated breakdown of gangue minerals that release lithophile elements (Al, Mn, Fe, Ba) as contaminants into the environment. This process can also result in the formation of new secondary minerals, which may have different geothechnical properties, undermining the long-term stability of constructed wetlands.

The nature of mine drainage effluents generally reflects the soluble weathering products of the parent ore body and the waste material. Chemistry of AMD may be characterised by:

- Depressed pH values (often < 3) i.e. increased acidity.
- Elevated dissolved solids.
- Elevated concentrations of dissolved heavy metals.
- High Fe concentrations.
- SO_4^{2-} concentrations which are usually high to extremely high with values rarely falling below 1000 mg/l (Fourie *et al.*, 1996).

AMD can develop at several points throughout the mining process, in underground workings, open pit mine faces, waste rock dumps, tailing deposits and ore stockpiles. Acid generation can last for decades, centuries or longer, and its impacts can migrate many kilometres downstream (Miningwatch, 1999). Since most of the South African coal mines are being worked, long-term deterioration of spoil heaps and unrehabilitated pits will continually expose new rock surfaces to oxidation, indicating that substantial quantities of AMD may be expected after closure of an open cast mine (Limpitlaw, 1995).

Other sources of acid mine drainage which are often ignored include abandoned mines, adits, shafts and open-cuts. These sources are responsible for some of the environmental impacts associated with the coal mining industry.

2.6 TREATMENT OF AMD

The main concern in the treatment of AMD in South Africa is to reduce SO_4^{2-} and increase pH because of the scarce water resources which have to be utilised by a large population, whereas in North America the emphasis is on the reduction of metal concentrations to acceptable levels (3 mg/l Fe and 2mg/l Mn) (Fourie *et al.*, 1996). Problems created by AMD have long been recognised by both the industry and the community, and there has been development and evaluation of possible treatment methods.

Early attempts to restrict acid drainage usually involved covering the sulphuric mine waste with a benign material (rock or soil) derived from the excavation of the next mine pit-strip (environment; SSG, 1999) and planting vegetation (trees, shrubs, grasses) to provide an aesthetically pleasing environment. By today's standards the success of these techniques has been limited and more effective management methods are now being implemented.

Since mine drainage water contains a certain amount of sulphuric acid it cannot be re-used directly in the mine or discharged to the environment without prior treatment. Polluted mine drainage effluent can be diverted to a water treatment plant and treated chemically to neutralise the acid and remove the heavy metal ions.

Water pumped from underground coal mining or from the bottom of opencast pits is treated by adding lime to the water, i.e. it is neutralised before being discharged into the water environment. Neutralisation of mine water acidity is the only widely applied treatment for mine waters in South Africa, for both acidity correction and residual metals precipitation (Wood, 1994).

Neutralisation of the acid mine water is not a straightforward process. If these effluents are neutralised in the normal way, voluminous gelatinous and sometimes colloidal precipitates are formed. The result is the creation of large volumes of sludge, ranging from 10 % to 30 % of the original volume of effluent treated, with a solids content of

only 1 % to 2 %. Disposal of this voluminous sludge presents an environmental problem and makes the cost of the neutralisation plant prohibitively high (Skinner, 1992)

To overcome these problems a special neutralisation technique was developed in the USA. It is known as HDS (High-Density Sludge) process. It reduces the volume of the sludge to be disposed of by producing a much denser sludge. This sludge settles at the bottom of the plant and it is disposed of safely in tailings dams.

2.6.1 HDS Plant At Kromdraai

The original Kromdraai Coronation Colliery, a mine with an underground area of approximately 1 800 ha, ceased operation in 1962. Since then, the workings have filled with water, reaching decant levels in 1971 (Dingemans, pers com in Limpitlaw, 1995). The coal measures are preserved in a hill feature and the water-filled workings act as perched aquifer, gradually releasing excess water into surface streams.

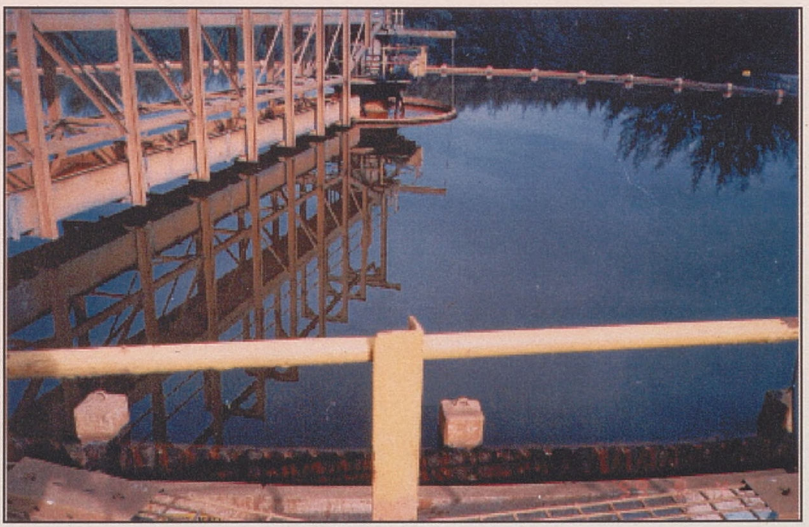


Figure 2.6 Kromdraai Liming Plant (04/08/1999)

Initial pollution control measures consisted of the construction of evaporation dams above the Kromdraaispruit. Acid water was channelled directly into these dams to be evaporated, but the approach was subsequently found unsatisfactory. In 1973 the system was refined with the addition of a liming plant (Fig.2.6) that neutralised the AMD before release to the evaporation dams.

Limestone is a sedimentary rock composed principally of calcite (calcium carbonate - $CaCO_3$). The limestone neutralisation process improves the water quality by the complete removal of free acid and acid associated with Fe (III). Sulphate is removed up to a point where the water is saturated with calcium sulphate ($CaSO_4$). The pH of the water can be increased from less than 3 to more than 7, while initial acidity and iron can be removed by 97 % and 95 % respectively (Water Research Commission, 1997).

The evaporation dams have been sealed off since 1997 because it was noted that there was a large seepage area between the dams and the stream, i.e. the dams were leaking. To date the neutralised water is being discharged from the liming plant directly into the stream. The HDS plant utilises limestone as it raises the pH of the drainage and it is inexpensive.

2.7 WETLAND TREATMENT PROCESSES

Natural systems can also be used to reverse the process that creates polluted mine drainage. Wetlands such as bogs, marshes and swamps are increasingly being recognised for their ability to treat AMD and other wastewaters. In the mining context, interest in wetlands began when the quality of drainage waters was found to improve after passing through natural bogs and marshes (Steffen *et al.*, 1990).

There are numerous definitions of the term wetland, but the one adopted by the United States Fish and Wildlife Service provides an adequate base on which to develop an understanding on wetlands:

"...lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. Wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes, (2) the substrate is predominantly undrained hydric soil, and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season each year" (p. 25, Cowardin *et al.*, 1987 in Mitsch & Gosselink, 1993).

This definition was used in the discussion of wetlands in this study.

2.7.1 Natural Wetlands

In general, natural wetlands occur in watercourses. They also develop where these watercourses have been impounded, where roads and railway lines impact on natural drainage lines and in seeps from the foot of waste rock dumps, tailings dams and discard dumps. These wetlands may receive water contaminated with sulphates, iron, manganese, aluminium and other contaminants associated with the mining activities. The role of wetlands in the processing of nutrients and chemicals for improving water quality is not a simple one, nor is it easy to generalise for all wetlands. Nevertheless, there are few principles that can be stated:

- Wetlands serve as sinks or transformers of chemicals depending on the wetland type and hydrologic conditions.
- Seasonal patterns of nutrient uptake and release are characteristics of many wetlands. During the height of the growing season, uptake of chemicals by plants and immobilisation of elements by microfauna and microflora lead to the retention of nutrients (Batchelor & Murray, 1994). The primary benefits of plants are that they provide surfaces for bacterial growth, act as sediment traps, translocate small quantities of oxygen to the root zone and restrict consolidation-induced reduction in the permeability of the wetland sediments (Fourie *et al.*, 1996). As the higher plants die, they have already translocated a significant portion of their nutrients to the roots and rhizomes, but a significant portion is left to decompose and leach the chemicals back into the water. This often leads to a

nett release of chemicals in the autumn and early spring (Batchelor & Murray, 1994).

- The biological and chemical processes in a wetland vary according to the contaminant being considered.
- The most fundamental characteristic of wetlands is that, saving physical filtration, their functions are almost solely regulated by microbiota and their metabolism, (Batchelor & Murray, 1994).
- The main concern in most wetlands is the reduction of metal concentrations in the influent water. This is achieved through the reaction of an aerobic environment in which metals (Fe^{3+}) precipitate as oxides or hydroxides, a process of positive Eh (Fourie *et al.*, 1996).

In general, observations on two natural wetlands impacted by mine drainages suggest that, under reduced flow conditions, they are capable of at least reducing the concentrations of a range of contaminants associated with the mine drainages (Batchelor, 1992)

2.7.2 Kromdraaispruit Wetland

The Kromdraaispruit wetland (Fig 2.7) is located about 2 km downstream of the HDS plant. It is a high plateau dominated by sedges. It has the following dimensions;

- Maximum width (north - south) 180m
- Average breadth ±100m
- Area 37 ha
- Elevation at bottom of wetland 1 380m above msl
- Elevation at top of wetland 1 400m above msl
- Direction of flow east to west (Limpitlaw, 1995).

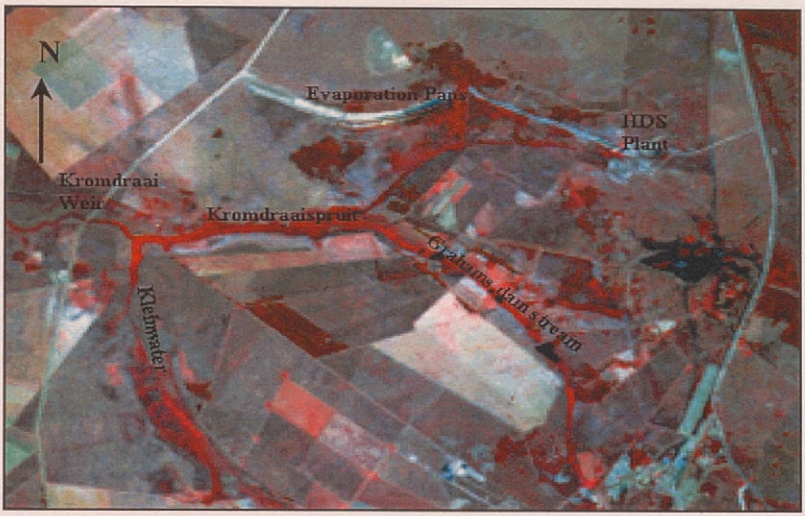


Figure 2.7 Landsat Image of the Kromdraaispruit wetland. (Colour Infrared Composite - TM432, 06/05/1990)

Figure 2.7 is a false colour composite generated in the Integrated Land and Water Information Systems (ILWIS) Geographic Information Systems (GIS) program by a combination of the Thematic Mapper (TM) bands 4,3,2. The streams flowing through the wetland are brighter red than the surrounding area. The roads are white, evaporation pans are light blue and the cultivated fields are grey in colour.

2.7.3 Degradation of Wetlands

Many effluent producers, like industrialists, consider wetlands useful as they believe that further purification will occur in the wetlands, thereby reducing the need for the full treatment of the effluent by the producer (Conley, 1987).

On the other hand, the Department of Water Affairs and Forestry (DWAF) perceives any further purification that may occur in a wetland as a bonus. The DWAF considers that wetlands should be allowed to cope with non-point source pollution and should not be used to treat point source pollution. Briefly, the policy of the DWAF is that natural wetlands and reed beds are not considered to be part of the effluent treatment plant and may not be used for tertiary treatment to achieve the required quality. The effluents must be treated to the quality requirements of the applicable standard before being discharged to the wetland. The creation of artificial wetlands such as reed beds or maturation ponds for tertiary treatment is not discouraged, but they must not be constructed in the riverbed and must form part of the effluent treatment works. In such cases the quality of the effluent discharged by that plant is monitored for pollution control at the point where it leaves the tertiary treatment facility on its way to the river (Conley, 1987).

2.8 CONSTRUCTED WETLANDS

The ability of wetland systems to treat wastewater is dependent on water flow distribution above and below ground and residence time. These factors are more easily controlled in constructed than in natural wetlands. Over time, constructed wetlands also adopt the same habitat functions as natural wetlands. In general, wetland systems are probably best suited to weakly acidic, low hydraulic flow situations or for the final stage of a staged treatment process and/or as a polishing step for treatment of AMD (Steffen *et al.*, 1990).

Physical properties are not constant throughout the wetland. The degree of wetness as well as the soil properties like density, porosity, chemical composition, depth and the amount of organic matter vary depending on the location. The change in soil properties may be a function of both the length and the width of the wetland at various points. Chemical characteristics, and in particular the pH and redox potentials, may change in response to water level changes (Batchelor & Murray, 1996).

Assessment of whether to use a wetland system at a mine will usually be based on surface area requirements for a given AMD flow regime, balanced against the availability of suitable land in the vicinity of the mine site. Information requirements to determine the necessary wetland surface area include estimated mean and maximum AMD flow and estimated mean and maximum concentrations of metals and pH in the drainage water to be treated.

Ideally, AMD flow can be minimised through appropriate water management methods. Since AMD flows tend to vary with season, wetland area requirements should be based on peak expected flows. Other design considerations for constructed wetlands include soil quality and depth, water depth, plant species and flow distribution (Steffen *et al.*, 1989).

2.8.1 Soil quality

The plant-substrate-microbial complex required for AMD treatment can develop in almost any soil types, from clay to pea gravel to natural wetland soil (Brodie *et al.*, 1988b). The main concern is that initial soil fertility must be sufficient to support plant growth.

2.8.2 Water Depth

Average water depth should generally be less than 0.3m. Depth tolerances of the available emergent aquatic vegetation can be observed at the vegetation donor sites or determined through simple pot tests.

2.8.3 Vegetation

The most practical approach to species selection for AMD wetlands is to start out with a wide variety of species obtained from natural wetlands close to the mine site, including aquatic mosses and emergent reed-like species. The biological approach to construction of a wetland is to introduce tolerant wetland plants such as typha, along with algae and bacteria, which are inexpensive and effective in treating AMD. Where natural wetlands

are not available nearby, transplants would have to be imported from a more distant location. The "rule of thumb" is to transplant while the plants are dormant (late November to late March). The nutrient reserves in the plant roots are greatest during this period (Steffen *et al.*, 1990).

2.8.4 Flow Distribution

Short-circuiting of water flow through a natural or constructed wetland reduces the exposure of drainage water to the treatment environment. Therefore flow distribution is recommended. Short-circuiting can be prevented in constructed wetlands by providing a length to width ratio of at least 10:1. In natural wetlands, existing channels can be rerouted by using earthen or log baffles to create a low velocity sheet flow. Dense vegetation and variable bottom topography, particularly if high points are oriented perpendicular to the direction of flow, also assist in distributing water flow and preventing short-circuiting (Steffen *et al.*, 1990).

Much work has been done on designing wetlands to ameliorate the impact of mine drainage on the environment in North America. More than 100 of these constructed wetland ecosystems were built over two years, from 1996 to 1998, at mine sites where small flows of AMD are a problem. However, it has been noted that the success rate has not been particularly encouraging. One of the likely reasons for this is a lack of detailed understanding of the processes and interactions in a wetland. Similarly, if the intention is to use an existing wetland as a treatment system, the ability of the wetland to achieve the desired water quality will have to be established at the outset (ctcnet.net, 16/11/1998).

Some natural wetlands can remove iron, manganese and other metals from acid drainage and have been doing so for geological ages. Sulphate concentrations entering a wetland system may be reduced through a number of pathways (Batchelor & Murray, p.13, 1994). Sulphur transformations are biologically mediated and are affected by redox and pH interactions (Batchelor & Murray, 1994). Typically, 95% of iron is removed and 20 - 50% of manganese and sulphate (US Bureau of Mines, 1987).

2.9 ADVANTAGES AND DISADVANTAGES OF WETLAND SYSTEMS

2.9.1 Advantages Of Wetland Treatment Systems

These advantages are relative to other treatment technologies (Fourie *et al.*, 1996).

- Adaptability of wetland systems to acid drainage (pH as low as 2.7) and elevated metal content is high.
- Ability of wetland systems to improve the quality of acid mine drainage is well documented.
- Capital costs of natural wetland systems are relatively low.
- Operational and maintenance costs of constructed wetland systems are relatively low. It also has a low energy requirement.
- Wetland systems are generally self-maintaining and require little or no operator supervision.
- Wetland treatment systems also provide additional environmental benefits such as wildlife habitat and flood control.
- Wetlands are water storage systems.

2.9.2 Disadvantages Of Wetland Systems

Relative to other treatment systems (Fourie *et al.*, 1996).

- In mountainous terrain where sufficient flat or gently sloping land is unavailable, the capital costs of constructed wetland systems are elevated due to earth-moving requirements.
- Land area requirement per unit flow of water to be treated can be large, typically around 50 m^2/m^3d^{-1}.
- Treatment during winter is reduced.
- Impacts on wildlife are still unknown.
- To date operating experience is lacking in most areas and treatment performance data are limited to experimental systems using modified natural wetlands.

2.10 SUMMARY

- The coal mining industry affects the water resources by increasing the acidity and burdening it with salts and suspended solids that are detrimental to all the users.
- AMD is a major problem in the coal mining industry in SA and it develops at all stages of the mining operation. Its impacts are felt many kilometres downstream affecting most of the receiving water bodies. The Kromdraai mine has many flooded, defunct underground galleries that need to be dewatered for opencast mining operations to commence. This means that the acidic water has to be treated. Primary treatment is undertaken at the liming plant, with the secondary purification done by the wetland downstream.
- Treatment effectiveness of wetland systems is seasonal with maximum treatment taking place during the summer and minimum treatment during the winter.

CHAPTER 3
WATER CHEMISTRY

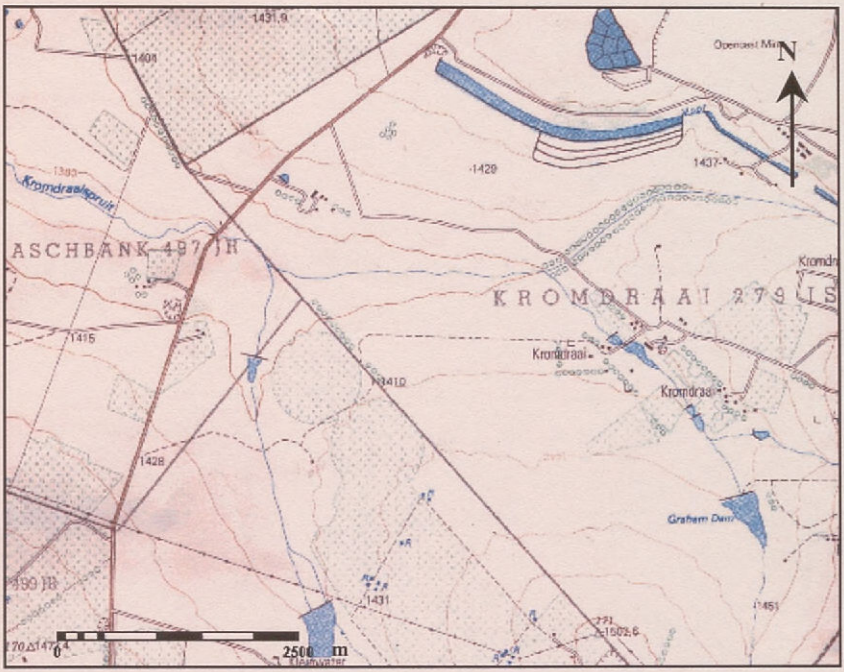


Figure 3.1 Extract from a 1 : 50 000 -topocadastral sheet 2529CC WITBANK showing the position of the Kromdraaispruit.

3.1 INTRODUCTION

Fieldwork was initiated in August 1998 and this report includes data (Appendices A, B, C, D, E, and F) collected up to August 1999. Details on physical parameters were extracted from 1: 50 000 maps (Fig .3.1) and aerial photographs.

Data gathered before visiting the wetland included information on the catchment (Olifants) as a whole (e.g. rivers, land-use patterns and area.), geospatial data and any available information specific to the wetland that is part of the Kromdraaispruit

system. (e.g. climate, altitude, general hydrology, regional soil type, geology, adjacent land-use, threats, general biological data, etc.) Information gathered during field trips included details of water chemistry and soil chemistry.

3.2 WATER SAMPLING SITES

Sampling sites for this research were chosen at random with priority being given to those areas that intercepted seepages and/or inflowing waters into the stream (dams and springs). These sampling points were affixed with a prefix - **KDSP** (**K**rom**D**raaispruit **S**ampling **P**oint) for laboratory identification (appendices A, B and C) but in the text they will be identified with the prefix - **P**.

The area studied is approximately 5 km in length. The Kromdraaispruit flows from the east in a westerly direction (Fig 3.2). The system includes 4 springs (P 10, P 19, P 24, P 29) a wetland (P 15, P 16, P 20, P21, P 23, P 26, P 30, P 34, P36, P37), inlet (Kleinwaterspruit, P 25 and water from Grahams Dam, P 17), evaporation dams and seepages (P 01, P 02, P 03, P 05) (Fig. 3.2).

3.3 WATER SAMPLING

The study was divided into two categories, the geochemical and geo-spatial studies. The geochemical study that consisted of both water and soil sampling helped characterise the chemical environment of the Kromdraaispruit, the seepages and soils around the stream.

Water sampling was done over a period of twelve months from September 1998 to enable the study of the effects of seasonal changes on different parameters. From September 1998, approximately 25 samples were taken from different points on a monthly basis. This was preceded by an intensive pre-investigation where samples were collected from as many different points as possible (37 points) to enable the selection of the most crucial points (Fig 3.2) in subsequent field data collection. In the

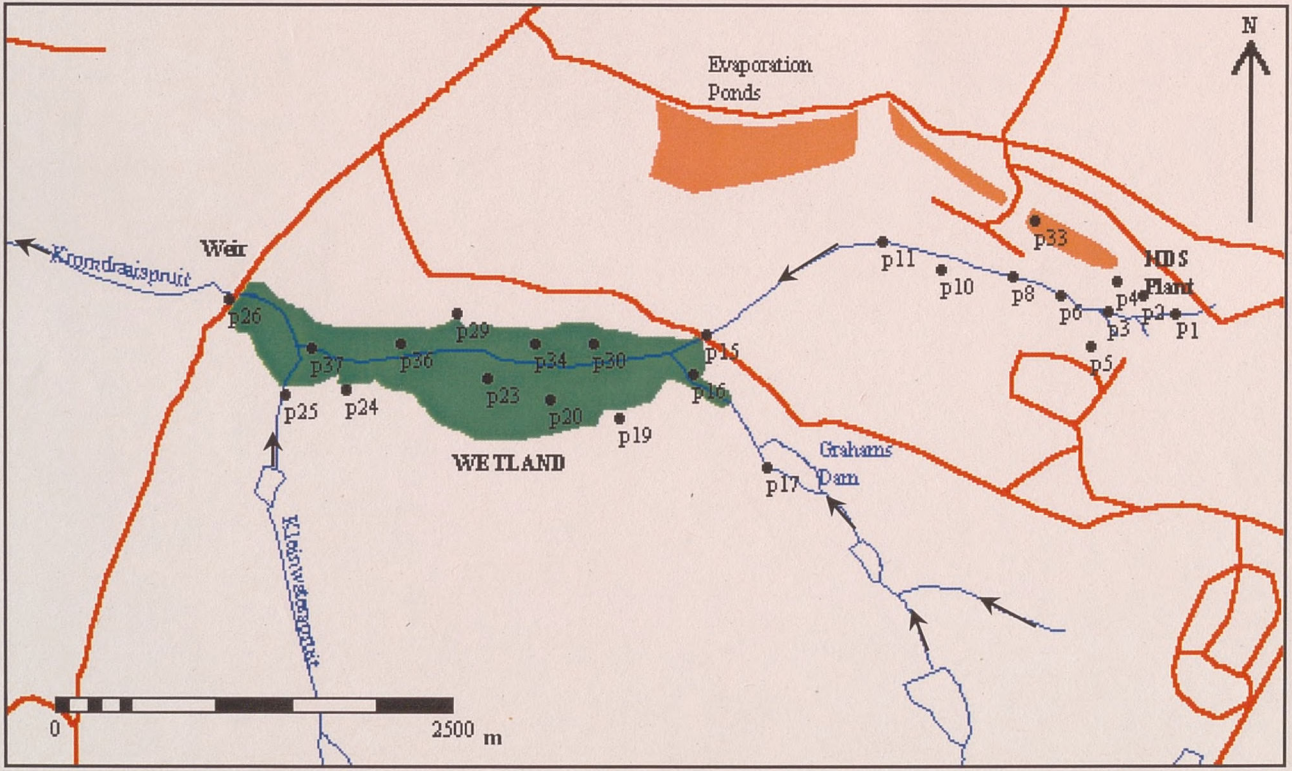


Figure 3.2 Water sampling points around the Kromdraaispruit

first water sample collection, each sampling point was marked with one of labels from P 01 to P 37. The sites that were chosen for further monitoring, maintained their original labels to avoid confusion in the laboratory analyses. Water analysis on each batch of samples was carried out in two stages:

- Field analysis: Grab-samples were collected in 1-litre bottles: Water samples were taken facing upstream and from just below the surface to avoid contamination with floating detritus. The values of pH, Eh and EC were determined on site, using a portable pH meter, a portable Eh meter and a portable conductivity meter respectively. This is because examination of water in the field is an important part of hydrologic studies because certain properties of water, especially its pH and EC, are closely related to the environment of the water. They are likely to be altered by sampling and storage, and a meaningful value can only be obtained in the field (Hem, 1985).

- Laboratory analysis: on the 1-litre grab samples was carried out at ACCL laboratories in Witbank. Samples were analysed for pH, EC, TDS, suspended solids, total alkalinity (TAlk), acidity, chloride, sulphate, calcium, magnesium, sodium, potassium, iron, manganese and aluminium. These specific variables were analysed for because they usually determine the degree of formation/presence of AMD.

3.4 GEOCHEMICAL CHARACTERISTICS OF WATER

To characterise water thoroughly requires considerable analytical equipment and the use of complicated procedures, but most water problems can be diagnosed and controlled through the use of a few important analyses and information on the operating conditions under which the water is to be used. A summarised table of the proposed DWAF water quality guidelines (Table 3.1) shows the acceptable and tolerable water levels used by the industry to control the disposal of effluents that in most cases end up in the watercourses used by the downstream communities.

Table 3.1 Water Quality Guidelines.

Water quality Variables	Units	Acceptable level guidelines	Tolerable level guidelines
Aluminium	mg/l	0.1 [2]	0.5 [2]
Calcium	mg/l	250 [2]	
Chloride	mg/l	100 [2]	320 [2]
Conductivity	mS/m	100 [2]	120 [2]
Fluoride	mg/l	1.0 [2]	2.0 [2]
Iron	mg/l	0.3 [2]	1.0 [2]
Magnesium	mg/l	70 [2]	
Manganese	mg/l	0.2 [2]	1.0 [2]
pH	-	6.5 - 8.5 [2]	6.0 - 9.0 [2]
Potassium	mg/l	70 [1]	
Sodium	mg/l	150 [1]	250 [1]
Suspended Solids (SS)	mg/l	10 [2]	250 [2]
Sulphate	mg/l	250 [2]	500 [2]
Total Dissolved Solids (TDS)	mg/l	680 [2]	820 [2]

(1) - Regional standards for industrial effluents, Water Act (Act 54 of 1956) of the Republic of South Africa, in Limpitlaw, 1995; (2) - Department of Water Affairs and Forestry (DWAF).

3.5 STATISTICAL ANALYSIS OF THE GEOCHEMICAL DATA

Statistical analysis of the data was carried out using the EcoSSe (Eco Spatial Statistical evaluation) program for Windows 95/98 and NT, a software for statistical and geostatistical analysis of spatial data created by Dr. Isobel Clark and Dr. Bill Harper, based on Dr. Isobel Clarks seminal work "Practical Geostatics" in 1979.

Before looking at correlation coefficients, the data was analysed to determine whether it fell under normal or lognormal distribution categories. In some cases, if the data was not normally distributed, then lognormal distributions were considered. If the

logarithm of a variable has a normal distribution, then that variable is said to have a lognormal distribution. It is necessary to take logarithms of the sample values and see whether these more closely resemble a normal distribution. To determine whether the data is lognormal or normal, a few calculations can be made (Equation 3.3).

$$\nu = n - 2 \quad \text{..... Equation 3.3}$$

where n = number of data samples (in this case 24 sampling points.)

ν = degrees of freedom

From the New Cambridge Elementary Statistical Tables, table no. 13 was used with a 5^0 significance; if:

$\nu >$ Correlation X/Y then, it is a normal distribution. This was the case for the Na and pH variables.

$\nu <$ Correlation X/Y then, it is a lognormal distribution as was the case with the variables TDS, EC, K, Ca, Mg, Cl, SO_4^{2-}, Fe, Al, Mn, SS, Acidity (TA) Total Alkalinity (T-Alk).

There are two types of correlations; if:

X/Y is a positive value (positive correlation), then when one component increases, the other increases too;

X/Y is a negative value (negative correlation), then as one component increases, the other decreases.

3.5.1 Correlations

Correlation coefficients were calculated for all the data and it was noted that all salts had some sort of correlation with each other except with respect to total alkalinity (T-Alk) and suspended solids (SS). On comparison of reported analyses, determinants fell into four categories (Table 3.2);

Table 3.2 Correlations of the analysed determinants.

	pH	TDS	EC	Na	K	Ca	Mg	Cl	SO_4^{2-}	Fe	Al	Mn	SS	Acidity	TAlk
pH	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
TDS	-3	x	x	x	x	x	x	x	x	x	x	x	x	x	x
EC	-3	+4	x	x	x	x	x	x	x	x	x	x	x	x	x
Na	-3	+4	+4	x	x	x	x	x	x	x	x	x	x	x	x
K	-2	+4	+4	+4	x	x	x	x	x	x	x	x	x	x	x
Ca	-2	+4	+4	+4	+4	x	x	x	x	x	x	x	x	x	x
Mg	-3	+4	+4	+4	+4	+4	x	x	x	x	x	x	x	x	x
Cl	-3	+2	+3	+3	+2	+1	+2	x	x	x	x	x	x	x	x
SO_4^{2-}	-3	+4	+4	+4	+3	+3	+4	+2	x	x	x	x	x	x	x
Fe	+2	+2	+3	+2	+3	+1	+2	+3	+2	x	x	x	x	x	x
Al	-4	+4	+4	+4	+4	+3	+4	+4	+4	+3	x	x	x	x	x
Mn	-4	-4	+4	+4	+3	+3	+4	+3	+4	+2	+4	x	x	x	x
SS	+1	-2	-1	-1	-1	-2	-1	-1	-1	-1	-1	-1	x	x	x
Acidity	-3	+4	+4	+4	+4	+2	+4	+4	+4	+3	+4	+4	-1	x	x
TAlk	+4	-2	-2	-2	-2	-2	-2	-1	-2	-1	-3	-3	+1	-2	x

Key : (+) - positive correlation, (-) negative correlation
1 – no correlation, 2- low correlation, 3 - correlation , 4 - strong correlation.

1. no correlation (X/Y <0.2)
2. low correlation (0.2 < X/Y < 0.5)
3. correlation (0.5 < X/Y < 0.6)
4. Strong correlation (0.7 < X/Y) (Clark, 1999)

Table 3.2 shows correlations where the negative (-) or positive (+) signs depict negative and positive correlations respectively and numbers 1, 2, 3, 4 represent no correlation, low correlation, correlation and strong correlation respectively.

Sulphate has positive correlation with all the variables except with SS, TAlk and pH. Sulphate is negatively correlated with TAlk and pH because an increase in SO_4^{2-} content increases acidity which signifies a decrease in alikalinity resulting in low pH values. The correlation between SO_4^{2-} and Ca (Fig 3.3) shows that there are two types of samples;

a) groundwater (fresh spring water) which has small amounts of SO_4^{2-} and Ca,
b) water that has high amounts of SO_4^{2-} and Ca^{2+}. The high content of Ca^{2+} is an indication of the presence of lime ($CaCO_3$).

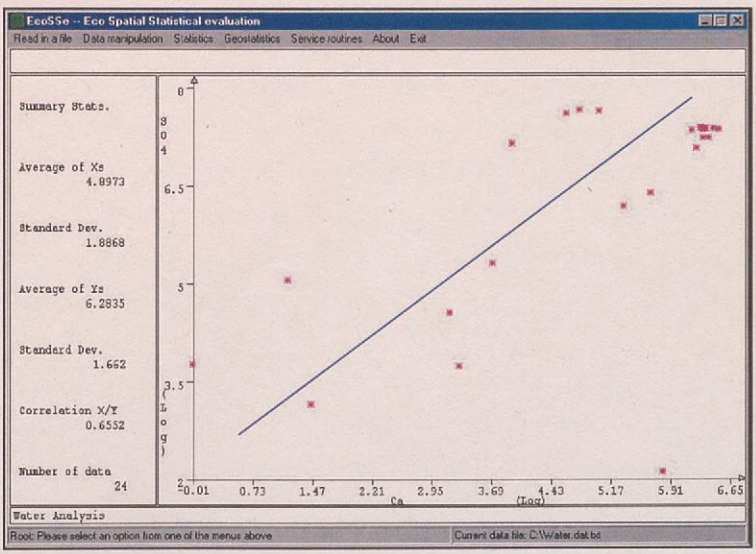


Figure 3.3 Positive correlation between SO_4^{2-} and Ca^{2+}.

The strong positive correlation (0.8003) between SO_4^{2-} and TDS (Fig. 3.4) shows that for the water samples collected in the study area, the greater the sulphate concentration (dissolved pyrite) in the water, the more the dissolved substances. This is similar for EC where the more sulphate in solution, the greater the conductivity, i.e. an increase in the number of free ions in solution promoting electro-conductivity. This explains the positive correlations of the other variables like K, Ca, Mg, Cl, Fe, Al and Mn (Table 3.2). The positive correlation between acidity and sulphate is due to the combination of pyrite and water in an oxidising environment to form sulphuric acid (an increase in acidity), hence the positive correlation with total acidity. Figure 3.4 shows two populations "a" and "b" in the system. Population "a" has low concentrations of SO_4^{2-} and TDS - groundwater. Population "b" has high concentrations SO_4^{2-} and TDS, which is the drainage from the mines. This is borne out by the respective sample localities.

pH has a positive correlation with total alkalinity (T-Alk) (Fig 3.5), a negative correlation with SO_4^{2-}, TDS, Na, TA, Cl, EC, K, Mg, Mn, Ca, Al and no correlation at all with SS (Fig.3.6). The positive correlation with TA is due to an increase in the amount of $CaCO_3$ (limestone). As more lime is added to the acidified water at the liming plant, the pH increases, hence an increase in alkalinity. pH has mostly negative correlations with most of the ions, the greatest negative correlations being with the toxic metals Al (Fig. 3.7) and Mn. The reason why Al^{3+} decreases when pH is increasing is that as pH increases, there is an excess of hydroxyl ions (OH^-). The OH^- ions bond with the Al^{3+} and Mn^{2+} to form Al $(OH)_3$ and Mn $(OH)_2$ respectively, i.e. Al^{3+} and Mn^{2+} ions are being removed from solution. The same applies to Ca^{2+} ions. The negative correlation with Ca (as pH increases, Ca decreases) is because the formation of Ca $(OH)_2$ is being promoted.

EC has a very strong positive correlation (X/Y > 0.7) with all the other salts except with suspended solids (SS) and TA, with which it has no correlation at all. For Fe and Cl, the correlations are low whereas for other variables like Na, K, Ca, Mg, SO_4^{2-}, Al and Mn, the correlations are very strong (Fig 3.8). i.e. as the concentration of these variables increases in the medium, it indicates that they are present as cations and anions, a suitable medium for electrical conductivity. From this statistical package, the results were what would have been expected.

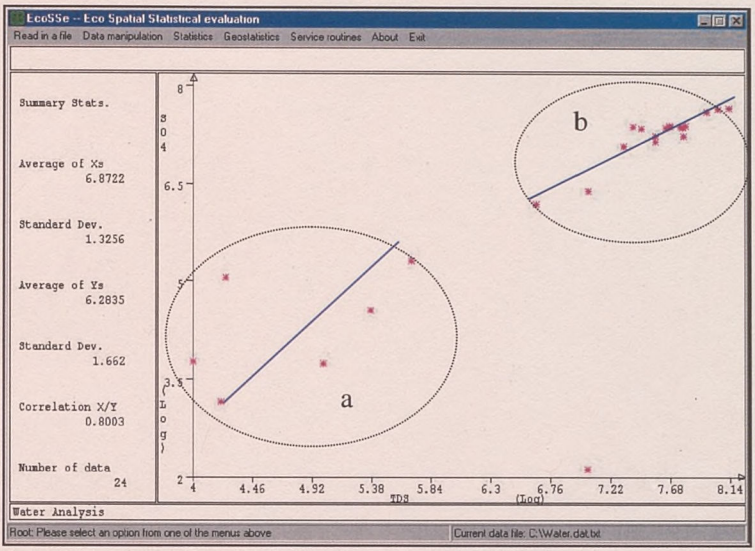


Figure 3.4 Positive correlation between SO_4^{2-} and TDS.

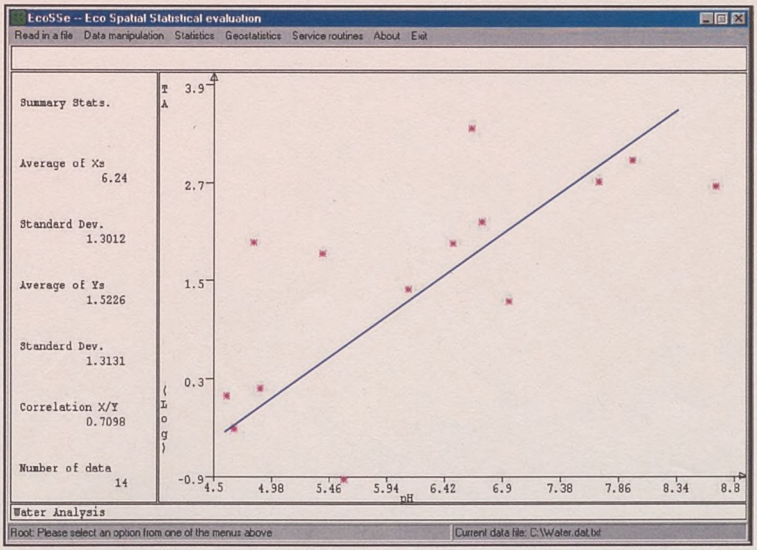


Figure 3.5 Positive correlation between Total Alkalinity (TA) and pH.

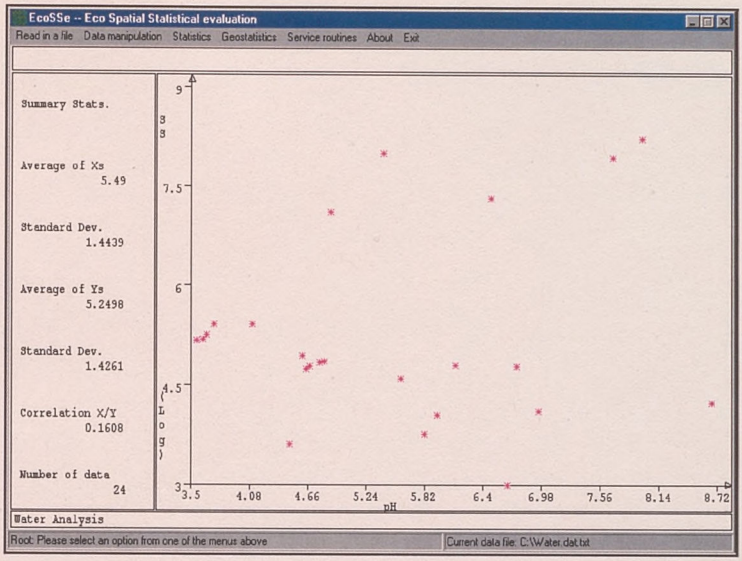


Figure 3 .6 No correlation between pH and SS

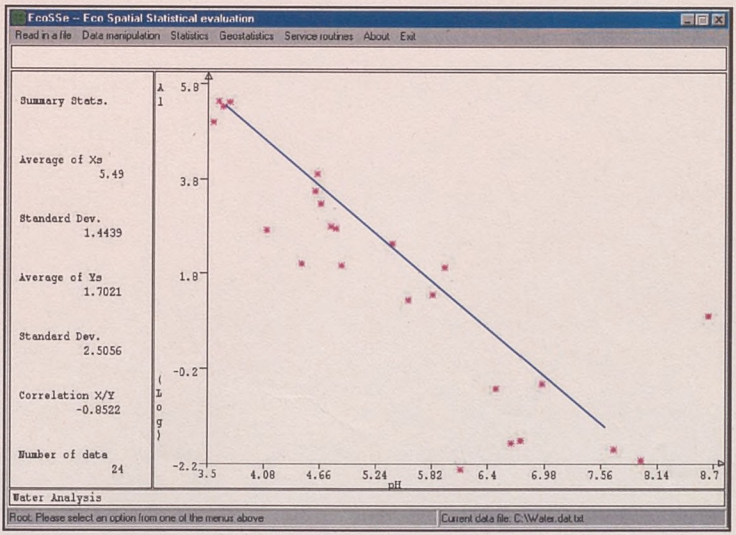


Figure 3.7 Negative correlation between Al^{3+} and pH.

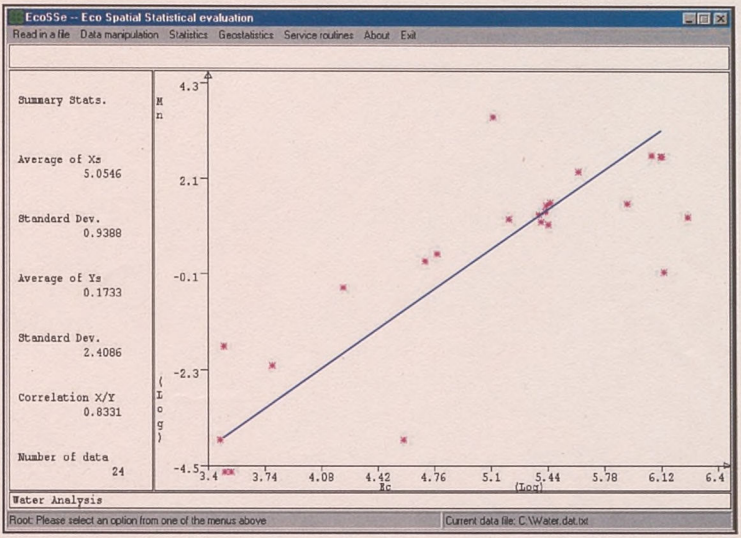


Figure 3.8 Positive correlation between Mn and EC.

3.6 GEOCHEMICAL ANALYSIS OF THE SYSTEM

3.6.1 Water Quality in the Liming Plant Stream

The liming plant, evaporation dams, seeps and a fresh water spring occur in the upper section of the Kromdraaispruit (Fig 3.9). The section is about 2 km in length and stretches from the liming plant to P15 i.e. the beginning of the wetland. A minor road demarcates the upper section from the wetland. The liming plant is used to increase the pH of the acid mine drainage that is being pumped form the flooded underground workings so that opencast mining can commence. The AMD seeps from the underground workings in the area are mostly concentrated at the liming plant area. These seeps used to flow into the stream prior to November 1999 when an automatic pump was installed to redirect them to the liming plant.

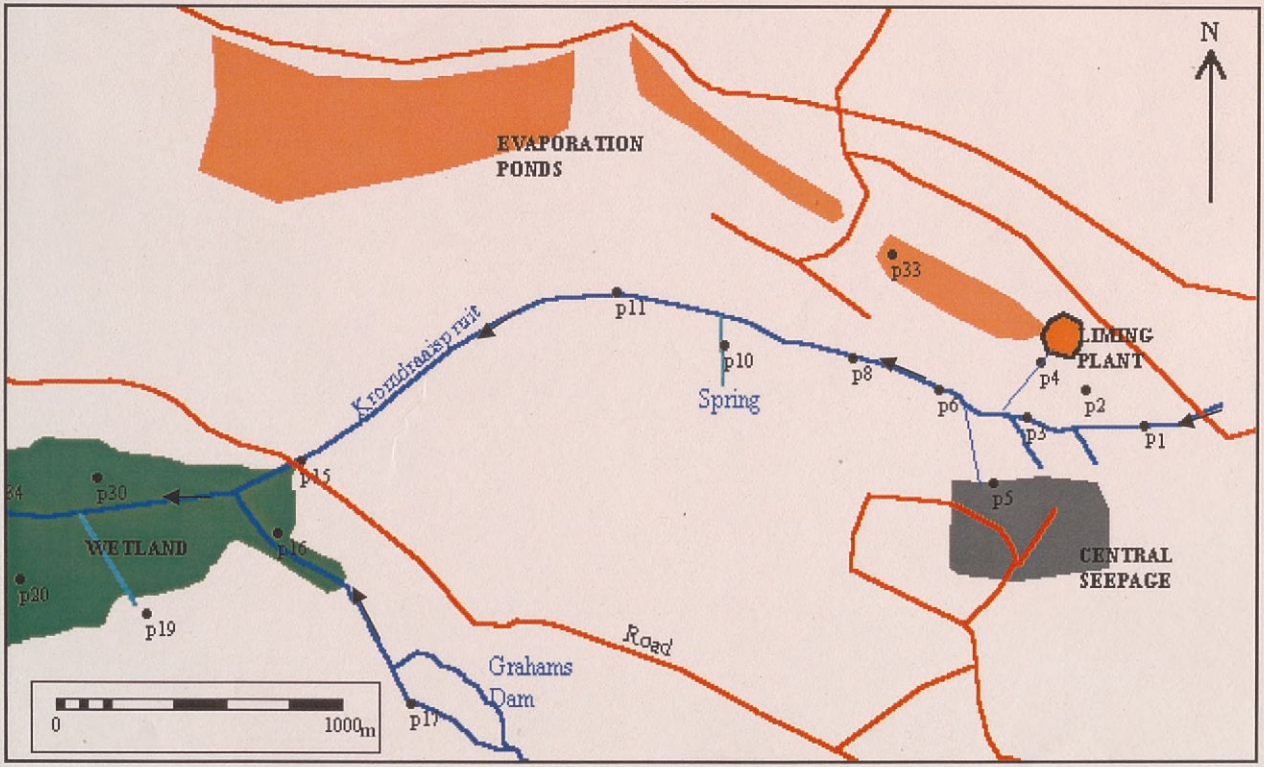


Figure 3.9 Sampling points in the liming plant (upper) section of the Kromdraaispruit

3.6.2 AMD in the Liming Plant

Results from the ACCL Laboratories showed that there was a dramatic decrease in the concentrations of most salts between entering and leaving the liming plant (Fig 3.10). In most cases the reduction was down to almost a third of the original concentration. The concentrations leaving the liming plant can be divided into three categories.

a) Those that decreased to amounts below permissible (tolerable) value (Fig 3.11).
   - Cl-
   - Fe
   - K
   - Mg
   - Mn
   - Na

b) Those that decreased, but to amounts still above permissible (tolerable) values.
   - SO_4^{2-}
   - EC
   - Al
   - Acidity
   - TDS

c) Those that increased, but to levels below permissible (tolerable) values.
   - pH
   - T-Alk
   - Ca

The decrease of most of the variables is attributed to the addition of lime ($CaCO_3$) in the liming plant. This process is explained in detail in Chapter 2. The lime's major function is to increase the pH, though during the process, since the water media is changing, the other salts are precipitating out and forming a dense sludge (yellow buoy). This is disposed of in the yellow buoy dams situated about 200 m from the plant.

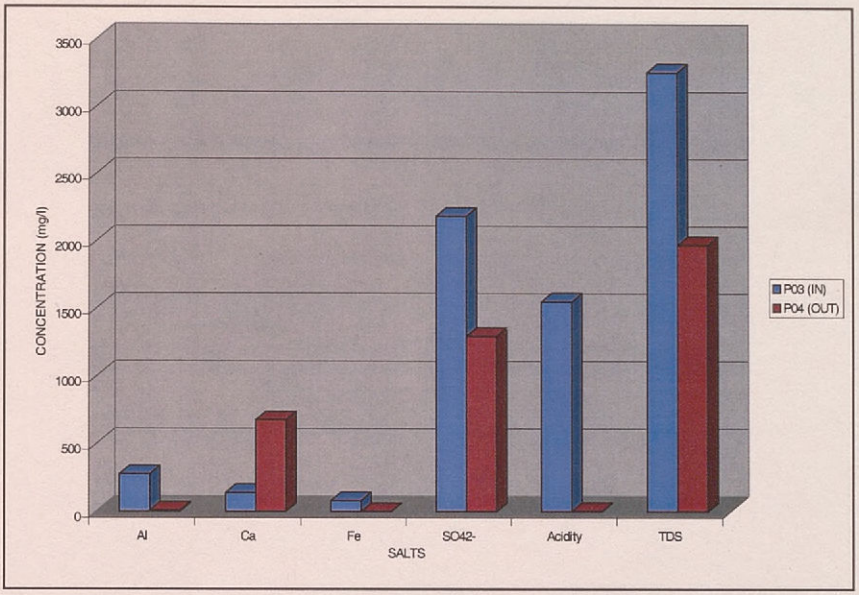


Figure 3.10 Difference in the concentration of major salts entering and leaving (P03 and P04 sampling sites respectively) the liming plant , April 1999.

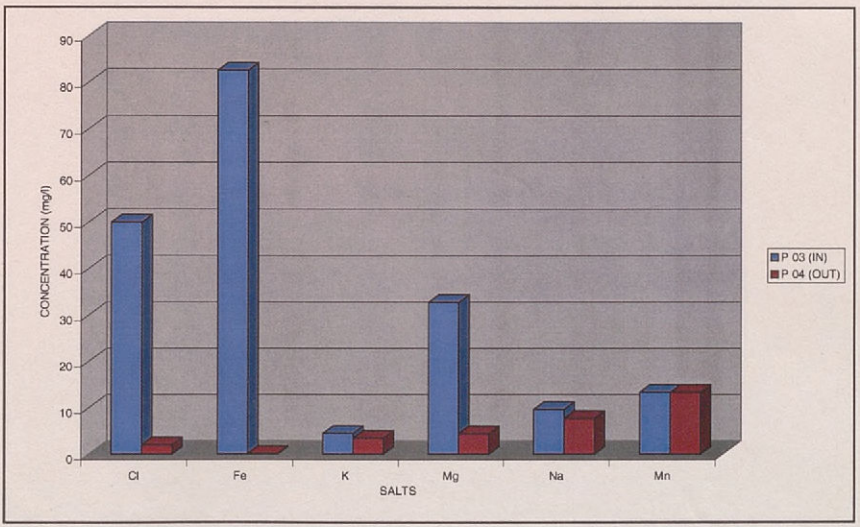


Figure 3.11 Difference in concentration of minor salts going in and leaving (P03 and P04 sampling sites respectively) the liming plant in July 1999.

3.6.3 Pollution from Central Seepage

The central seepage area with acidic seeps from the underground workings is located south of the liming plant about 200 m downstream (see inset in Fig 3.12, the black dot shows the location of this area with respect to the whole system). The acidic seep was sampled at P 05 denoted by KDSP 05 in the laboratory analyses (App. A, B, C). This is an area dissected by deep trenches about 3 – 6 m in depth (Fig. 3.12). These trenches seem to be getting deeper due to the erosion effect of the seep emanating from the old flooded underground workings. From the laboratory results it was noted that the seep is acidic with pH values ranging from 3 to 5.

The seep (P 05) from underground workings at the central seepage area was noted to have an effect on the concentration of some salts in the Kromdraaispruit stream despite their being decreased by the liming plant. Inflow of the seep (P 05) resulted in



Figure 3.12 Deep trenches found in the central seepage area (03/08/1999).

an increase in the concentration of SO_4^{2-} downstream (Fig 3.13). Although the concentrations may be different, this trend is similar for other variables like:

- Al
- Cl
- EC
- Fe
- K
- Mg
- SS
- SO_4^{2-}
- TDS
- Acidity

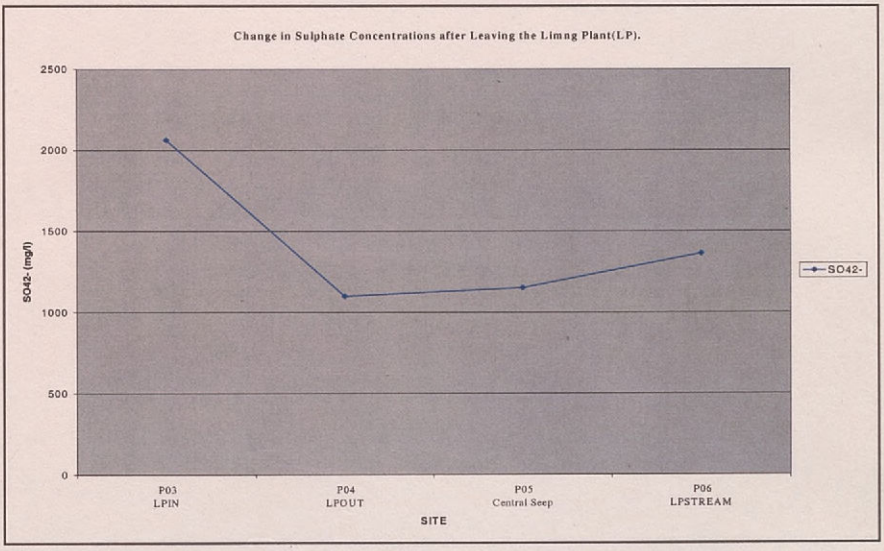


Figure 3.13: Impact of the liming plant on the sulphate concentrations (P 03, LPIN - water flowing into the liming plant; P 04, LPOUT - water flowing out of the liming plant; P05, Central Seep - water from the central seepage area; P 06, LPSTREAM - water in the liming plant stream).

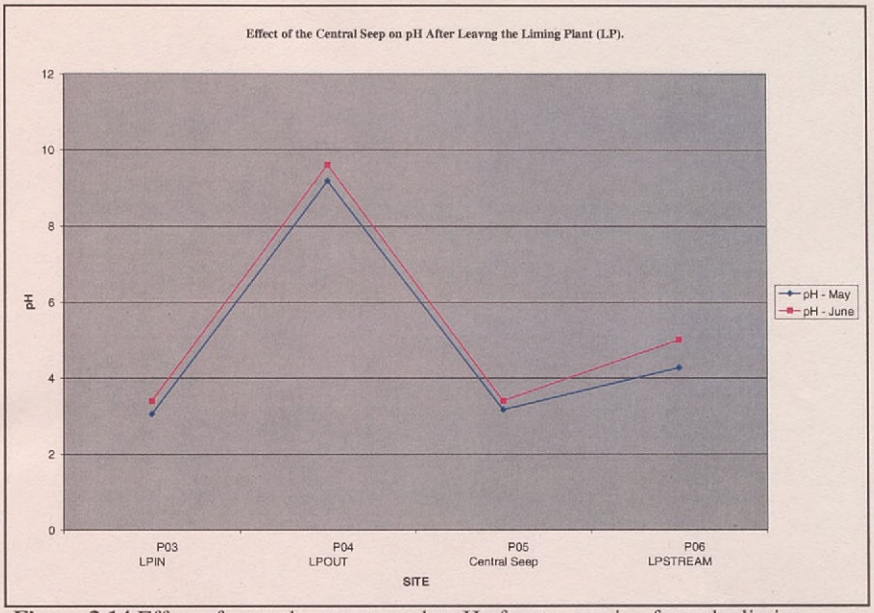


Figure 3.14 Effect of central seepage on the pH of water coming from the liming plant (Location of the different points can be seen in Fig 3.9).

On the other hand, P 05 caused a decrease in pH from 9 to around 4 - 5 (Fig 3.14) because it is acidic. From P 06 up to the end of this section, where the stream enters the wetland, the pH remains constant with values ranging between pH (4) to pH (5). It is also noted that some determinants, like SO_4^{2-}, Al, TDS and T-Alk, enter the system from the liming plant with their values above the permissible levels.

3.6.4 Water Quality in the Wetland

The lower section of the Kromdraaispruit system (the wetland) is approximately 3 km in length and about ± 80 m in width. Other physical parameters are described in Chapter 2.

The wetland receives water from several sources (Fig 3.15):

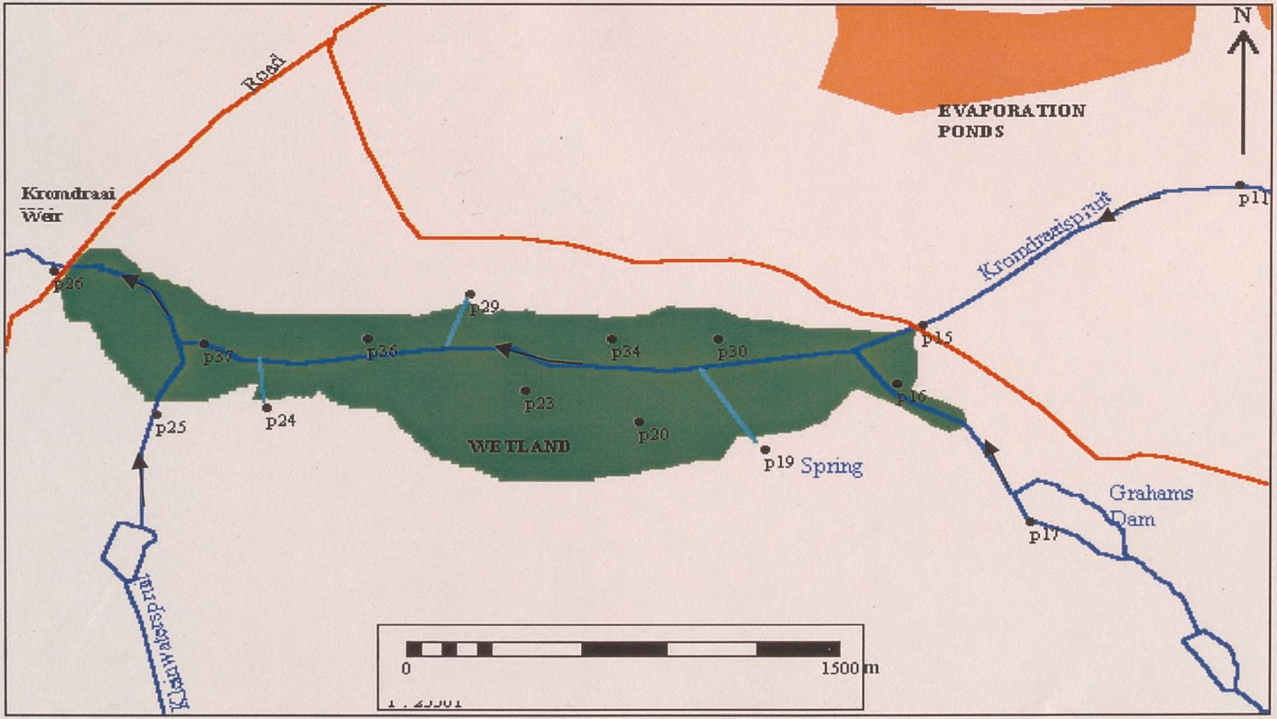


Figure 3.15 Sampling sites in the wetland region of the Kromdraaispruit

a) Surface water from the Grahams Dam stream, the Kleinwaterspruit and the liming plant stream.
b) Ground water at three points, two (P 16 and P 19) on the southern side of the Kromdraaispruit and one (P 29) on the northern side

From the results obtained, it was noted that the pollution entering via Kleinwaterspruit is low (Fig. 3.16). All the concentrations measured were below the permissible levels set by the Department of Water Affairs and Forestry (DWAF). This also applied for all determinants entering via Grahams Dam - P 16 (App. C). Of the eleven monthly samples for pollution in Kleinwaterspruit, the highest SO_4^{2-} concentration was recorded in June (< 100 mg/l), which is well below standards set by DWAF (250 – 500 mg/l) (SA water quality guidelines, 1996). The amounts of TDS and calcium present were also below permissible levels.

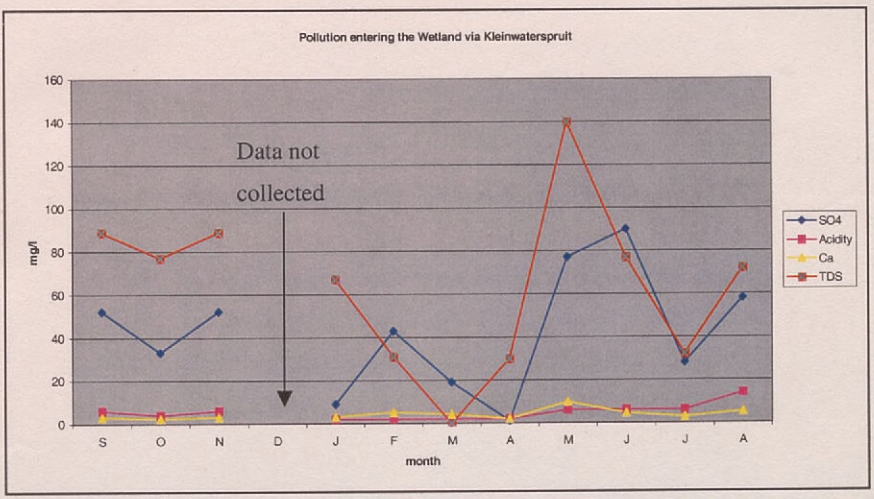


Figure 3.16 Concentration of SO_4^{2-} (limit -500mg/l), Ca^{2+} (limit-250mg/l), TDS (limit –820mg/l) and Acidity (measured as $CaCO_3$), entering the wetland via Kleinwaterspruit from September 1998 to August 1999.

Comparing plots of pollution entering and leaving the wetland, it was noted that there was a significant change in the concentrations of most of the determinants. Largely, there is a decrease between the sulphate concentrations entering and leaving the wetland (Fig 3.17). The sulphate concentration entering the wetland lies between 1100 - 2200 mg/l, with the highest value in March and the lowest in January and June. The SO_4^{2-} contents leaving the wetland lie between 900 - 1400 mg/l, with the highest content in March, and lowest in January (Fig 3.17). The high value in March was a singular spike which might not be repeated in other years and the low values in January were caused by dilution due to high summer rains (Fig 3.18).

Figure 3.18 shows the monthly average rainfall during the period of the study. The results of the Bethal station were purchased from the Agricultural Research Centre (ARC) in Pretoria, as it is the closest station (Appendix D). The database for

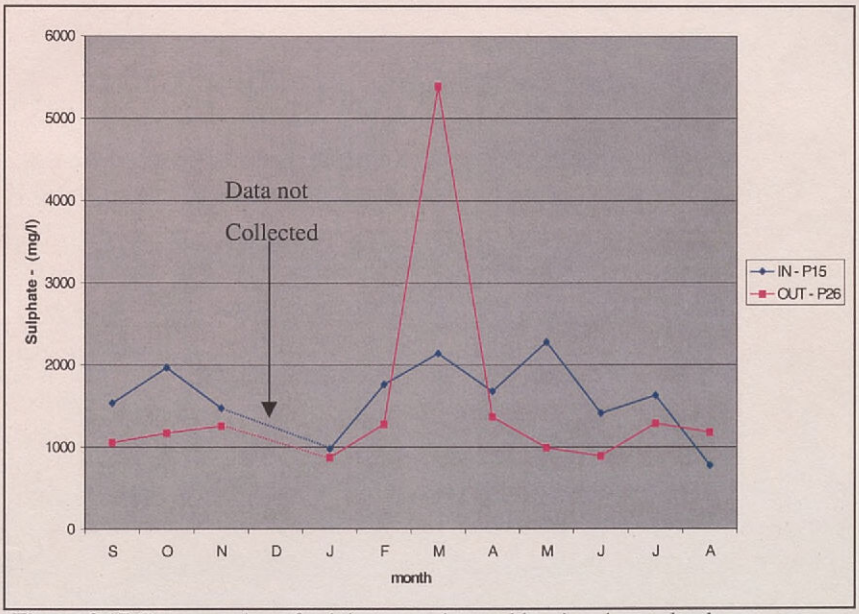


Figure 3.17 Concentration of sulphate entering and leaving the wetland.

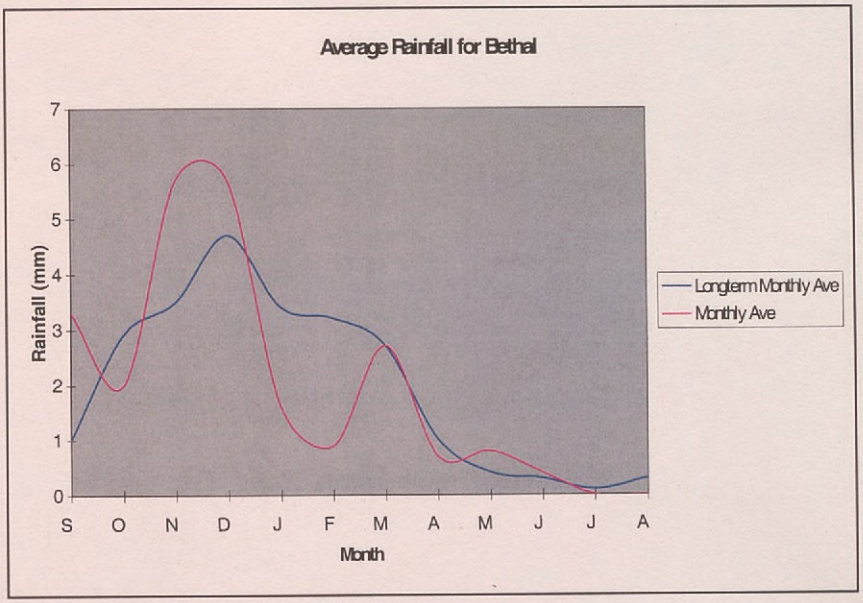


Figure 3.18 Rainfall in the sampling area.

Kromdraai was incomplete. The graph shows two plots, the average monthly rainfall and the long-term monthly summary of rain for 16 years ending 1999. This was to help determine if the area had received too much or too little rainfall in terms of average annual precipitation. It is noted that, in the months of November and December 1998, the area received more rainfall than the long-term average. The reason why the December samples were not collected was the above average rainfall and flooding which rendered the area, especially the wetland, inaccessible.

Looking at some of the minor determinants entering the wetland via the liming plant stream (Fig 3.19), it was noted that F and K occur in high concentrations (Fig 3.19) above tolerable values seen in Table 3.1. This was with the exception of Na and Cl concentrations.

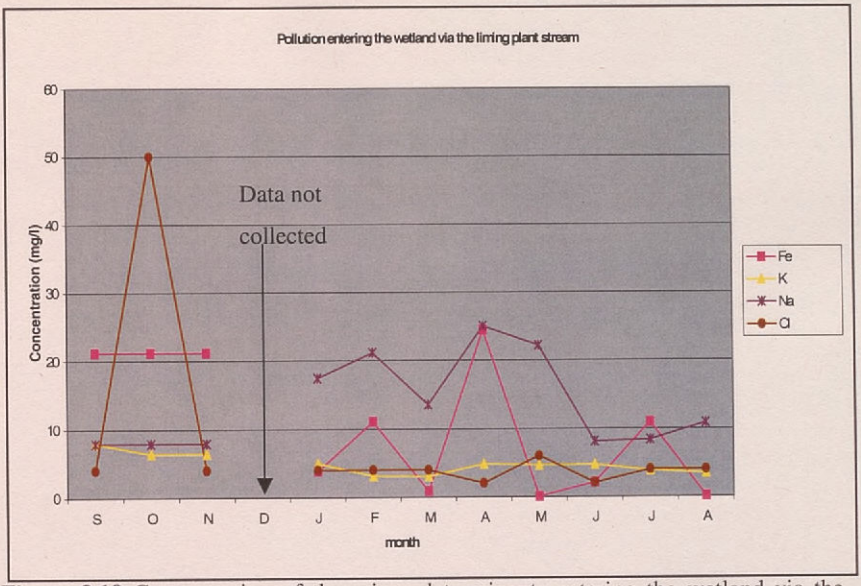


Figure 3.19 Concentration of the minor determinants entering the wetland via the liming plant stream at P 15.

The decrease in sulphate content is due to bacterial degradation (sulphate reducing bacteria) in the wetland sediments. Water flowing into the wetland from Kleinwaterspruit the Grahams Dam stream and the springs may also have caused dilution in the wetland. These wetland processes were discussed in Chapter 2.

From the results obtained, it was noted that there was a change in some of the determinants, similar to that of sulphate, after the water had passed through the wetland. The percentage improvement of some the determinants can be seen in Table. 3.3. Al had the highest percentage improvement whereas pH actually deteriorated by 7.43%. The deterioration of pH might have been due to the decomposition of the wetland vegetation in an aerobic environment. Other determinants like Na had concentrations of 5 – 30 mg/l (less than 150 mg/l and 250 mg/l, acceptable, tolerable values respectively) leaving the wetland. For Al, there was a large decrease in concentration although the amounts leaving the wetland are closer to the permissible levels allowed in South African waters.

Table 3.3 Average percentage improvement of some determinants passing through the wetland.

Determinant	Average Value at P15 (inlet)	Average Value at P26 (outlet)	Percentage Improvement
pH	4.84	4.48	-7.43%
SO_4^{2-}	1595.45 mg/l	1534.54 mg/l	3.82%
EC	220.17 mS/m	167.20 mS/m	24.05%
Ca^{2+}	570.92 mg/l	476.61 mg/l	16.52%
Mg^{2+}	21.73 mg/l	17.16 mg/l	21.03%
Al^{3+}	15.75 mg/l	7.59 mg/l	51.81%
Cl^-	7.82 mg/l	7.63 mg/l	2.43%
K^+	6.21 mg/l	3.83 mg/l	38.33%
TDS	2348.5 mg/l	1732.90 mg/l	26.21%

The concentrations of Cl entering and leaving the wetland are negligible and below tolerable and acceptable values. The same applies for K concentrations. There were decreases in some months, but the amounts present are negligible. Mg concentrations are variable, and possibly affected by the wetland. In six months there is an increase in winter and in five months a decrease (Fig. 3.18).

The change in pH (Fig 3.20) shows a decrease between P 15 and P 26, i.e. there is an increase in acidity. The biogeochemical processes in the wetland should cause a decrease in acidity. The wetland is supposed to improve the quality of water by increasing the pH, but this does not happen. Liming with coarse lime commenced in June 1999 and, it was noted that the pH of water leaving the wetland improved slightly. A month later, in July 1999, a photograph taken at P 15 (Fig 3.21) showed lime coated with an orange precipitate, iron sulphate. This was due to the slow rate of reaction of the coarse lime which has a smaller surface area compared to the fine lime.

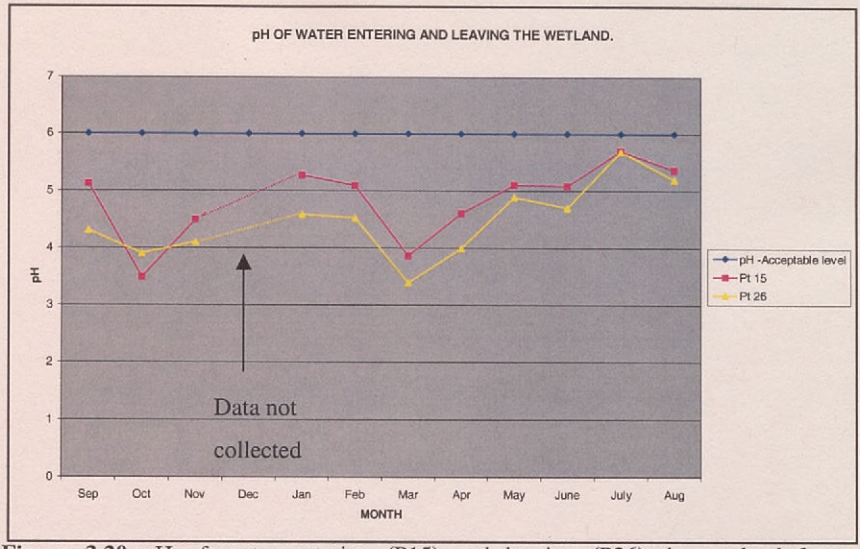


Figure 3.20 pH of water entering (P15) and leaving (P26) the wetland from September 1998 to August 1999.

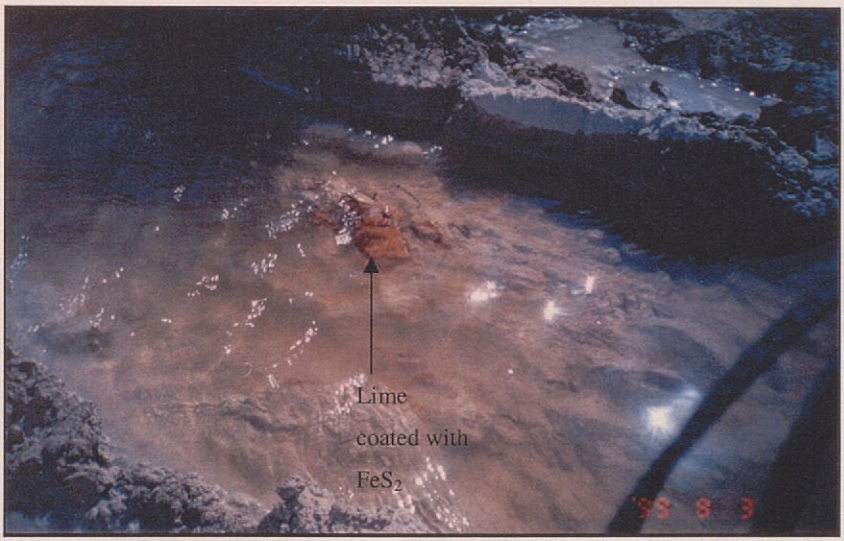


Figure 3.21 Coarse lime coated with Iron Sulphate (03/08/1999).

In August, the mine management started using the finer Savannah lime. Unfortunately, the study was ending, so the long-term effects of this lime on the wetland were not studied. In July 1999 (winter), a yellow precipitate was noted in the wetland (Fig 3.22) as the waters were receding. This is due to the addition of lime to the wetland, a reaction of $CaCO_3$ with pyrites. The sludge that forms is not being collected and disposed of in a safe place. It accumulates at the bottom of the wetland. Of all the salts going through the wetland, the determinants that improved, but with their concentrations still exceeding those permissible by DWAF, can be seen in Table 3.4.

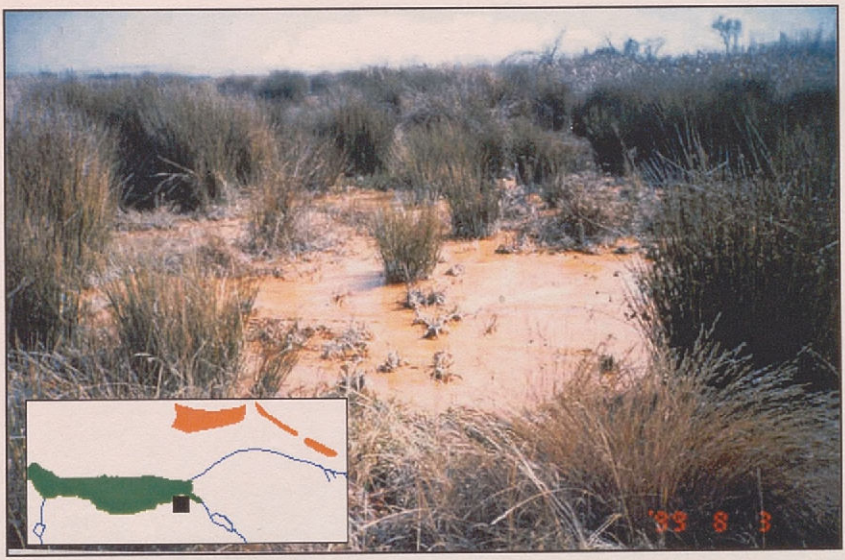


Figure 3.22 Yellow buoy forming at the bottom of the wetland when the water has receded in winter (03/08/99). Inset shows the location with respect to the wetland.

Table 3.4 Determinants improved by the wetland and those in excess of the tolerable values accepted by the South African Department of Water Affairs and Forestry.

Determinant	Acceptable Value	Tolerable Value	Improved by Wetland	Value in excess of Tolerable value
Al	0.1 mg/l	0.5 mg/l	X	X
Ca	200 mg/l	-	X	X
Cl	100 mg/l	320 mg/l	X	-
EC	100 mS/m	120 mS/m	X	X
Fe	0.3 mg/l	1.0 mg/l	X	-
K	70 mg/l	-	X	-
Mg	70 mg/l	-	X	-
Mn	0.2 mg/l	1.0 mg/l	X	X
Na	150 mg/l	250 mg/l	X	-
pH	6.5 – 8.5	6.0 – 9.0	X	X
SO_4^{2-}	250 mg/l	500 mg/l	X	X
TDS	680 mg/l	820 mg/l	X	X

3.7 BLENDING WATERS IN THE SYSTEM

The Kromdraaispruit system has a number of inlets flowing into it at different points along the stream. The four major inlets are springs, acidic seeps, Grahams Dam and Kleinwaterspruit (Fig 3.23). The impacts of these inlets on the pH of the water from the liming plant were studied using the STASOFT Version 3.0 computer programme. This programme presented by Loewenthal *et al*, 1988 (Friend & Loewenthal, 1992) is based on the chemical equilibrium model of the Ca–Mg–CO_3 system. It provides rapid numerical solutions to characterisation of water and the dosing requirements to obtain the desired chemical water quality for a prescribed input. Originally the model was appropriate only for low salinity waters, i.e. waters with TDS < 1000 mg/l. The average range of TDS of water in the area was found to be 50 – 3420 mg/l (App.C, table 12).

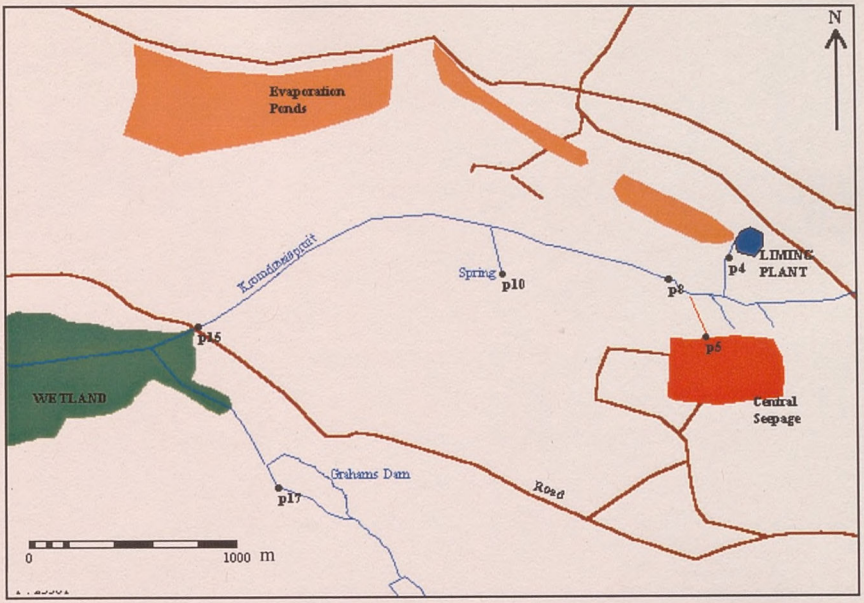


Figure 3.23 Water inlets into the Kromdraaispruit.

In the upgraded programme, STASOFT Version 3.0 (Friend, 1991, in Friend & Loewnthal, 1992), the Ca–Mg–CO_3 equilibrium model is extended to incorporate waters with TDS up to about 15000 mg/l. STASOFT is designed for application to both terrestrial waters, where ion-pairing effects are negligible and the TDS is less than 1000 mg/l, and higher salinity waters, where ion-pairing effects are significant (Friend & Loewenthal, 1992).

STASOFT offers the option of studying the results when different types of water are mixed (Blending). Blending was utilised in this study. In this option, two aspects can be determined: either the fractions required to blend two waters to a specified pH, or the final state of water after blending several waters (maximum 20). The values used in this program were average values of the determinants for each sampling point (App. C, table C12). With this software, it was possible to determine the impacts on the stream water after blending waters of different percentages from three different inlets, i.e. the central seepage (P 05), the spring (P 10) and Grahams Dam (P 17)) (Fig. 3.23).

The addition of just 10% of the acidic seep from central seepage (P 05) to the limed water (P 04) caused a dramatic drop from pH 8.67 to pH 4.53 (Fig. 3.24). This is close to the average value of pH (4.62) found downstream at sampling site P06, immediately after the intersection of the seep with the liming plant stream. However further addition of P 05 did not cause further dramatic drops. Blending spring water (P10) with liming plant stream water (P 08) (Fig. 3.25) has a smaller impact compared to that caused by the acidic seep because, at P 08, the liming plant water is already mixed with seepage water. The addition of 10% (P 10) shows a slight increase of 1.71% from pH 4.68 to pH 4.76 compared to the effects of the seep (P 05) where the decrease in pH was 47.75%. P11 is a sampling point found after the intersection of the spring with the liming plant stream. The average pH at this point is 4.65, similar to the calculated pH 4.76. The effects of the other inlet into the Kromdraaispruit (Grahams Dam, P17) (Fig. 26) showed that an addition of 10% P17 to P15 (stream) caused a 3% increase in pH from pH 4.84 to pH 4.99.

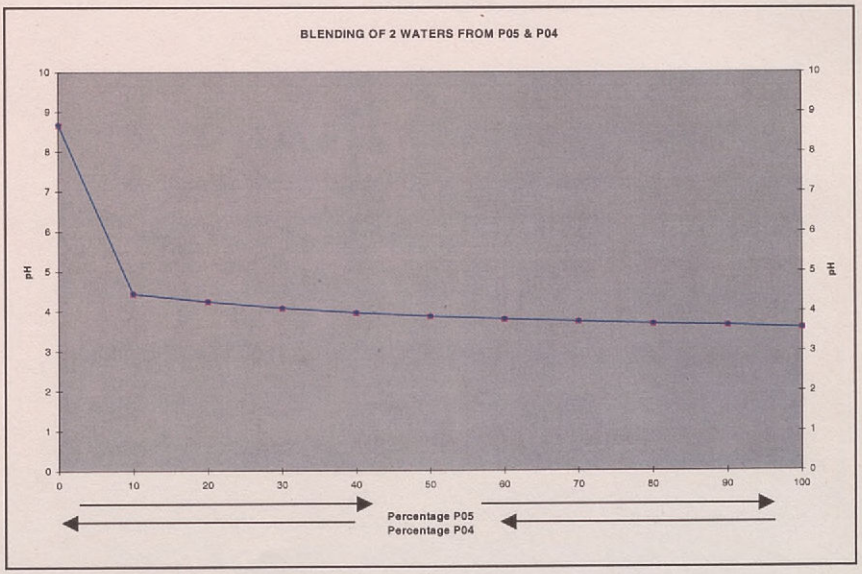


Figure 3.24 Effect of blending water from an acidic seep (P05) with Liming Plant water (P04).

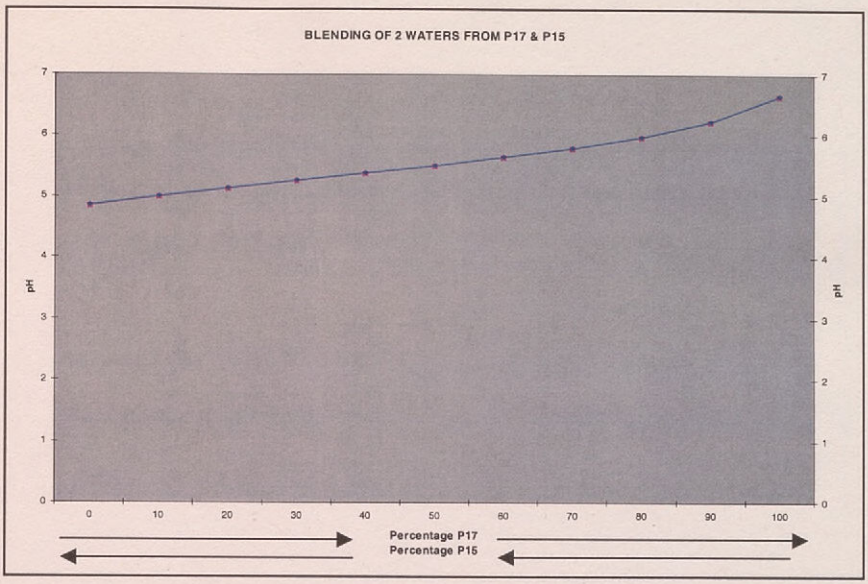


Figure 3.25 Effect of blending water from a spring (P10) and liming plant water (P08).

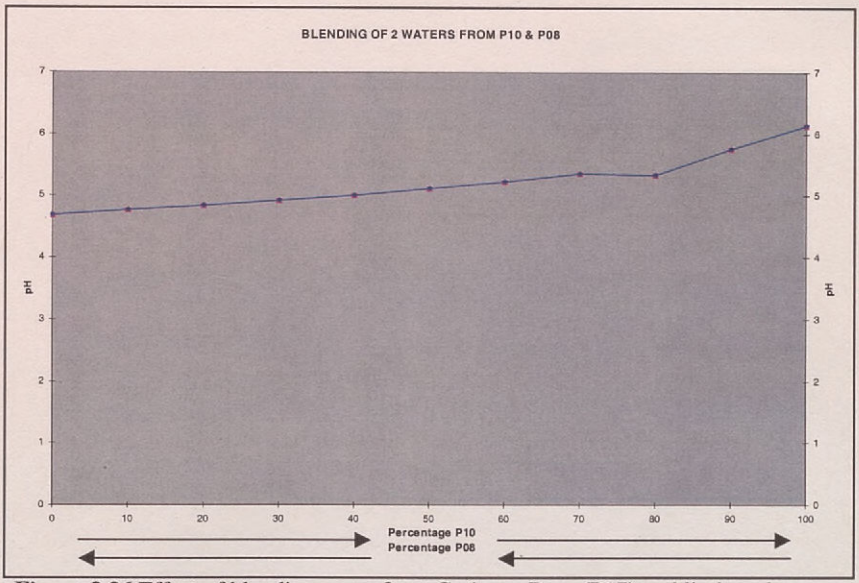


Figure 3.26 Effect of blending water from Grahams Dam (P17) and liming plant water (P 15)

3.8 SUMMARY

- Since the mine management is dewatering abandoned underground workings in order to continue with opencast mining, large volumes of water are being released into the wetland. The amount of water flowing into the wetland due to the dewatering exercise exceeds the assimilative capacity of the wetland.

- The high volume of water flowing into the wetland has created channelised flows. This means that the water is not being retained in the wetland long enough for treatment, as the residence time has been reduced. In order to maximise the efficiency of the wetland the water has to be evenly dispersed within the wetland for a long period of time.

- There is yellow buoy ($FeSO_4^{2-}$) (Fig.3.22) deposit accumulating in the wetland. In this case, the salts are not leaching through the yellow buoy for plant uptake or anaerobic bacterial action. Since lime is being introduced directly into the wetland at P15, the production of sludge, because of its density, is going to increase this effect. It is therefore recommended that the management discontinue this exercise. The water should be predosed and put in a settling pond for the precipitated salts to settle out before discharging it into the wetland.

- The dramatic drop in the pH of limed water in the Kromdraaispruit is caused by the acidic seep from the central seepage area (Fig 3.14). This is why the treated water from the liming plant becomes acidic 200 m downstream. To eliminate this effect, the acidic drainage from the seep should be diverted to the liming plant for treatment.

- Through modelling with STASOFT, it was noted that the addition of acidic seep to treated water has a much greater effect, i.e. reduction of pH, than the addition of pure ground waters. This is because mining water is acidic and has high concentrations of dissolved salts.

CHAPTER 4

KROMDRAAI SOILS

4.1 INTRODUCTION

A general definition of soil is given in the Soil Survey manual of the United States Department of Agriculture (1951) (Hesse, 1971).

" Soil is the collection of natural bodies occupying portions of the earth's surface that support plants and that have properties due to the integrated effects of climate and living matter acting upon parent material, as conditioned by relief, over periods of time."

All soils develop from weathered rock, volcanic ash deposits or accumulated plant residue (Miller & Donahue, 1990). Although both physical and chemical processes taking place on the earth's surface are constantly forming soils, their formation tends to be slower than their loss.

Soils are nature's dispose-all, its' sewage treatment plant, its' water purifier and at times, also a pollutant. Although soil is the most universal and extensive substance that cleans waters and recycles wastes, it is not infinite in capacity. Many toxins added to soils can build up to concentrations that become serious threats to plant and animal health. Materials accumulate when added in larger amounts than their decomposition rate (Miller & Donahue, 1990). The Kromdraai soils were studied to see if they were in any way contributing to the AMD in the Kromdraaispruit due to accumulation of toxins.

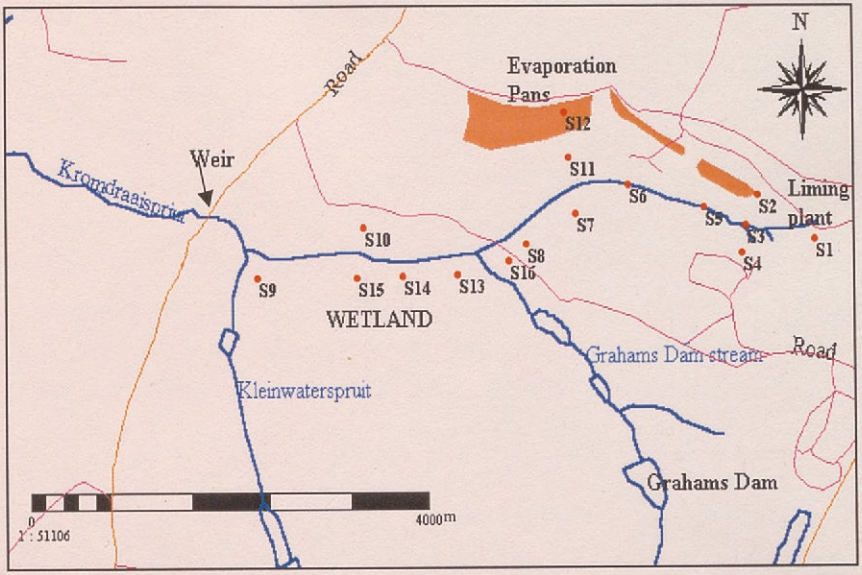


Figure 4. 1 Soil sampling points around the Kromdraaispruit.

4.2 SAMPLING

A total of sixteen site locations (Fig. 4.1) from the Kromdraai area were identified and sampled. Two sets of soil samples were procured from the sixteen locations around the 5 km stretch of the Kromdraaispruit. The geographic co-ordinates of each sampled site was determined using a Global Positioning System (GPS). (App. E, Fig E 1).

Samples were collected during spring in September 1998 and six months later during autumn in March 1999. Sampling was done only twice because the soil properties that were measured do not change as readily as the water properties. Sampling points were affixed with the prefix KDS (**K**rom**D**raai **S**oils) for laboratory identification (App. E and F), but in the text this will be shortened to the prefix S, i.e. KDS 01 in the appendix is similar to S1 in the text. Representative soil samples were taken from the streambed (S3, S5, S6), seepage areas (S1, S2, S4), wetland area (S9, S13, S14, S15, S16) as well as the area around the mine (S8, S10, S11, S12). In general, samples were collected to ensure a good spread across the area.

Soil sample collection was done with a bucket augur. At each point, two samples were collected:

Sample A - Top sample was from the surface up to depth of 30 - 40 cm.

Sample B - Bottom sample was from a depth of 40 cm to 60 cm.

The Agricultural Research Council at the Institute for Soil, Climate and Water in Pretoria carried out the soil analysis. Samples were analysed for total anions and cations, Sodium Adsorption Ratio (SAR), saturation, pH, electrical conductivity (EC) and the concentrations of Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, SO_4^{2-}, F^{-}, Cl^{-}, NO_2^{-}, NO_3^{-} and available PO_4. Analytical methods employed can be found in "Handbook of Standard Soil Testing Methods for Advisory Purposes" compiled by "The Non–Affiliated Soil Analysis Work Committee" in 1990.

The main objective of obtaining a comprehensive soil characterisation was to investigate whether the soil had an impact on, or contributed to, the pollution of the Kromdraaispruit. Any chemical of natural or anthropogenic origin is considered a pollutant if it accumulates in the soil medium and changes the natural soil equilibrium.

4.3 NATURE AND PROPERTIES OF THE KROMDRAAI SOILS

The properties of the 16 locations (Fig. 4.1) around the Kromdraaispruit are described in appendix F, tables F1 and F2, for winter and summer respectively. Wide ranges in acidity (pH 3 – 5) and conductivity (EC 9 to 464 mS/m) were evident.

4.3.1 Chemical Properties of Kromdraai Soils

The chemical properties of soils include mineral solubility, nutrient availability, soil reaction (pH), cation exchange and buffering action (Miller & Donahue, 1990). As an example, chemical examination of solutions extracted from soils from arid and semi-arid climatic areas (similar to the area of investigation) reveal Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-} and CO_3^{2-} as the major ionic components (Yaron *et al.*, 1996).

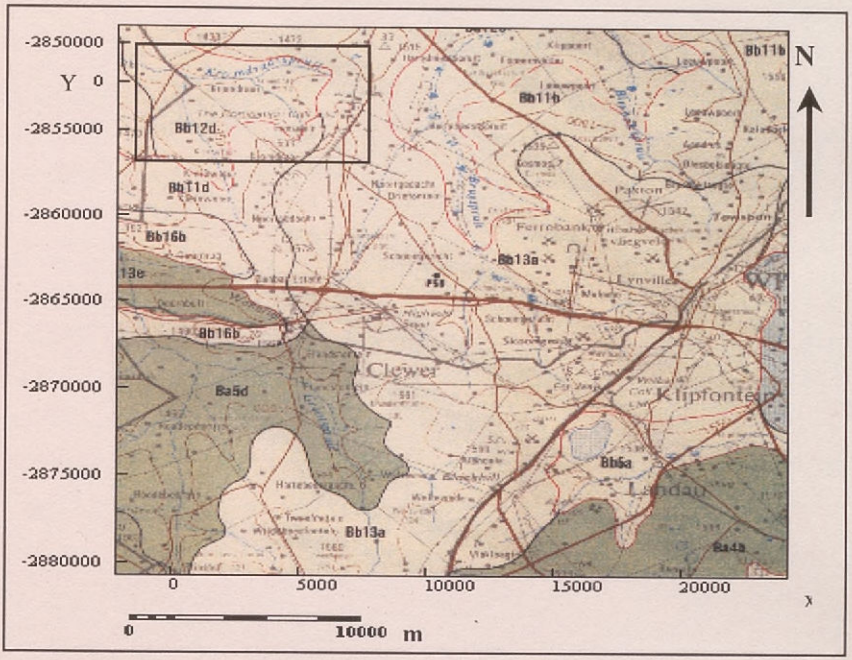


Fig 4.2 Extract from the 1: 250 000 Land Type sheet 2528 PRETORIA showing the type of soils found in the area of study indicated by black rectangle.

Under special conditions - mainly as a result of human activity – the salt presence in the soil, as reflected by the quantity and its ionic ratio, is potentially harmful to the environment (Yaron *et al.*, 1996).

The extract from 1:250 000 Land Type series sheet 2528 Pretoria (Fig 4.2) shows the soils in the area of study depicted as dystrophic (yellow area). Dystrophic refers to soils that have suffered marked leaching (Soil Classification Working Group, 1991). Dystrophic soils are poor in nutrients and have a low buffering capacity (the capacity of soil solids and liquids to resist appreciable change in the pH of the soil solution). Any acidic solutions moving through these soils will stay acidic. Since the area is not buffered, it will always have an acidity problem. The soils in the area are also of phillitic catena type; i.e. have a high content of Fe^{2+}, tending to high contents of $Fe3^{+}$ (due to Fe^{2+} oxidation) and Al^{3+}.

4.3.2 The Soil reaction (pH)

Soil reaction is an indication of the acidity or basicity of the soil and is measured in pH units. The soil pH is easily determined and provides various clues about other soil properties. The soil pH has a significant effect on the solubility of minerals (Miller & Donahue, 1990).

The pHs for the soils in the Kromdraaispruit area are in a range from pH 3.44 to pH 6.96 (Fig 4.3 and Fig 4.4). In these figures, sample A is the topsoil (0 – 30/40 cm) and sample B is the bottom soil (40 – 60 cm). pHs less than 4.5, which were measured in summer, occur in extremely weathered mineral soils of low fertility, in soils subjected to acidifying agricultural practices and where the buffering capacity is low. Soil pH markedly less than 4 will also be encountered in peat soils and acid sulphate soils (Peverill *et al.*, 1999). Since the major activity of the area is coal mining, the presence of pyrite (FeS_2) is certain. In winter all the soils had pH ranging between 3.44 – 5.5 (Fig 4.3). This was caused by significant soil acidification. In this soil pH range, the process of mineral weathering is dominant, and exchangeable cations such as Al and Mn may exhibit toxicity to plants (Peverill *et al.*, 1999). pH affects the availability of nutrients. If the soil has a low buffering capacity, it will also have a low capacity to supply cations.

Generally, soil pH values range from as low as 3.5 to over 10 (Fig.4.5). The soils in the Kromdraai area range from very strong to slightly strong in the acidity range. Plants grow well between pH 5 and pH 8 (Miller & Donahue, 1990). Soil pH governs the availability of many elements that are essential for, or toxic to, plant growth. If the adsorbed ions on the colloids are mostly Al $(OH_2)^+$ and some H^+, the soils are acidic. Strongly acidic soils are undesirable because soluble aluminium and manganese can reach toxic levels and microbial activity is greatly reduced. Soils become acidic (even from basic parent materials) by the leaching away by rainwater of the basic cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) and replacement of many of them by H^+ from carbonic acid (H_2CO_3) formed from water and dissolved CO_2. Eventually, Al $(OH_2)^+$ replaces H^+ (Miller & Donahue, 1990).

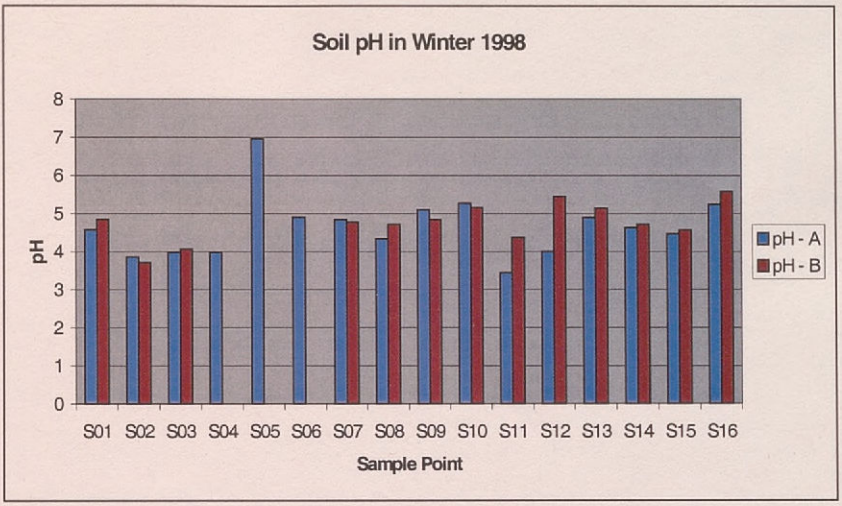


Figure 4.3 Soil pH in Sample A and Sample B in winter 1998

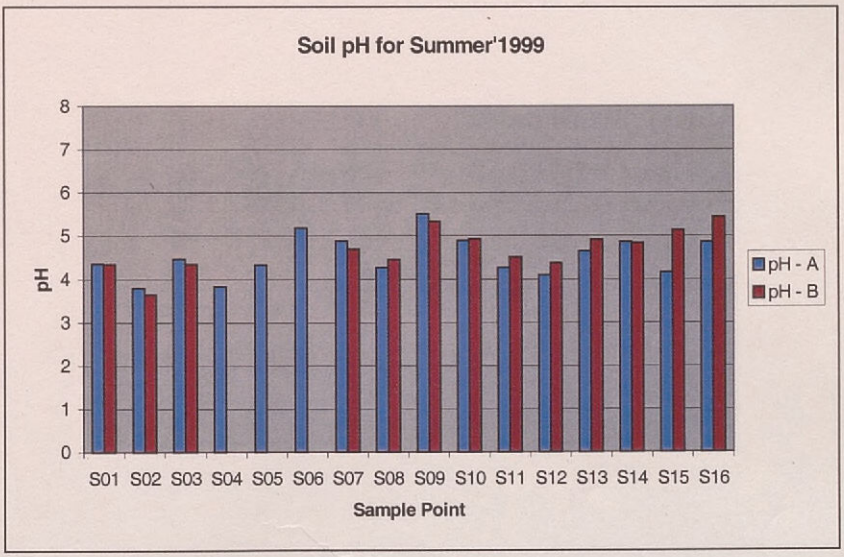


Figure 4.4 Soil pH in Sample A and Sample B in summer 1999.

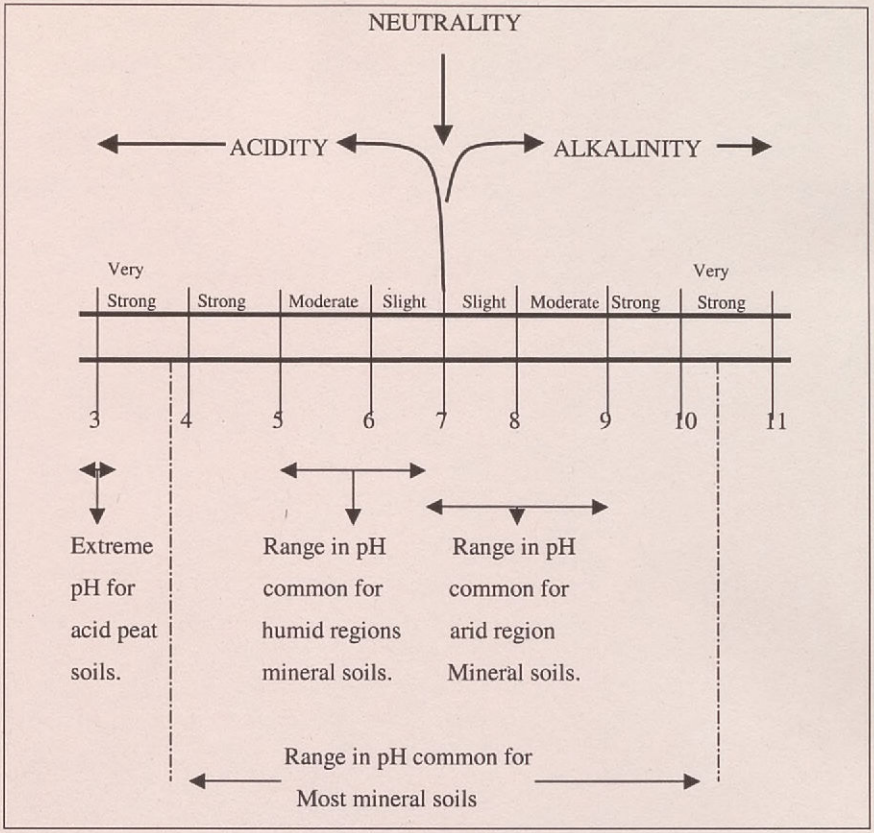


Figure 4. 5 Soil pH range (Paverill *et al.*, 1999)

Although rain has neutral pHs, it actually causes acidity. Water is an extremely weak acid, but soil water contains stronger acids, mostly of biological origin. Carbonic acid is the most abundant and is formed when CO_2 gas from respiration and fermentation dissolves in water (Singer & Munns, 1992). Even as rainwater passes through unpolluted air, it absorbs enough CO_2 to lower its pH, from 7.0 to about 5.5, so in summer the soils are more acidic than in winter because rainwater combines with CO_2 in the soil, promoting the formation of carbonic acid. This is noted with most of the sample pH readings for winter and summer (Fig 4.3 and Fig 4.4 respectively) for the Kromdraai area. More H^+ ions cause a low pH that leads to Al^{3+} being knocked off the exchange complex.

Acidity in soils accumulates and does not leach out. This phenomenon is explained by considering two important aspects, the anions of the acids (their conjugate bases) and cation exchange (Singer & Munns, 1992).

With every addition of acid to soil, some H^+ is adsorbed onto colloids by its attachment to pH–dependent charge sites or by the exchange of H^+ with Ca^2, Mg^{2+}, K^+ and Na^+. The retention of H^+ is aided when leaching removes the anions of the acids along with the displaced Ca^{2+}, Mg^{2+}, Na^+ and K^+ (Fig 4.6) that would otherwise compete with H^+ for attachment to the colloids. Progressively, over the years or centuries, the soil "exchange complex" and the soil solution together become more acidic.

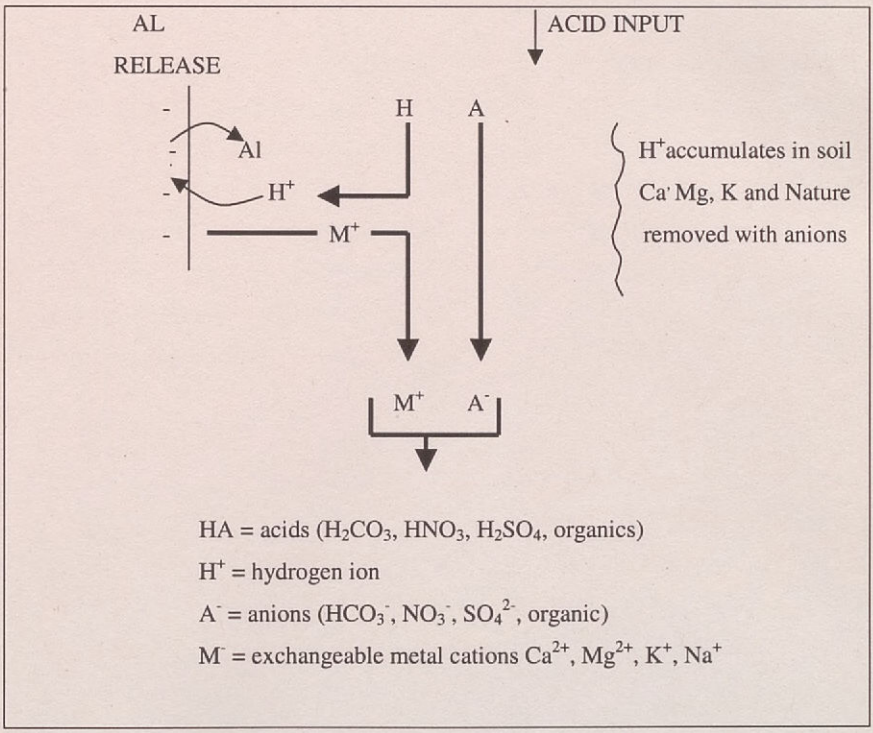


Figure 4.6 Roles of acid inputs, cation exchange and leaching in soil acidification (Singer & Munns, 1992).

The mechanism explains why acid soils develop mostly under conditions of vigorous leaching and biological activity. It also explains why acid soils often contain little exchangeable and soluble Ca^{2+}, Mg^{2+}, K^{+} and Al^{3+} (Fig 4.6) and why soil acidity develops most readily on parent materials that contain low concentrations of these elements.

To examine if Al^{3+} will tend towards toxicity in soils found in the research area, the saturation percentage is considered. The saturation percentage is the water content of soil when all pores are filled with water (Miller *et al.*, 1990). The saturation percentage in the area for both winter and summer ranges from 33 – 78 % with most values above 50% (Fig 4.7 and 4.8). Al^{3+} will have a tendency to be toxic if the saturation percentage is greater than 50 %. Al^{3+} toxicity is plausible in soils that have saturation percentage > 50%.

In the topsoil, S10, S14 and S15 had a saturation percentage greater than 50% in both summer and winter, S16 was greater than 50% in winter and S15 was greater than 50% in summer. In the subsoil, none of the samples had a saturation percentage greater than 50 % except for S10 which was greater than 50% in summer. The number of soil samples with saturation percentage > 50% is greater in summer than in winter (Fig 4.7 & Fig 4.8). Both figures (Fig 4.7 & 4.8) show that the saturation percentage was greatest in the wetland samples (S09, S10, S13, S14, S15, S16) compared to those collected elsewhere in the area because it is a waterlogged system.

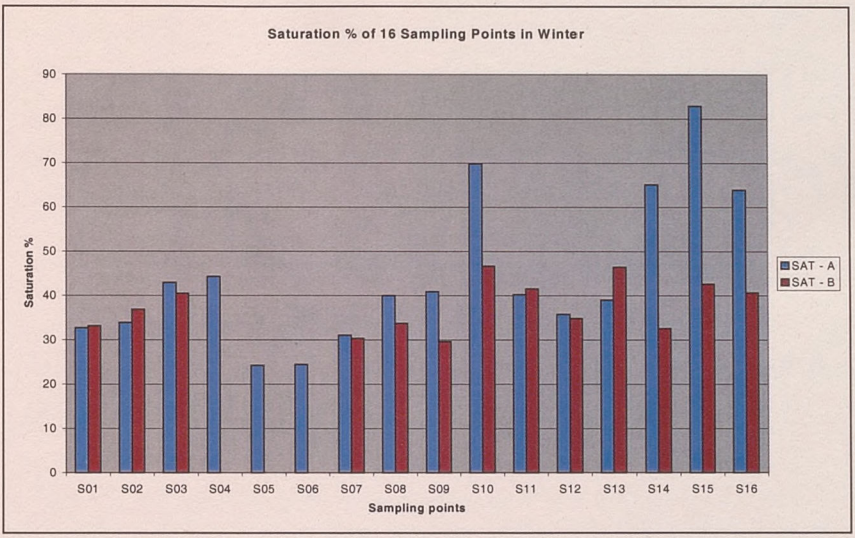


Figure 4.7 Saturation percentage of soils in winter September 1998 (SAT –A & SAT – B are the saturation percentages of samples A and B respectively).

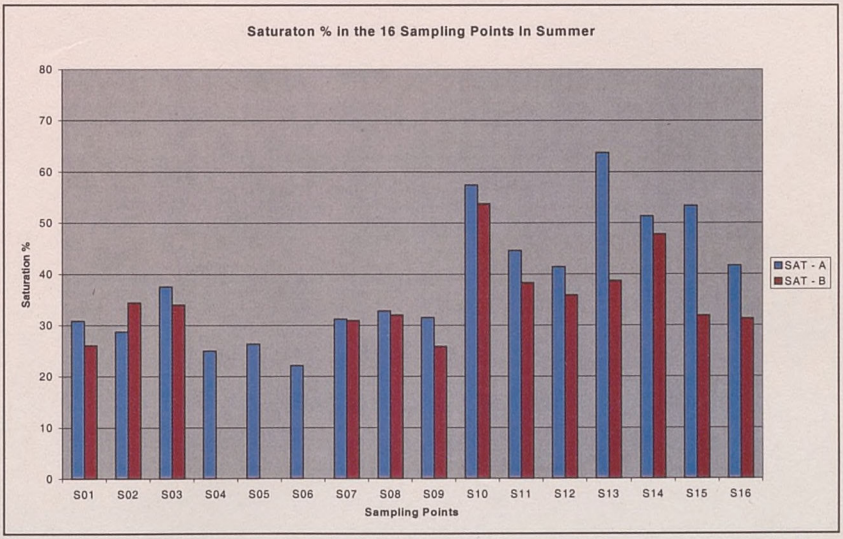


Figure 4.8 Saturation percentage of soils in summer March 1999 (SAT –A & SAT – B are the saturation percentages of sample A and B respectively).

4.3.3 TDS, SAR & EC

Salinity or total salt concentration is usually expressed as total dissolved solids (TDS) or as the electrical conductivity of the solution (EC). The major fractions of the anions comprise Cl^-, SO_4^{2-}, and NO_3^- and the common cations are Ca^{2+}, Mg^{2+}, Na^+ and K^+ (Yaron *et al.*, 1996).

Salted soils are classified on the basis of 2 criteria;

1) the total soluble salt content, and
2) the exchangeable sodium percentage or, more recently, Sodium Adsorption Ratio (SAR).

Because ions in water conduct electrical current, electrical conductivity (EC) is a fast, simple method of estimating the amount of total soluble salts in a soil sample. In terms of electrical conductivity (a measurement of total salt content) and SAR, three salt-affected soils are defined (Miller & Donahue, 1990). The SAR is used to estimate what the exchangeable sodium percentage of a soil is, or what it is likely to become, if the water that comprises the sampled soil water is in that soil for long periods of time (Miller & Donahue, 1990).

Table 4.1 Classification of salt - affected Soils (Miller & Donahue, 1990).

Name for Soil	Electrical Conductivity of Saturation Extract EC_e x 10^2(*mS/m*)	Sodium Adsorption Ratio (SAR)
Normal Soils	Less than 4.0	Less than 13
Saline Soils	More than 4.0	Less than 13
Sodic Soils	Less than 4.0	More than 13
Saline-sodic soils	More than 4.0	More than 13

All the soils in the Kromdraai area with the exception of 8A in 1998 and 2B in 1999 have an EC of less than 4.0 dS/m (4.0 X 10^2 mS/m) and they all have an SAR of less than 13 (Figs. 4.9, 4.10, 4.11, 4.12). This generally classifies them as normal soils according to Table 4.1.

Comparing EC values with pH in the soils, it was noted that they have an inverse relationship. As pH increases, EC decreases and vice versa. In most areas (App. F), the EC in sample A (0 – 30/40cm) for summer is greater than that for winter of the same sample (Fig. 4.13, Fig 4.15). The same trend is noted for sample B (40 –60 cm) (Fig. 4.14, Fig. 4.16). EC readings in the wetland soils are greater than in other areas. From the graphs, it is also noted that the pH of sample A at most sites in summer (Fig.4.15) is greater than the pH of sample B (Fig. 4.16) in the same season because the rains are causing dilution in the top layer. It is the opposite in winter, with pH of sample B (Fig. 4.14) being greater than the pH of sample A (Fig. 4.13), because the water has leached into the lower levels.

Samples S4B, S5B, S6B have no readings because, during the collection of Sample A, the augur hit rock at these points.

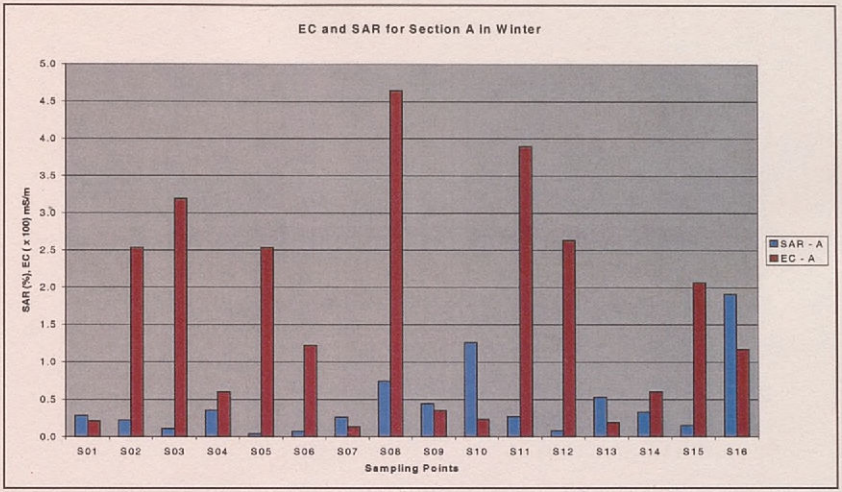


Figure 4.9 EC and SAR in Sample A of 16 locations in winter 1998.

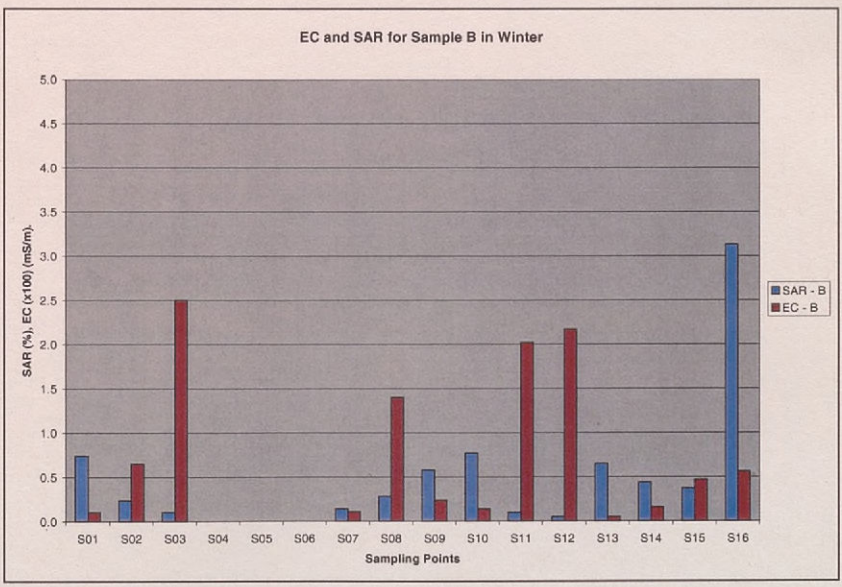


Figure 4.10 EC and SAR in Sample B of 16 locations in winter 1998. S04, S05 and S06 were not collected because in these areas only the top sample (Sample A) existed.

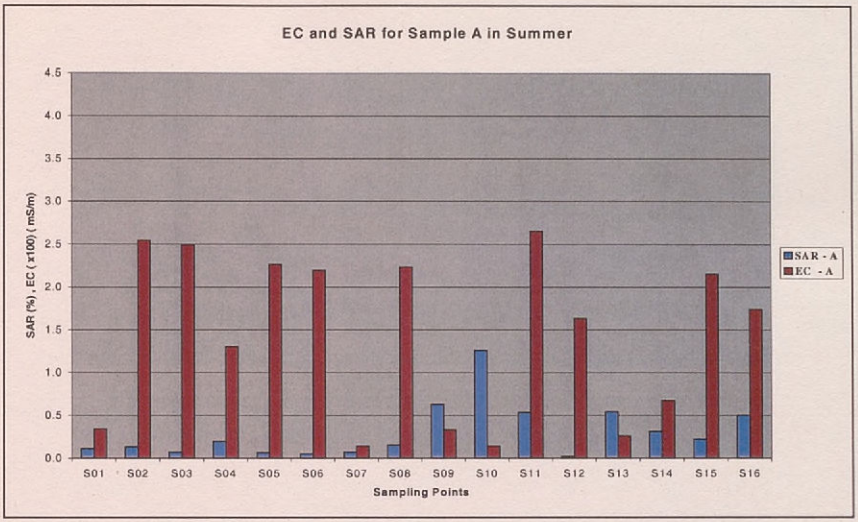


Figure 4.11 EC and SAR in Sample A of 16 locations in summer 1999.

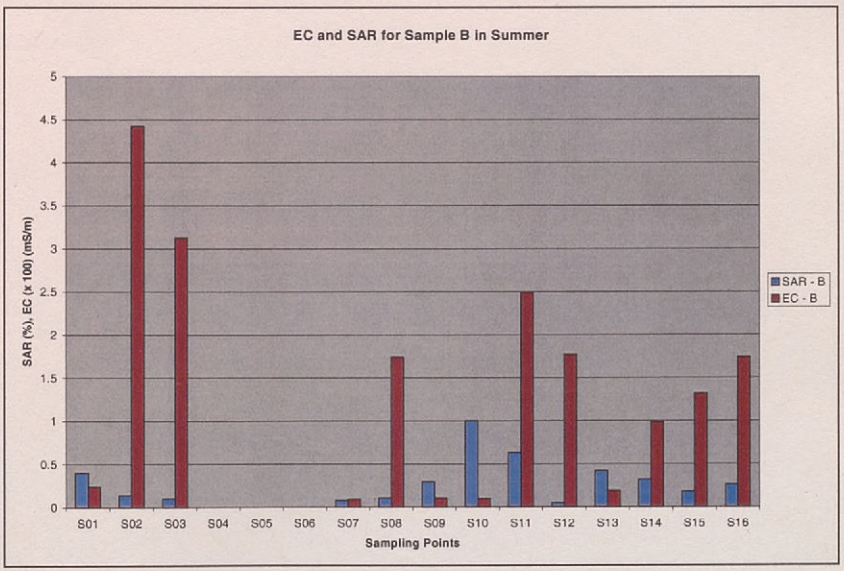


Figure 4.12 EC and SAR in Sample B of 16 locations in summer 1999. S04, S05 and S06 were not collected because in these areas only the top sample (Sample A) existed.

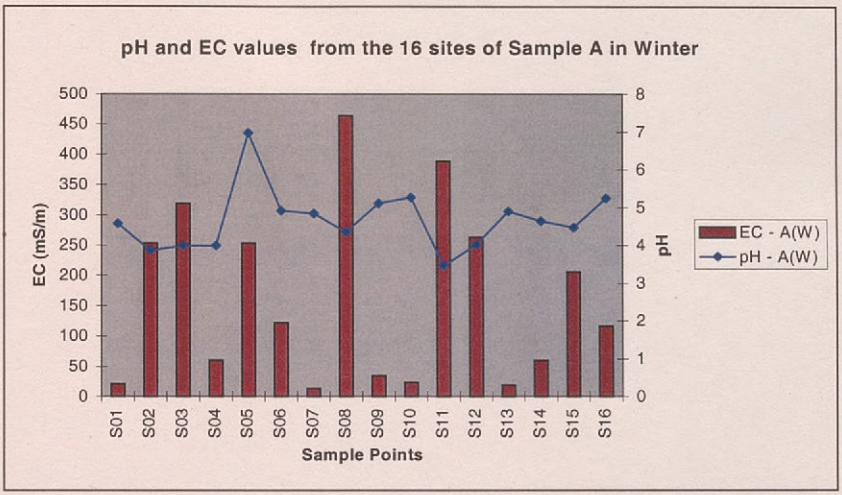


Figure 4.13 pH and EC values of sample A in winter 1998

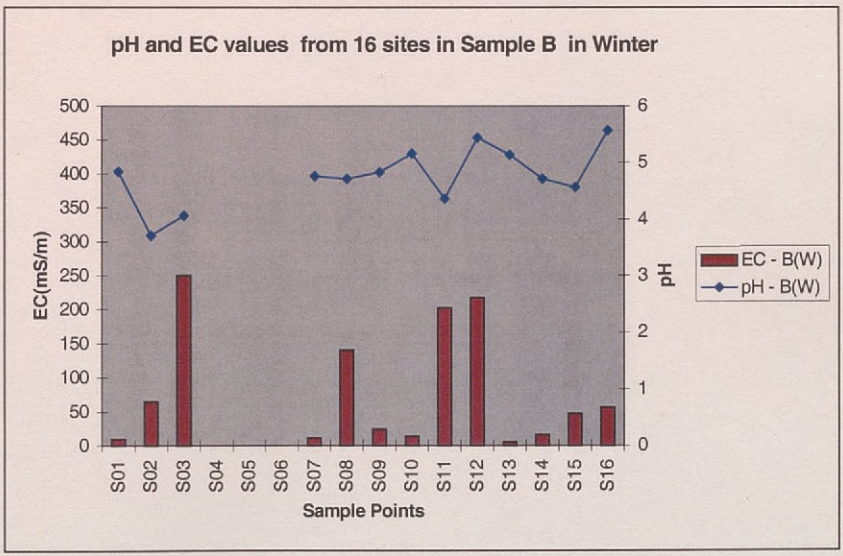


Figure 4.14 pH and EC values of sample B in winter 1998. S04, S05 and S06 were not collected because in these areas, only the top sample (Sample A) existed.

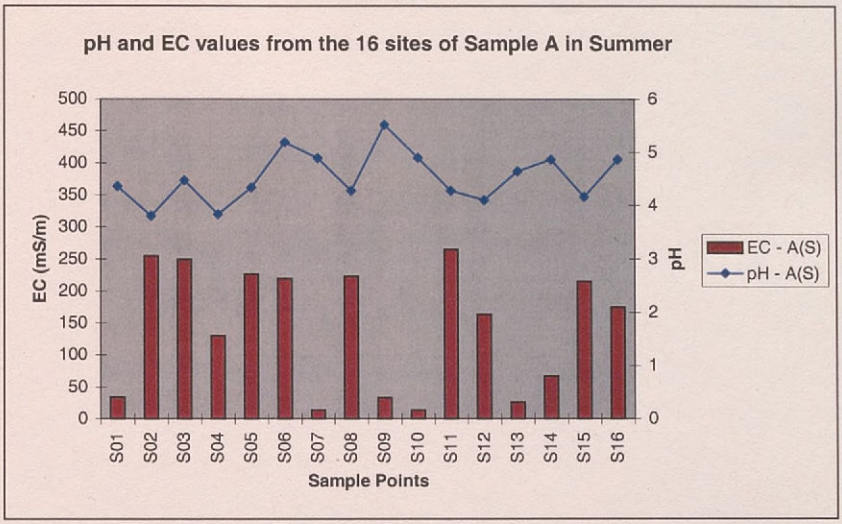


Figure 4.15 pH and EC values of Sample A in summer 1999

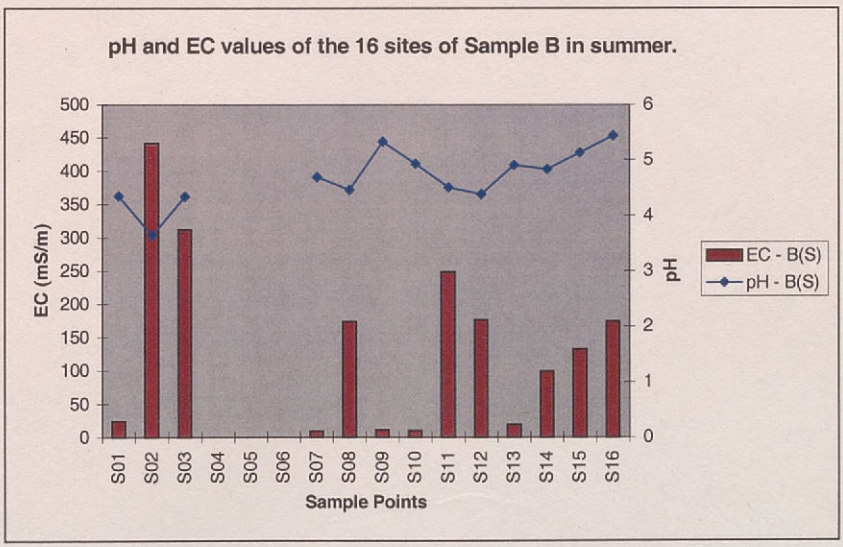


Figure 4.16 pH and EC values of Sample B in summer 1999. S04, S05 and S06 were not collected because in these areas, only the top sample (Sample A) existed.

4.4 SUMMARY

- From observations, the soils in the research area are acidic (pH 3.3 – 5.5) and, from the saturation percentage calculations, have a high tendency towards Al^{3+} toxicity. It was noted that, since the amount of rainfall is not high (Fig 3.18), the chances of Al^{3+} toxicity affecting the Kromdraaispruit system are minimal as there is not sufficient media to promote the movement of the Al^{3+} ions.
- The soils in the Kromdraai area are classified as "normal soils" (Miller & Donahue, 1999).
- The pH values of the soils in summer are lower i.e. more acidic than in winter, because of the rains. This is because rainwater combines with CO_2 in the soil to form carbonic acid. Although carbonic acid is formed, it does not mean that it will affect the water in the system. If that were the case, the ground water in the region would have had a lower pH compared to the measured pH (6-7) in the field.
- From these observations it was concluded that the soils in the region do not affect the streams, i.e. they do not contribute to nor ameliorate acid mine drainage in the Kromdraaispruit system.

CHAPTER 5
GEOSPATIAL ANALYSIS OF KROMDRAAI

5.1 INTRODUCTION

Geospatial analysis in this study was done with the help of geographic information systems. A geographic information system (GIS) is a computer system for managing spatial data, i.e. manipulating maps, digital images and tables of geocoded (geographically located) data items, such as the results of a geochemical survey. GIS are designed to bring together spatial data from diverse sources into a unified database (Bonham-Carter, 1994).

One of the main benefits of using a geographical information system is that data from many different sources can be compared without too much difficulty. The only prerequisite is that all the data should be able to be brought into the system by digitising or by some other means. The ideal application of GIS is in the creation of a database consisting of both graphical and non-graphical data, in which the two types of data are linked. Finally, the numerical abilities of a computer mean that changes in map scale and projection are not difficult to achieve (Silberbauer, 1987 in Boham - Carter, 1994).

GIS is used as a tool in the analysis of environmental impact resulting from human activities on the surface of the earth. Many practical applications of GIS have been implemented and more are still being developed in various development sectors. Some of the most pressing problems of today, like tropical deforestation, the future of the global climate, the need for the ecologically sensitive development of global natural resources, acid rain, and rapid urbanisation are being monitored and managed by GIS technology.

Environmental degradation maps should represent the environmental qualities of different media such as soil, topography, surface water, ground water and vegetation, and should be able to show the distribution of cumulative impacts as well as areas of mixed influences. Maps indicating areas of significant environmental alteration improve our understanding of environmental degradation by providing detailed summaries of

spatial and temporal behaviour of impacts, thereby allowing appropriate responses (Limpitlaw & Fabbri, in press, 1999). This study attempts to address the problems associated with environmental assessment with reference to the impacts arising from AMD in and around the Kromdraaispruit.

Different data sets from different sources are available for this investigation. The thrust of the analysis is to detect change in the environment, to infer a decrease/increase in environmental quality and then to assess the significance of these changes. To this end spatial data from maps, aerial photographs and satellite images have been integrated with conventional quality data collected by the mine. These maps were digitised and taken into ILWIS (Integrated Land and Water Information Systems).

5.2 REMOTE SENSING

One of the methods employed to identify areas of vegetation stress in the ecosystem is the manipulation of Landsat data. Since the area studied was sufficiently large, remotely-sensed data was used to determine the system's response to pollution. Data included Landsat Thematic Mapper (TM), which is capable of high-resolution data acquisition over small areas i.e. using vegetation indices. Through manipulation of this data with a GIS package (ILWIS), areas that were likely sites for acid seeps could be identified.

ILWIS for Windows contains a set of image processing tools for enhancement and analysis of data from spaceborne or airborne platforms. Image enhancement techniques, explained in this chapter, made it possible to modify the appearance of images for optimum visual interpretation.

5.2.1 Remotely Sensed Data.

Remote sensing is the science and act of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (Lillesand & Kiefer, 1994).

Table 5.1 Thematic Mapper Spectral Bands (Lillesand & Kiefer, 1994).

Band	**Wavelength (μm)**	**Nominal Spectral Location**	**Principal Applications**
1	0.45-0.52	Blue	Designed for water body penetration. Also useful for soil/vegetation discrimination, forest type mapping.
2	0.52-0.60	Green	Designed to measure green reflectance peak of vegetation for vegetation discrimination and strength assessment.
3	0.63-0.69	Red	Designed to sense in a chlorophyll absorption region, aiding in plant species differentiation. Also useful for cultural feature identification.
4	0.76-0.90	Near infrared	Useful for determining vegetation strength, and biomass content, for delineating water bodies, and for soil moisture discrimination.
5	1.55-1.75	Mid-infrared	Indicative of vegetation moisture content and soil moisture. Also useful for differentiation of snow from clouds.
6	10.4-12.5	Thermal infrared	Useful in vegetation stress analysis, soil moisture discrimination and thermal mapping applications.
7	2.08-2.35	Mid-infrared	Useful for discrimination of mineral and rock types. Also sensitive to vegetation moisture content.

Remotely sensed data, such as satellite images, are measurements of reflected solar radiation, energy emitted by the earth itself or energy emitted by Radar systems that is reflected by the earth. Satellite remote sensing has brought a new dimension to the understanding, not only of the natural wonders and processes operative on our planet, but also of the impacts of human kind on earth's fragile and inter-connected resource base (Limpitlaw, 1998).

Remotely sensed data of the area of study from the satellite Landsat 5 thematic mapper (TM) was imported into the ILWIS. These were used for the entire study to construct colour composite maps that showed the effect of mining on the areas surrounding Kromdraai. Table 5.1 shows the characteristic applications of the seven TM bands.

5.2.2 Colour Composites

Colour composites are created and displayed on the screen by combining the spectral values of 3 individual bands. Each band is displayed using one of the primary colours. A representation stores the values of red, green and blue. The value of each colour represents the relative intensity in ranges from 0 to 255. Putting the three bands together in one colour composite rather than displaying one band at a time can give a better visual impression of the reality on the ground. There are generally three types of colour composites that are formed by different combinations, some of which are shown in Table 5.2.

1) Natural colour composites use the green, blue and red part of the spectrum. This results in an image with realistic colours (Fig 5.1).
2) Pseudo-colour composites are created with other parts of the spectrum, but the result has natural looking colours.
3) In false colour composites, the colours in the image are not the same as reality e.g. vegetation can be red and urban areas blue (Fig 5.2)

Table 5.2 Colour combinations used to generate six colour composites (Lillesand & Keifer, 1994).

Plate	Blue	Green	Red	Composite (Type)
A	1	2	3	Normal Colour Composite
B	2	3	4	Colour Infrared composite
C	3	4	5	False colour composite
D	3	4	7	False colour composite
E	3	5	7	False colour composite
F	4	5	7	False colour composite



Figure 5.1 Normal colour composite of the Kromdraai wetland (TM321, 06/05/1990). Streams are dark green, roads are light brown.



Figure 5.2 False colour composite of the Kromdraai wetland (TM543, 1990). Vegetation is bright green, roads are pink, and the waterbodies are black

5.2.3 Normalised Difference Vegetation Index

Remotely sensed data is increasingly providing information of use to environmental management, especially in sensitive areas that would be difficult to monitor using conventional techniques, such as wetlands (Welch *et al.*, 1995). Ratio images are often useful for discriminating subtle differences in spectral variations in a scene that is masked by brightness variations. Given the number of spectral bands of the satellite image, different band ratios are possible. The utility of any given ratio depends upon the particular reflectance characteristics of the features involved and the application at hand, e.g. near–infrared /red ratio images might be useful for differentiating between areas of stressed and non-stressed vegetation.

Various mathematical combinations of satellite bands (vegetation indices) have been found to be sensitive indicators of the presence and condition of green vegetation. Two such combinations are;

1) Simple Vegetation Index (V I)
2) Normalised Difference Vegetation Index (NDVI)

Both are based on the reflectance properties of vegetated areas. Vegetated areas have a high reflectance in the near-infrared and a low reflectance in the visible spectrum. Green vegetation has high values for the index, water has negative values and bare soil has near zero indices. The NDVI, as a normalised index, is preferred over the VI because the NDVI also compensates for changes in illumination conditions, surface slopes and aspect. To create an NDVI, Landsat TM imagery was used. The following bands were used; TM band 3 & TM band 4. An NDVI image (Fig.5.3) was generated for the data collected. The figure shows a grey representation of a pseudo colour

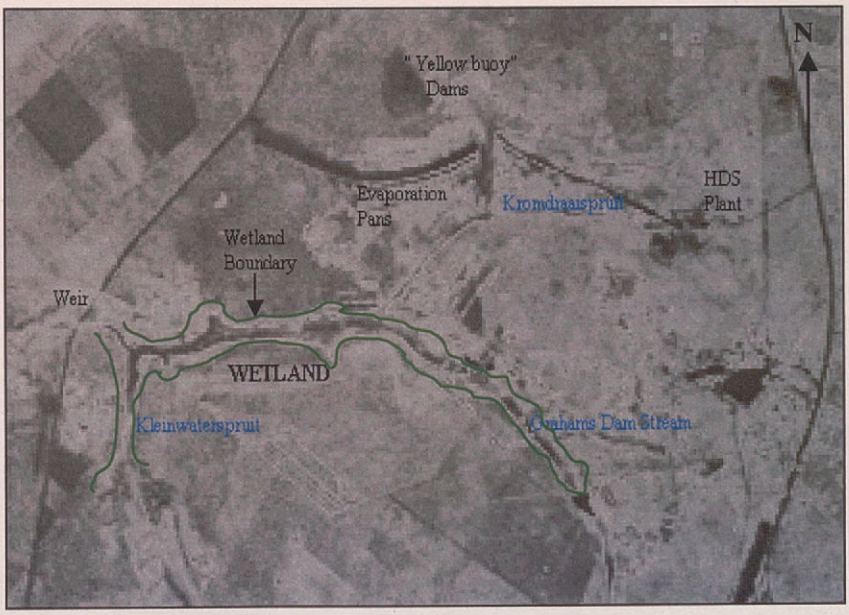


Figure 5.3 Normalised Difference Vegetation Index of the Kromdraai wetland. Grey pseudo colour representation. TM bands 3 and 4 (06/05/1990).

composite of the area around the Kromdraaispruit.

TM data was acquired for the date 06/05/1990. This data represents ground reflectance values of the area. A common method for measuring the presence and condition of green vegetation is NDVI, which is a combination of reflectance in the red and near infrared wavebands received by satellite. Using this combination of bands, vegetation reflects strongly (i.e. has a high digital number, DN, and appears white) and soil, rocks and hard man-made surfaces appear dark (low DN). Vegetation assemblages and plant structures are good indicators of environmental change. In the Kromdraai area (Fig 5.2), agricultural fields, wetland vegetation and natural savannah vegetation appears light grey or white, depending on the density of the foliage. The water bodies, mines and roads appear black, as they are free of vegetation. The green outline demarcates the outline of the vegetation in the wetland i.e. telling us the size of the wetland. The advantage is that if data from different years is collected, an NDVI can help determine whether the wetland is decreasing or increasing in size.

5.3 DIGITAL ELEVATION MODEL OF KROMDRAAI

Digital Elevation Models (DEMS) are digital representations of altitude. This can be the altitude of the terrain surface or the altitude of soil–layers, contact of soil-rock, water table, etc. Digital elevation modelling (DEM) was carried out. From this model both digital streamlines, i.e., what the drainage system is meant to be, and digital pollution plumes were propagated.

A digital elevation model was generated from the contour map of the Witbank area. From the DEM it is possible to start delineating streamline flows. It is then possible to model surface runoff.

The DEM shown here was made by interpolation of contour lines (Fig 5.4). When neither existing DEMs derived from photogrammetric techniques nor detailed point data are available, the contour information on existing topographic maps is the only

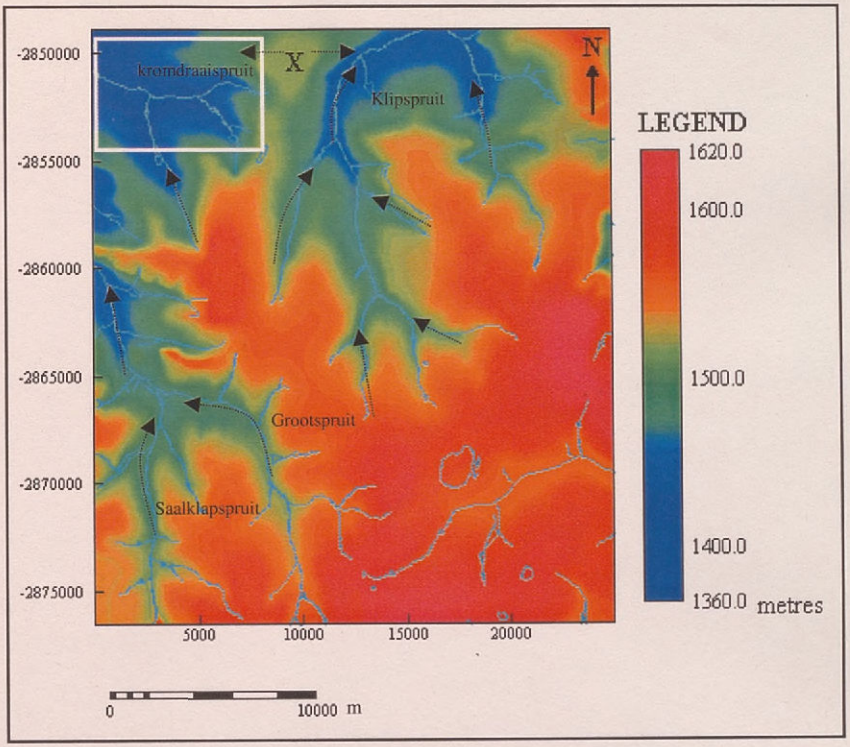


Figure 5.4 DEM of the Witbank area (pseudo representation). Arrows show drainage flow direction.

source from which to generate a DEM. In that case the contour lines are digitised and interpolated. The white rectangle demarcates the study area. In Figure 5.4 it can be seen that the general drainage flow (shown with black dashed arrows) is in a north-westerly direction because the high ground is in the south-eastern side and low ground is in the north-western side. The opencast mine is situated in the area marked with **X**. In this region, which was previously an underground mine, dewatering is being undertaken so as to proceed with the opencast operation. As seen on the DEM, the mine is situated on the watershed, so in addition to potentially polluting the stream to the west in the study area (Kromdraaispruit), it can also potentially pollute another drainage system to the east, the Klipspruit (Fig.5.4).

Some of the developments in remote sensing include improved visualisation by combining multispectral data with DEMs obtained from satellite altimeters. DEMs have many uses. Among the most important are the following (Patrono, 1995);

a) cut and fill problems in civil engineering.
b) for analysis of cross-country visibility.
c) for planning routes of roads, locations of dams etc.
d) for computing slope maps, aspect maps and, slope profiles that can be used to prepare shaded relief maps, assist in geomorphological studies, or eliminate erosion and run-off, outline drainage network, watersheds, etc.
e) provide data for image simulation models of landscapes and landscape processes.

5.4 STATISTICAL GEOSPATIAL ANALYSIS

The statistical package used in geospatial analysis is Eco Spatial Statistical Evaluation (EcoSSe).

Apart from working out correlations, as was demonstrated in Chapter 3, EcoSSe can be used for Kriging from a semi-variogram. A semi-variogram is a graph of difference between sample values versus distance between sample locations. Kriging produces a map that reflects the actual values measured at actual sample locations. This method was determined by D. G. Krige, a South African mining engineer who, in the 1950s, developed empirical methods for determining true ore grade distributions from distributions based on sampled ore grades. This is similar to plotting moving averages in ILWIS but is user-friendly because different maps can be overlaid for comparison.

Looking at the Kriged SO_4^{2-} graph (Fig 5.5), it can be seen that the high SO_4^{2-} concentrations decrease towards the west (downstream). This is an indication that its source is upstream. The lowest concentrations occur in the wetland where there is a high concentration of fresh water springs. This confirms the results obtained earlier in the geochemical analysis (Chapter 3). The same scenario occurs for parameters like TDS, Ca, Fe etc. For pH (Fig. 5.6), it is the opposite. Low pH values are evident upstream

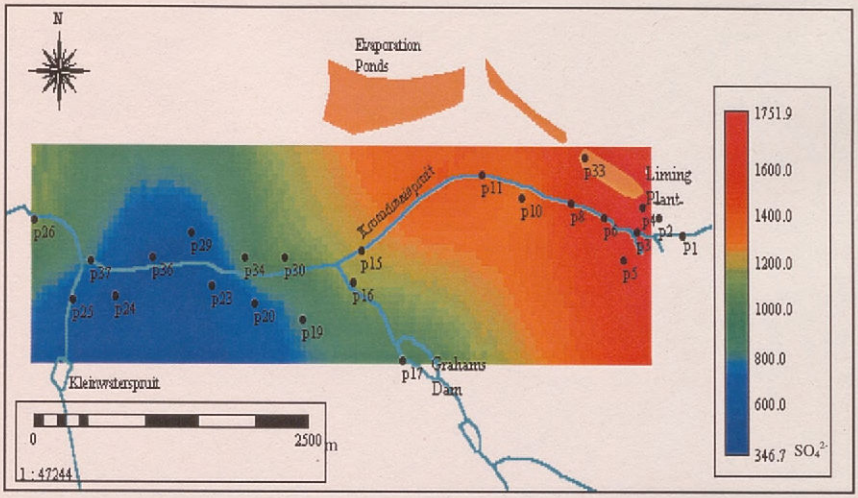


Figure 5.5 Moving averages showing SO_4^{2-} concentration around the Kromdraaispruit.

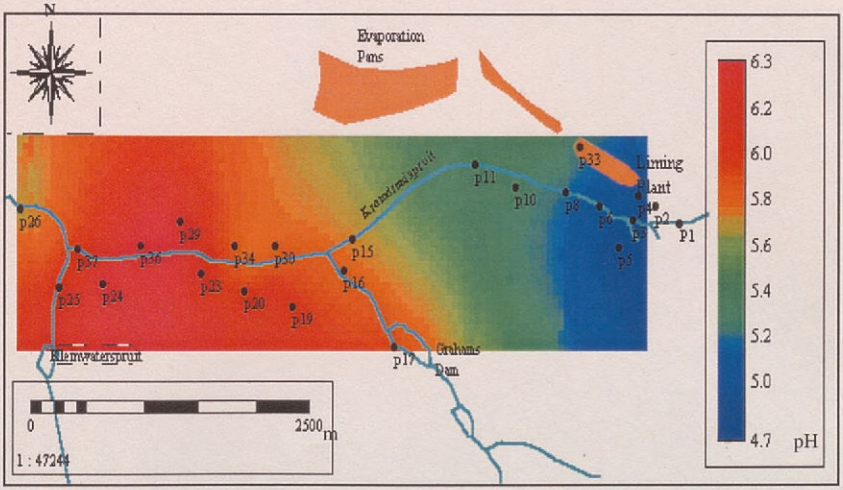


Figure 5.6 Moving averages showing pH around the Kromdraaispruit.

(where the opencast workings and flooded underground workings occur) and along the stream whereas high pH values occur in the wetland region, especially where the springs occur.

5.5 SUMMARY

- From the DEM, it was noted that the mine site and the flooded underground workings are situated on a watershed. The acid mine drainage from that area can potentially affect not only the Kromdraaispruit system but also the Klipspruit system to the east of the Kromdraai mine. Studies should be carried out to find out the rate of flow of the drainage in both directions.

- From the moving averages in figures 5.5 and 5.6, it was noted that the source of pollution in this region occurs upstream where flooded abandoned mines are found. Therefore, the water and seeps in the upper part of the Kromdraaispruit system should be dosed with lime before letting them into the wetland.

CHAPTER 6

CONCLUSION

The water leaving the Kromdraaispruit system has become increasingly polluted since Limpitlaw studied this area in 1995. This is supported by the results of the chemical modelling conducted on samples collected during the study and historical data collected by both the mine and Limpitlaw during his study, "The Assimilative Capacity of the Kromdraaispruit Wetland."

In this study, it was noted that although the amount of salts leaving the liming plant had been drastically decreased to almost a third of the original load, there were determinants like Al^{3+}, SO_4^{2-} and TDS that entered the system with concentrations above permissible amounts. These led to the identification of the pollution sources and their impacts on the water. It was noted that the interception of the acidic seep from the central seepage area caused a dramatic deterioration in pH, from around pH 10 to about pH 4, of the water coming from the liming plant. To eliminate this impact, this seep has to be redirected to the liming plant as has been done at the seepage area near the liming plant. In that case, an automatic pump was installed in the constructed drain around the liming plant. This drain traps the seeps and the pump redirects the acidic water back to the liming plant.

From the geochemical analysis, the Kromdraaispruit wetland was found to improve the quality of water passing through it. For some determinants like Al^{3+}, Ca^{2+}, Mn^{2+}, SO_4^{2-} and TDS, this improvement was not sufficient to comply with current discharge requirements set by the Department of Water Affairs and Forestry and concentrations remained above the maximum permissible limits. It was realised that the amount of water being released into the wetland exceeded its natural assimilative capacity. The high volume created channelised flows in the wetland, and consequently, the water was neither retained nor evenly dispersed in the wetland for longer periods to enable sufficient treatment. The Kromdraaispruit is a valuable passive treatment resource that could continue to treat mine water long after mine closure. In order to realise this resource, effective management of the wetland must be instituted.

Satellite data acquired in 1990 showed unhealthy vegetation in the wetland region. This was due to AMD from the mine. Photographic evidence taken in August 1999, when water had receded, showed the bottom of the wetland coated with yellow buoy (Fig. 3.22). This may have been the result of direct addition of lime to the wetland, an exercise that commenced in June 1999, promoting the formation of iron III hydroxide (yellow buoy). The yellow buoy formed a suspension in the wetland, thus decreasing oxygen intake for both the aquatic life and vegetation. Since the main sinks i.e., containing bacteria that take up the ions are found in the wetland sediments, the yellow buoy suspension may decrease the ionic leaching and decrease the efficiency of the purification process. The continued lime addition to the wetland is going to increase this impact.

The evaporation pans are no longer being utilised so they have dried up. The treated water is now being drained straight into the Kromdraaispruit from the liming plant. The seepage area between the pans and the Kromdraaispruit has also dried, indicating that the seepage used to emanate from the evaporation pans.

From observations, it was noted that the soils in the Kromdraai area are acidic in nature because of the formation of carbonic acid. They have a pH ranging from 3 to 5 and they are susceptible to aluminium toxicity. It was concluded that the soils in the region do not contribute to nor ameliorate acid mine drainage in the area. This is because South Africa is a semi arid region where the amount of rainfall is minimal and the migration of ions like aluminium is slow. Thus seasonal fluctuations have minimal impacts on both the water and soils in the system.

Further Investigations/ Recommendations

Since there is already a system in place, the wetland should be reconstructed by extending it to accommodate the amount of inflow. The inflow should be studied so that the size of wetland can be increased to the size needed to decrease the salts to levels acceptable to the Ministry of Water Affairs and Forestry. An alternative to the extension of the wetland would be the construction of baffles in the channels to allow the dispersal of the water entering the wetland, thus increasing its residence time.

Since the yellow buoy has been detected in the wetland and is decreasing the assimilative efficiency of the sediments, it is recommended that leaching tests should be carried out on it. This will help ascertain if yellow buoy has any impact on, or has the potential to hinder the assimilative process in the wetland.

Further investigations should also be carried out on the soils, i.e. study the leaching capacity and the aluminium toxicity under different environments. This should be done so that mine management is prepared for the consequences of unexpected changes in climate.

APPENDICES

APPENDIX A – WATER SITES

Table A 1 Geographic positions of the water sites

Site	Latitude	Longitude	Description
KDSP 01	25° 46' 34.27"S	29° 04' 55.65"E	Seepage at Liming Plant
KDSP 02	25° 46' 30.76"S	29° 04' 48.85"E	Seepage at Liming Plant
KDSP 03	25° 46' 32.96"S	29° 04' 41.57"E	Seepage at Liming Plant
KDSP 04	25° 46' 23.73"S	29° 04' 41.56"E	HDS (Liming) Plant
KDSP 05	25° 46' 45.27"S	29° 04' 37.21"E	Central Seepage
KDSP 06	25° 46' 29.89"S	29° 04' 31.37"E	Liming Plant Stream
KDSP 08	25° 46' 26.38"S	29° 04' 19.24"E	Liming Plant Stream
KDSP 10	25° 46' 25.51"S	29° 04' 04.19"E	Spring
KDSP 11	25° 46' 20.24"S	29° 04' 50.11"E	Liming Plant Stream
KDSP 15	25° 46' 37.40"S	29° 04' 11.28"E	Liming Plant Stream
KDSP 16	25° 46' 45.31"S	29° 04' 08.86"E	Wetland
KDSP 17	25° 47' 02.89"S	29° 04' 24.89"E	Grahams Dam Stream
KDSP 19	25° 46' 50.59"S	29° 04' 50.90"E	Spring
KDSP 20	25° 46' 49.28"S	29° 04' 35.85"E	Wetland
KDSP 23	25° 46' 45.76"S	29° 04' 21.77"E	Wetland
KDSP 24	25° 46' 47.97"S	29° 04' 49.74"E	Spring
KDSP 25	25° 46' 49.29"S	29° 04' 36.63"E	Kleinwaterspruit
KDSP 26	25° 46' 30.83"S	29° 04' 24.49"E	Kromdraai Weir
KDSP 29	25° 46' 40.06"S	29° 04' 15.95"E	Spring
KDSP 30	25° 46' 40.04"S	29° 04' 46.04"E	Wetland
KDSP 33	25° 46' 16.27"S	29° 04' 24.47"E	Evaporation Ponds
KDSP 34	25° 46' 38.29"S	29° 04' 32.94"E	Wetland
KDSP 36	25° 46' 39.62"S	29° 04' 01.87"E	Wetland
KDSP 37	25° 46' 40.94"S	29° 04' 44.40"E	Wetland

APPENDIX B - WATER DATA
FIELD DATA

Table B1 Water - Field Data 28/08/1998

Site	pH	EC (mS/m)	Eh(mV)
KDSP 01	2.90	164.00	446
KDSP 02	2.73	115.00	518
KDSP 03	2.89	167.00	446
KDSP 04	2.92	24.00	417
KDSP 05	4.59	137.00	471
KDSP 06	4.13	30.00	304
KDSP 07	4.26	130.00	282
KDSP 08	4.47	119.00	280
KDSP 09	4.68	117.00	278
KDSP 10	5.51	10.00	201
KDSP 11	4.36	122.00	278
KDSP 12	4.90	220.00	340
KDSP 13	5.00	229.00	295
KDSP 14	5.15	223.00	298
KDSP 15	5.13	225.00	301
KDSP 16	5.40	225.00	315
KDSP 17	6.60	9.60	283
KDSP 18	6.80	0.50	227
KDSP 19	7.60	0.20	217
KDSP 20	4.90	8.40	142
KDSP 21	4.30	18.00	367
KDSP 22	4.40	12.00	381
KDSP 23	4.30	13.40	348
KDSP 24	6.20	0.20	262
KDSP 25	4.40	16.00	401
KDSP 26	4.30	16.50	359
KDSP 27	2.90	30.50	400
KDSP 28	4.10	15.00	393
KDSP 29	7.70	0.00	223
KDSP 30	5.20	13.00	245
KDSP 31	4.10	20.70	389
KDSP 32	4.60	24.10	321
KDSP 33	7.60	27.40	257
KDSP 34	4.10	19.30	408
KDSP 35	4.40	14.50	374
KDSP 36	4.30	15.50	401
KDSP 37	4.30	16.00	381

Table B2 Water - Field Data 02/10/1998

Site	pH	EC (mS/m)	Eh(mV)
KDSP 01	3.70	24.80	366
KDSP 02	3.10	26.10	474
KDSP 03	3.50	23.90	413
KDSP 04	NS	NS	NS
KDSP 05	3.00	17.50	499
KDSP 06	3.60	27.00	363
KDSP 08	3.60	26.80	368
KDSP 10	6.60	0.20	263
KDSP 11	3.60	26.00	361
KDSP 15	3.50	21.30	371
KDSP 16	3.60	24.00	410
KDSP 17	6.60	9.30	328
KDSP 19	7.40	0.40	124
KDSP 20	4.80	7.50	195
KDSP 23	4.10	12.50	360
KDSP 24	8.00	0.20	262
KDSP 25	7.60	0.70	202
KDSP 26	3.90	19.00	385
KDSP 29	7.00	0.30	162
KDSP 30	3.80	23.00	425
KDSP 31	DRY	DRY	DRY
KDSP 33	7.20	26.00	302
KDSP 34	3.90	23.90	338
KDSP 36	6.50	1.50	113
KDSP 37	3.80	18.40	427

Table B3 Water - Field Data 10/11/1998

Site	pH	EC (mS/m)	Eh (mV)
KDSP 01	3.50	28..7	403
KDSP 02	3.40	24.30	491
KDSP 03	3.60	28.20	390
KDSP 04	7.00	22.40	152
KDSP 05	3.20	15.70	476
KDSP 06	4.40	22.20	280
KDSP 08	4.60	21.60	266
KDSP 10	6.00	0.20	228
KDSP 11	4.70	22.00	261
KDSP 15	4.50	22.10	268
KDSP 16	6.10	24.50	62
KDSP 17	7.40	8.50	155
KDSP 19	7.70	0.50	-35
KDSP 20	6.80	10.80	200
KDSP 23	4.60	15.60	354
KDSP 24	7.60	0.30	245
KDSP 25	7.70	0.90	208
KDSP 26	4.10	19.90	390
KDSP 29	6.10	0.30	142
KDSP 30	3.90	24.00	425
KDSP 31	DRY	DRY	DRY
KDSP 33	4.60	24.70	354
KDSP 34	3.70	24.10	367
KDSP 36	4.30	15.20	407
KDSP 37	3.90	20.00	380

Table B4 Water - Field Data 21/01/1999

Site	pH	EC (mS/m)	Eh (mV)
KDSP 01	4.90	25.60	501
KDSP 02	4.29	14.30	458
KDSP 03	4.16	16.70	472
KDSP 04	11.23	17.60	180
KDSP 05	3.94	14.00	497
KDSP 06	5.34	12.80	317
KDSP 08	5.33	97.70	300
KDSP 10	7.21	0.00	289
KDSP 11	5.33	13.90	306
KDSP 15	5.28	15.50	290
KDSP 16	5.40	17.80	186
KDSP 17	7.04	8.20	43
KDSP 19	6.42	1.00	276
KDSP 20	5.19	12.90	305
KDSP 23	5.04	13.90	142
KDSP 24	7.15	0.00	245
KDSP 25	6.53	8.00	165
KDSP 26	4.58	15.80	433
KDSP 29	7.20	0.00	192
KDSP 30	4.49	18.50	455
KDSP 31	DRY	DRY	DRY
KDSP 33	5.18	13.60	423
KDSP 34	4.34	22.80	494
KDSP 36	7.04	0.00	126
KDSP 37	4.68	16.50	495

Table B5 Water - Field Data 23/02/1999 (Eh not sampled due to calibration problems with the Eh meter).

Site	pH	EC (mS/m)	Eh (mV)
KDSP 01	4.43	28.10	-
KDSP 02	4.20	21.40	-
KDSP 03	4.12	21.60	-
KDSP 04	7.86	26.70	-
KDSP 05	3.73	15.00	-
KDSP 06	4.32	26.40	-
KDSP 08	4.66	26.60	-
KDSP 10	5.37	1.00	-
KDSP 11	5.10	23.00	-
KDSP 15	5.10	23.70	-
KDSP 16	5.30	22.80	-
KDSP 17	6.90	0.70	-
KDSP 19	6.80	1.00	-
KDSP 20	5.40	19.00	-
KDSP 23	5.20	19.00	-
KDSP 24	7.64	0.00	-
KDSP 25	7.48	17.60	-
KDSP 26	4.52	21.00	-
KDSP 29	DRY	DRY	-
KDSP 30	4.50	27.00	-
KDSP 31	DRY	DRY	-
KDSP 33	5.16	22.00	-
KDSP 34	4.60	25.00	-
KDSP 36	7.26	0.00	-
KDSP 37	4.51	21.00	-

Table B6 Water - Field Data 23/03/1999

Site	pH	EC (mS/m)	Eh (mV)
KDSP 01	2.90	24.10	477
KDSP 02	2.98	30.10	433
KDSP 03	2.91	28.10	442
KDSP 04	9.44	1.79	135
KDSP 05	2.64	9.60	438
KDSP 06	4.20	18.70	411
KDSP 08	4.22	18.60	310
KDSP 10	5.66	0.20	242
KDSP 11	4.24	18.20	278
KDSP 15	3.87	18.60	300
KDSP 16	6.76	6.70	207
KDSP 17	4.39	6.40	244
KDSP 19	5.46	0.00	245
KDSP 20	4.05	19.00	300
KDSP 23	4.05	19.00	390
KDSP 24	5.54	0.50	234
KDSP 25	6.50	0.40	176
KDSP 26	3.39	12.00	340
KDSP 29	DRY	DRY	DRY
KDSP 30	3.50	27.20	419
KDSP 31	DRY	DRY	DRY
KDSP 33	4.16	24.80	333
KDSP 34	3.60	27.30	333
KDSP 36	6.06	1.00	240
KDSP 37	3.60	23.00	410

Table B7 Water - Field Data 21/04/1999

Site	pH	EC (mS/m)	Eh (mV)
KDSP 01	3.05	28.20	428
KDSP 02	2.85	26.90	522
KDSP 03	2.97	28.20	443
KDSP 04	8.36	20.10	228
KDSP 05	3.01	18.60	417
KDSP 06	4.35	22.60	270
KDSP 08	4.39	22.50	254
KDSP 10	5.76	0.10	194
KDSP 11	4.36	25.60	225
KDSP 15	4.61	23.90	235
KDSP 16	4.55	24.00	90
KDSP 17	5.63	11.60	186
KDSP 19	7.60	0.00	197
KDSP 20	4.63	17.00	333
KDSP 23	5.06	17.00	258
KDSP 24	7.48	0.00	208
KDSP 25	7.30	0.30	154
KDSP 26	3.99	21.70	386
KDSP 29	DRY	DRY	DRY
KDSP 30	3.73	23.40	364
KDSP 31	DRY	DRY	DRY
KDSP 33	4.56	25.30	323
KDSP 34	3.71	23.70	406
KDSP 36	4.89	1.00	286
KDSP 37	4.01	22.00	247

Table B8 Water - Field Data 25/05/1999

Site	pH	EC (mS/m)	Eh (mV)
KDSP 01	3.87	25.00	410
KDSP 02	3.79	25.00	413
KDSP 03	3.78	25.30	413
KDSP 04	7.90	23.80	231
KDSP 05	3.85	15.40	471
KDSP 06	4.61	35.00	264
KDSP 08	5.06	27.80	262
KDSP 10	5.47	2.00	243
KDSP 11	5.00	24.80	288
KDSP 15	5.11	30.80	252
KDSP 16	6.13	15.30	189
KDSP 17	6.43	8.80	187
KDSP 19	7.05	0.00	164
KDSP 20	5.01	11.00	228
KDSP 23	5.45	4.00	238
KDSP 24	7.13	0.00	180
KDSP 25	6.94	2.00	155
KDSP 26	4.89	13.00	255
KDSP 29	6.64	0.70	169
KDSP 30	4.79	24.90	248
KDSP 31	DRY	DRY	DRY
KDSP 33	5.11	21.00	238
KDSP 34	4.79	24.90	388
KDSP 36	7.18	1.20	214
KDSP 37	4.79	15.30	314

Table B9 Water - Field Data 22/06/1999

Site	pH	EC (mS/m)	Eh (mV)
KDSP 01	3.22	25.20	409
KDSP 02	3.23	24.80	412
KDSP 03	3.22	25.20	411
KDSP 04	8.75	18.00	280
KDSP 05	3.35	15.50	477
KDSP 06	4.84	20.00	294
KDSP 08	4.98	20.00	252
KDSP 10	7.67	1.00	217
KDSP 11	4.84	20.00	245
KDSP 15	5.09	20.40	253
KDSP 16	4.80	21.00	285
KDSP 17	6.61	10.10	244
KDSP 19	6.25	1.00	285
KDSP 20	6.25	7.00	287
KDSP 23	6.60	4.00	275
KDSP 24	6.30	0.00	250
KDSP 25	6.60	1.00	281
KDSP 26	4.70	14.00	360
KDSP 29	6.22	15.00	245
KDSP 30	3.87	22.60	372
KDSP 31	DRY	DRY	DRY
KDSP 33	4.40	21.70	335
KDSP 34	4.52	20.10	335
KDSP 36	5.90	1.00	301
KDSP 37	4.90	15.00	400

Table B10 Water - Field Data 27/07/1999

Site	pH	EC (mS/m)	Eh (mV)
KDSP 01	4.69	25.40	325
KDSP 02	4.57	23.40	334
KDSP 03	4.55	19.50	349
KDSP 04	7.09	23.10	256
KDSP 05	3.35	14.10	397
KDSP 06	4.81	26.30	298
KDSP 08	4.47	22.00	248
KDSP 10	7.01	2.00	198
KDSP 11	4.47	25.30	243
KDSP 15	5.71	23.90	172
KDSP 16	5.80	17.80	192
KDSP 17	6.37	10.30	154
KDSP 19	7.02	1.00	190
KDSP 20	5.47	19.00	279
KDSP 23	5.95	10.00	281
KDSP 24	6.96	0.00	156
KDSP 25	6.62	0.00	162
KDSP 26	5.69	18.00	273
KDSP 29	7.01	0.10	196
KDSP 30	5.20	23.80	289
KDSP 31	DRY	DRY	DRY
KDSP 33	5.66	21.00	289
KDSP 34	4.28	21.00	265
KDSP 36	5.00	1.00	253
KDSP 37	5.60	12.50	216

Table B11 Water - Field Data 31/08/1999 (some of the sample not collected because access to that area was denied by the farmer).

Site	pH	EC (mS/m)	Eh (mV)
KDSP 01	4.72	24.60	258
KDSP 02	4.68	26.60	408
KDSP 03	4.63	25.50	417
KDSP 04	10.40	17.80	333
KDSP 05	4.57	27.30	400
KDSP 06	6.26	11.50	148
KDSP 08	5.75	11.05	111
KDSP 10	7.00	1.00	160
KDSP 11	5.19	19.30	211
KDSP 15	5.37	19.80	256
KDSP 16	5.74	18.00	105
KDSP 17	6.13	10.00	16
KDSP 19	NS	NS	NS
KDSP 20	NS	NS	NS
KDSP 23	NS	NS	NS
KDSP 24	6.60	0.00	123
KDSP 25	6.51	0.00	100
KDSP 26	5.19	17.20	143
KDSP 29	NS	NS	NS
KDSP 30	NS	NS	NS
KDSP 31	DRY	DRY	DRY
KDSP 33	DRY	DRY	DRY
KDSP 34	NS	NS	NS
KDSP 36	NS	NS	NS
KDSP 37	NS	NS	NS

NS –Not Sampled

APPENDIX C – WATER DATA
LABORATORY DATA.

Table C 1 Water Laboratory Data 28/08/1998 (laboratory – ACCL)

Site	pH	EC	SS	TDS	T-Alk	Acidity	Chloride	Sulphate	Nitrate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	3.2	220	194	3926	0	1578	50	2122	0.9	135.15	49.14	11.94	8.29	28.93	14.94	263.37
KDSP02	3.1	199	100	3394	0	1398	50	1883	2.4	115.56	42.11	15.75	7.70	2.47	10.76	254.59
KDSP03	3.1	221	170	3846	0	1508	50	2157	1.0	175.90	51.51	13.20	9.03	34.88	14.98	254.49
KDSP04	3.1	207	169	2133	0	1588	30	2214	1.5	581.40	51.82	12.42	11.63	0.01	4.37	0.01
KDSP06	4.6	216	220	2137	0	252	6	1715	1.0	440.98	47.44	13.58	12.73	0.09	3.36	6.57
KDSP07	4.6	221	157		0	230	4	1718	0.9							
KDSP08	4.6	208	190	2141	0	222	4	1658	1.1	469.23	44.76	14.06	12.78	0.05	3.08	6.32
KDSP09	4.7	217	205		0	188	6	1737	1.2							
KDSP10	6.0	7	25	109	4	2	8	35	0.6	0.55	0.18	6.80	1.59	0.04	0.01	0.01
KDSP11	4.6	209	208	2148	0	204	4	1671	0.7	358.73	33.63	7.92	6.35	21.21	11.35	142.90
KDSP12	4.6	197	175		0	190	8	1594	1.0							
KDSP13	4.6	174	181		0	172	8	1548	0.9							
KDSP14	1.8	176	169		0	70	6	1477	0.8							
KDSP15	4.8	201	173	2200	0	86	6	1534	0.7	506.08	44.49	12.96	12.69	0.05	3.65	7.55
KDSP16	4.6	199	166	2422	0	120	8	1493	0.8	541.54	48.50	13.51	3.57	0.07	8.64	1.64
KDSP17	6.3	80	17	639	20	2	6	525	0.6	162.28	7.95	8.34	0.71	0.02	0.00	0.08
KDSP18	5.7	43	5238		84	6	40	35	0.8							
KDSP19	6.3	18	122	108	4	2	6	45	0.5	2.68	1.53	9.71	3.56	0.87	0.32	0.06
KDSP20	4.4	66	28	932	0	12	8	453	1.2	218.64	10.04	9.14	0.61	0.03	1.08	1.76
KDSP21	3.8	103	36	1283	0	30	8	716	2.2							
KDSP22	4.0	101	68		0	30	8	689	0.2							
KDSP23	3.9	113	43	1283	0	36	6	817	1.9	318.46	13.88	10.83	1.31	0.19	1.40	3.85
KDSP24	6.4	3	479	49	4	2	6	26	0.6	0.82	0.34	7.04	0.27	0.02	0.00	0.07
KDSP25	3.9	136	46	89	0	48	6	980	1.1	3.02	1.68	9.12	1.44	0.24	0.01	0.28
KDSP26	3.8	149	46	1826	0	50	6	1059	1.3	437.24	18.09	12.18	2.07	0.11	2.98	7.97
KDSP27	2.5	162	21		0	700	40	838	0.4							
KDSP28	4.7	138	97		0	50	8	1049	1.2							
KDSP29	6.5	4	226	56	10	2	6	25	0.3	1.38	0.38	6.92	1.02	2.14	0.03	0.23
KDSP30	5.7	107	8693	2323	8	20	6	790	0.3							
KDSP31	3.8	168	51		0	330	12	1431	0.4							
KDSP32	4.3	193	162	2582	0	158	6	1622	2.0	655.92	17.01	11.33	3.45	0.07	5.25	17.84
KDSP33	6.8	228	62	2519	12	10	6	1842	1.9	699.12	14.67	12.59	4.96	0.07	2.10	2.28

Table C 2 Water Laboratory Data 02/10/1998 (Laboratory - ACCL).

Site	pH	EC	SS	TDS	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	3.6	248	683	3363	1474	0	50	2186	151.11	41.96	6.74	5.26	2.05	13.22	265.51
KDSP02	3	258	137	3473	1710	0	100	2307	98.76	34.76	10.39	5.02	9.59	8.97	308.4
KDSP03	3.2	244	542	3170	1440	0	90	2178	131.36	37.96	7.43	4.77	5.83	11.19	267.03
KDSP05	2.8	174	101	1873	988	0	50	1260	43.71	16.86	9.78	2.63	6.71	8.79	172.66
KDSP06	4.3	434	150	3532	1326	0	50	2209	307.78	33.17	8.88	6.08	46.25	11.29	175.09
KDSP08	3.3	270	193	3255	1122	0	40	2060	355.05	35.02	8.02	6.33	29.42	12.23	159.31
KDSP10	5.8	9	27	111	14	2	6	74	1.85	0.01	1.16	0.31	0.01	0.01	0.27
KDSP11	3.3	264	200	3103	960	0	50	1460	358.73	33.63	7.92	6.35	21.21	11.35	142.9
KDSP15	3.4	220	72	2766	254	0	24	1966	439.16	18.85	7.02	5.37	0.08	5.44	49.34
KDSP16	3.5	242	251	2394	330	0	22	1673	502.9	29.39	8.81	6.53	0.01	8.18	60.29
KDSP17	6.7	96	31	728	4	28	8	489	187.17	10.86	5.16	4.98	0.01	0.01	0.01
KDSP19	5.9	7	123	74	2	2	8	42	2.77	0.01	2.18	1.37	0.01	0.01	0.01
KDSP20	4.3	70	27	501	8	0	8	372	131.59	6.71	5.46	2.8	0.01	0.89	0.19
KDSP23	3.7	128	50	1051	30	0	10	729	263.87	13.01	7.51	5.34	0.01	2.02	2.56
KDSP24	5.6	4	12	43	2	2	6	24	2.13	0.05	2.26	0.01	0.01	0.01	0.01
KDSP25	5.8	7	45	77	4	10	16	33	2.44	0.01	4.91	1.65	0.01	0.01	0.01
KDSP26	3.6	188	30	1771	56	0	12	1176	450.81	22.8	8.71	8.84	0.01	4.9	6.14
KDSP29	6.3	8	7649	73	4	4	8	36	8	0.86	2.1	2.51	15.07	0.01	0.01
KDSP30	3.6	227	54	2313	212	0	10	1550	499.08	24.1	7.57	6.79	0.01	7.34	29.5
KDSP33	7	260	123	2664	4	14	10	1779	700.99	6.11	4.18	3.72	0.01	0.14	0.01
KDSP34	3.8	239	126	2492	184	0	10	1631	582.36	24.98	8.22	9.77	0.01	8.8	29.44
KDSP36	5	25	10	165	2	2	8	99	18.85	0.65	4.06	1.66	0.01	0.01	0.01
KDSP37	3.9	184	92	1682	60	0	10	1176	386.01	23.21	7.38	7.44	0.01	4.33	5.09

Table C 3 Water Laboratory Data 10/11/1998 (Laboratory - ACCL).

Site	pH	EC	S.S	TDS	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	3.0	290	176	3926	0	2320	40	2558	135.15	49.14	11.94	8.29	28.93	14.94	263.37
KDSP02	3.3	242	1162	3394	0	1798	160	2100	115.56	42.11	15.75	7.70	2.47	10.76	254.59
KDSP03	3.1	302	741	3846	0	2540	140	2503	175.90	51.51	13.20	9.03	34.88	14.98	254.49
KDSP04	5.6	225	94	2133	12	4	8	1426	581.40	51.82	12.42	11.63	0.01	4.37	0.01
KDSP05	3.2	151	57	1750	0	976	60	1146	48.56	22.32	16.28	3.89	5.70	9.02	134.77
KDSP06	4.4	223	129	2137	0	88	6	1462	440.98	47.44	13.58	12.73	0.09	3.36	6.57
KDSP08	4.4	224	118	2141	0	72	6	1535	469.23	44.76	14.06	12.78	0.05	3.08	6.32
KDSP10	5.3	7	32	109	8	2	2	80	0.55	0.18	6.80	1.59	0.04	0.01	0.01
KDSP11	4.6	224	127	2148	0	70	4	1534	358.73	33.63	7.92	6.35	21.21	11.35	142.90
KDSP15	4.2	222	196	2200	0	72	8	1471	506.08	44.49	12.96	12.69	0.05	3.65	7.55
KDSP16	4.8	261	1086	2422	0	220	60	1685	541.54	48.5	13.51	3.57	0.07	8.64	1.64
KDSP17	6.3	84	14	639	44	14	4	456	162.28	7.95	8.34	0.71	0.02	0.00	0.08
KDSP19	5.8	10	24361	108	96	76	4	33	2.68	1.53	9.71	3.56	0.87	0.32	0.06
KDSP20	4.6	108	25	932	0	26	4	638	218.64	10.04	9.14	0.61	0.03	1.08	1.76
KDSP23	4.0	148	39	1283	0	56	2	925	318.46	13.88	10.83	1.31	0.19	1.40	3.85
KDSP24	5.1	6	26	49	6	8	8	3	0.82	0.34	7.04	0.27	0.02	0.00	0.07
KDSP25	5.8	8	5	89	12	6	10	52	3.02	1.68	9.12	1.44	0.24	0.01	0.28
KDSP26	3.9	189	66	1826	0	92	14	1261	437.24	18.09	12.18	2.07	0.11	2.98	7.97
KDSP29	5.5	6	94	56	10	10	4	23	1.38	0.38	6.92	1.02	2.14	0.03	0.23
KDSP30	3.9	236	90	2323	0	90	4	1562	604.76	37.65	11.31	6.92	0.22	5.86	8.72
KDSP32	4.1	249	44	2528	0	158	4	1688	655.92	17.01	11.33	3.45	0.07	5.25	17.84
KDSP33	4.5	245	45	2519	0	34	6	1638	699.12	14.67	12.59	4.96	0.07	2.10	2.28
KDSP34	3.9	238	57	2326	0	100	4	1597	607.05	34.47	11.20	6.29	0.08	5.47	9.25
KDSP36	3.9	149	22	1269	0	42	4	893	333.77	14.29	10.43	0.96	0.35	3.16	2.48
KDSP37	3.7	198	49	1916	0	90	8	1271	481.34	17.75	10.16	1.31	0.36	2.81	6.64

Table C 4 Water Laboratory Data 21/01/1999 (Laboratory - ACCL).

Site	pH	EC	S.S	TDS	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	3.0	246	15	3180	0	1532	20	2073	118.18	27.16	17.58	5.73	40.64	12.60	169.33
KDSP02	3.2	138	17	1477	0	688	28	992	53.31	16.39	16.27	5.01	1.97	8.60	84.20
KDSP03	3.2	180	101	2065	0	984	20	1388	82.29	23.42	16.80	5.67	6.88	9.70	111.03
KDSP04	10.9	143	12	1440	4	0	2	918	378.90	0.65	16.30	4.86	0.90	0.02	4.25
KDSP05	3.1	119	9	1440	0	684	8	927	40.12	12.56	19.65	5.36	4.20	7.13	87.93
KDSP06	4.6	157	11	1634	0	116	4	1071	384.57	4.54	16.01	4.39	2.60	1.08	13.76
KDSP08	4.6	166	8	1671	0	114	4	1113	393.54	5.73	17.16	4.64	8.65	1.34	13.72
KDSP10	5.9	36	41	50	6	2	2	17	0.59	0.41	12.69	3.14	0.07	0.01	0.13
KDSP11	4.6	159	36	1654	0	116	4	1116	421.48	5.98	17.46	4.91	3.83	1.57	14.83
KDSP15	4.1	151	189	1526	0	152	6	977	276.46	25.89	18.86	9.30	0.04	12.22	17.58
KDSP16	4.4	170	14304	1708	0	70	6	1141	226.22	88.57	26.53	13.51	0.13	3.84	6.80
KDSP17	6.8	75	5	652	56	2	2	399	133.75	7.06	16.33	4.05	0.04	0.01	0.01
KDSP19	5.6	101	9	96	2	4	6	30	1.71	0.78	15.00	6.24	0.12	0.01	0.14
KDSP20	3.9	114	9	1093	0	32	2	726	243.99	11.08	16.89	4.91	0.00	1.82	2.86
KDSP23	5.8	30	6	18	4	2	7	9	0.63	0.25	13.31	3.22	0.03	0.01	0.07
KDSP24	4.0	126	11	1211	0	60	2	803	249.37	10.90	16.15	3.83	0.08	1.86	6.06
KDSP25	6.3	83	16	67	16	2	4	9	3.04	1.78	14.25	4.19	0.51	0.01	0.11
KDSP26	3.5	142	8	1439	0	70	6	876	288.27	12.36	16.41	3.74	0.15	2.55	7.04
KDSP29	5.7	47	7	57	10	2	2	21	0.41	0.13	12.98	3.42	0.26	0.01	0.28
KDSP30	3.5	164	4	1694	0	170	6	1078	300.63	10.18	16.63	7.44	0.40	2.97	20.92
KDSP32	Dry							Dry							Dry
KDSP33	4.1	127	39	1163	0	26	4	761	246.41	8.96	17.69	4.19	0.12	1.56	3.20
KDSP34	3.3	208	6	2218	0	146	6	1368	405.92	16.37	18.62	9.99	0.82	4.36	15.51
KDSP36	5.8	54	250	58	10	2	4	16	1.13	0.41	13.37	3.24	1.46	0.01	0.06
KDSP37	3.6	150	383	1523	0	96	4	158	52.03	23.39	21.03	3.95	0.01	2.08	1.48

Table C 5 Water Laboratory Data 23/02/1999 (Laboratory - ACCL).

Site	pH	EC	S.S	TDS	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	2.9	277.0	4	3581	0	1874	20	2322	73.20	25.73	17.44	4.47	40.48	7.43	118.39
KDSP02	2.9	204.0	3	2331	0	1110	20	1514	71.11	25.73	17.44	4.47	40.48	7.43	118.39
KDSP03	3.0	208.0	3	2371	0	1110	20	1523	71.11	22.92	15.44	4.07	40.42	7.40	118.05
KDSP04	8.2	234.0	2	2635	22	6	2	1774	580.90	14.33	19.40	3.13	0.01	0.12	2.25
KDSP05	3.2	137.0	566	1614	0	806	392	1087	32.27	13.20	17.18	2.66	10.96	7.49	97.41
KDSP06	4.0	241.0	24	2651	0	134	2	1808	535.40	15.19	18.44	4.49	14.37	1.03	8.15
KDSP08	4.3	243.0	28	2630	0	112	4	1751	513.20	12.57	16.38	3.12	13.36	0.91	7.42
KDSP10	6.8	53.6	3	47	4	4	4	28	3.63	1.63	14.56	1.35	0.07	0.01	0.17
KDSP11	4.4	238.0	8	2612	0	108	4	1804	509.05	13.19	21.15	3.12	11.05	0.94	7.38
KDSP15	4.2	236.0	9	2589	0	80	6	1758	540.82	15.24	19.57	3.28	2.50	0.94	7.29
KDSP16	4.3	248.0	1052	2583	0	88	2	1825	570.13	15.54	18.04	3.27	0.01	1.03	8.41
KDSP17	7.3	102.0	3	840	0	10	2	593	179.54	10.72	17.31	1.35	0.03	0.03	0.56
KDSP19	5.6	54.1	1146	39	4	4	6	28	12.47	4.24	16.18	1.84	0.17	0.01	0.44
KDSP20	4.0	177.0	5	2020	0	64	2	1250	366.16	13.71	16.82	0.60	0.08	1.55	8.20
KDSP23	3.8	179.0	620	1782	0	90	6	1276	372.24	18.39	23.48	3.53	0.09	1.87	7.63
KDSP24	6.4	28.7	2	18	4	2	2	60	7.13	2.82	19.33	0.63	0.01	0.01	0.03
KDSP25	7.3	41.8	3	31	18	2	2	43	4.98	4.11	14.63	0.30	1.26	0.01	0.25
KDSP26	3.6	163.0	3	1649	0	98	6	1280	322.12	20.35	19.06	0.86	0.58	2.71	7.41
KDSP29	Dry						Dry								Dry
KDSP30	3.6	238.0	684	2672	0	150	4	1770	522.54	12.35	21.42	2.72	0.09	1.80	13.12
KDSP32	Dry						Dry								Dry
KDSP33	4.0	208.0	6	2204	0	62	4	1532	445.73	13.02	17.37	0.91	0.01	2.26	5.51
KDSP34	3.6	234.0	204	2502	0	154	4	1717	484.17	13.41	16.53	3.66	0.33	12.90	13.76
KDSP36	6.4	59.0	3148	45	12	16	2	35	2.31	0.69	13.03	0.41	1.12	0.01	0.04
KDSP37	3.6	185.0	194	2065	12	120	2	1431	385.36	14.94	15.56	2.14	0.21	2.70	9.75

Table C 6 Water Laboratory Data 23/08/1999 (Laboratory - ACCL)(SS & TDS were not determined by the labs).

Site	pH	EC	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	2.8	195	0	1264	30	1814	111.32	32.72	16.97	5.74	26.23	11.23	149.74
KDSP02	2.8	278	0	1946	40	2589	115.95	34.87	14.48	4.33	134.62	16.27	231.42
KDSP03	2.8	268	0	1734	30	2362	107.24	13.37	14.69	4.53	93.05	14.23	201.98
KDSP04	11.1	156	42	0	4	1122	461.28	0.59	12.88	2.26	0.01	0.01	1.53
KDSP05	3.0	133	0	844	110	1099	38.31	14.81	15.80	2.93	12.86	9.21	107.43
KDSP06	4.6	274	0	114	2	2210	847.12	18.17	13.37	2.86	2.54	1.36	18.92
KDSP08	4.6	263	0	122	6	2128	880.54	18.95	13.30	2.68	2.53	1.54	17.84
KDSP10	5.8	65	4	2	4	13	0.46	0.13	11.28	0.81	0.15	0.01	0.01
KDSP11	4.5	246	0	116	4	2120	996.26	20.85	13.52	3.05	0.86	1.83	20.11
KDSP15	3.8	264	0	130	6	2136	1061.72	23.82	13.65	3.11	0.16	2.71	19.74
KDSP16	6.6	98	64	2	4	555	320.10	12.60	14.29	4.35	0.10	0.03	0.01
KDSP17	6.9	97	62	4	6	593	362.65	12.79	13.69	2.03	0.14	0.01	0.01
KDSP19	5.7	40	2	2	4	7	0.90	0.34	11.52	0.30	0.30	0.03	0.47
KDSP20	4.0	180	0	56	6	1306	763.12	16.94	14.44	4.09	0.28	1.72	7.85
KDSP23	3.9	191	0	56	4	1277	812.94	19.49	16.02	3.63	0.28	2.13	8.22
KDSP24	5.6	61	2	2	2	5	0.84	0.25	11.64	0.21	0.13	0.01	0.01
KDSP25	6.2	77	14	2	8	19	4.20	1.71	13.42	0.56	0.60	0.01	0.01
KDSP26	3.6	182	0	76	6	5394	833.51	19.73	15.08	4.75	0.60	3.54	11.10
KDSP29	Dry						Dry						Dry
KDSP30	3.4	260	0	126	6	1930	1385.99	22.03	14.13	3.03	1.39	4.20	18.85
KDSP32	Dry						Dry						Dry
KDSP33	3.8	237	0	76	6	1737	1289.62	27.30	18.06	3.88	0.24	7.50	10.95
KDSP34	3.4	253	0	108	4	1873	1329.31	22.36	14.24	3.57	1.00	5.05	17.07
KDSP36	5.9	97	14	4	2	9	1.77	0.22	12.19	0.46	1.68	0.01	0.01
KDSP37	3.5	205	0	80	6	1466	1065.15	21.46	15.22	4.32	0.54	4.22	12.87

Table C 7 Water Laboratory Data 21/04/1999 (Laboratory - ACCL).

Site	pH	EC	S.S	TDS	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	3.1	218.3	135	3556	0	1738	140	2351	135.60	38.15	24.74	5.00	77.02	15.84	236.13
KDSP02	2.8	217.3	111	2853	0	1364	80	1898	106.23	33.70	26.93	7.03	59.13	13.95	234.21
KDSP03	3.0	206.2	116	3255	0	1552	80	2184	136.39	37.84	25.67	5.91	78.80	16.06	273.87
KDSP04	7.8	162.7	73	1972	48	2	4	1294	675.10	3.30	24.47	5.74	0.22	0.02	6.45
KDSP05	3.0	147.2	521	2236	0	1036	60	1381	58.09	19.68	27.11	3.58	28.36	13.16	198.11
KDSP06	4.4	173.9	145	2221	0	178	60	1446	675.45	7.86	25.18	5.36	0.26	1.54	26.43
KDSP08	4.4	175.7	142	2265	0	144	40	1490	679.07	8.41	24.95	5.20	0.33	1.76	25.12
KDSP10	6.1	31.3	4	27	4	2	4	91	0.70	0.17	21.73	1.32	0.07	0.01	0.06
KDSP11	4.5	170.5	136	2312	0	146	2	1681	615.21	7.78	25.03	4.77	24.47	1.64	17.61
KDSP15	4.4	205.0	182	2473	0	130	17	1679	720.03	9.49	24.79	4.45	4.02	1.81	19.85
KDSP16	4.5	208.7	4149	2622	0	80	2	689	775.72	14.02	25.70	5.08	0.05	3.65	12.26
KDSP17	6.3	110.2	50	961	46	8	2	35	279.35	11.70	23.86	1.57	0.01	0.01	0.06
KDSP19	6.4	146.3	143	45	20	2	4	1048	4.72	0.44	23.01	0.46	0.08	0.02	0.03
KDSP20	4.2	144.4	79	1543	0	34	4	1167	448.31	11.51	24.79	1.67	0.01	0.84	5.15
KDSP23	4.1	148.7	93	1693	0	40	4	51	479.23	12.85	25.07	1.67	0.06	0.96	5.83
KDSP24	5.3	5.0	3	26	4	2	4	2	1.12	0.38	22.12	0.48	0.05	0.01	0.02
KDSP25	6.4	10.0	381	30	6	2	4	1	1.96	0.78	22.38	0.23	0.90	0.01	0.19
KDSP26	6.4	95.8	86	2098	0	84	4	1371	667.68	16.48	25.42	1.69	0.44	2.46	12.19
KDSP29	6.4	16.4	8579	91	32	8	6	16	6.71	2.29	25.56	3.77	14.58	0.05	0.06
KDSP30	3.7	177.4	104	2362	0	104	4	1599	756.76	10.47	24.89	3.73	0.22	2.29	16.17
KDSP32	Dry						Dry								Dry
KDSP33	3.9	218.7	131	2711	0	86	8	1790	814.32	34.74	28.20	3.22	0.07	4.48	11.30
KDSP34	3.6	195.3	135	2361	0	120	4	1572	722.73	11.93	25.09	3.63	0.41	2.81	16.38
KDSP36	5.5	19.1	7693	45	12	6	6	2	2.46	0.53	24.38	1.11	3.67	0.17	0.12
KDSP37	3.7	166.7	11375	2363	0	102	4	1499	696.43	15.97	28.06	2.42	67.45	2.53	6.71

Table C 8 Water laboratory Data 25/05/1999 (Laboratory - ACCL)

Site	pH	EC	S.S	TDS	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	3.06	2551.0	157	3245	0	112	6	1902	139.10	33.55	22.89	3.35	38.85	13.57	204.33
KDSP02	3.05	2485.0	109	3223	0	116	4	1854	104.36	31.05	23.66	4.66	57.82	13.90	201.37
KDSP03	3.05	2538.0	117	3128	0	108	2	1854	123.28	31.85	23.05	3.97	48.53	13.56	204.60
KDSP04	9.17	3001.0	118	3543	6	6	6	1895	918.50	22.46	22.66	4.96	0.01	0.35	0.69
KDSP05	3.16	1514.0	390	1981	0	574	4	1155	53.53	19.56	24.87	2.33	6.11	10.22	140.12
KDSP06	4.26	3593.0	568	4502	0	512	8	2203	750.40	59.70	23.04	5.64	0.88	32.56	89.14
KDSP08	3.69	313.8	274	4032	0	158	8	1920	616.00	25.93	22.89	5.64	0.20	5.28	29.71
KDSP10	6.46	28.8	1185	26	40	16	6	22	0.55	0.16	18.93	1.33	0.04	0.01	0.16
KDSP11	4.83	299.3	237	3619	0	38	6	1973	609.53	21.40	22.16	4.61	0.06	2.50	6.14
KDSP15	4.40	313.8	274	3998	0	96	8	2279	691.81	26.02	22.58	5.11	0.38	3.07	20.03
KDSP16	4.47	303.4	920	3640	0	66	6	1749	713.99	27.08	23.08	5.31	0.11	5.19	13.82
KDSP17	7.10	107.9	5	891	24	8	6	556	227.04	10.18	21.84	3.13	0.09	0.01	0.95
KDSP19	5.69	47.0	1532	31	8	60	4	317	1.79	0.63	22.35	1.58	4.88	0.39	0.11
KDSP20	4.27	113.5	88	841	0	10	8	577	242.15	10.10	22.33	5.61	0.04	0.63	2.07
KDSP23	4.40	42.5	75	293	0	6	4	215	63.22	3.42	21.33	2.66	0.01	0.31	0.44
KDSP24	5.71	35.9	99	24	2	4	6	11	0.58	0.27	19.51	0.38	0.44	0.01	0.08
KDSP25	6.42	16.9	702	140	4	6	12	77	9.74	5.13	23.37	1.54	0.08	0.01	0.04
KDSP26	3.89	160.0	21	1778	0	34	10	992	382.88	10.90	22.67	6.14	0.11	1.88	6.82
KDSP29	6.37	122.8	23587	108	56	10	4	35	7.83	4.48	21.72	3.72	2.41	0.01	0.07
KDSP30	3.70	270.3	74	243	0	96	10	1825	752.17	18.47	22.68	5.11	0.38	4.07	20.92
KDSP32	Dry							Dry							Dry
KDSP33	4.06	226.0	52	2314	0	44	12	1574	578.01	23.40	23.39	4.90	0.02	3.30	9.24
KDSP34	3.66	265.5	38	2871	0	94	6	1801	757.39	18.71	23.37	5.40	0.45	4.22	19.77
KDSP36	5.63	63.4	1654	39	8	6	4	30	0.77	0.06	21.00	1.33	0.47	0.01	0.03
KDSP37	3.94	163.6	188	-1	0	46	8	999	454.41	13.90	23.78	7.92	0.30	2.75	7.31

Table C 9 Water Laboratory Data 22/06/1999 (Laboratory - ACCL)

Site	pH	EC	S.S	TDS	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	3.1	242.30	900	2873	0	1740	20	1961	98.54	34.47	12.87	6.33	53.72	13.21	250.09
KDSP02	3.4	238.30	101	2834	0	1650	60	2079	111.86	35.84	10.04	4.13	41.71	12.03	257.22
KDSP03	3.4	244.70	94	2937	0	1780	60	2062	100.85	33.61	11.14	4.99	48.94	12.38	235.02
KDSP04	9.6	172.60	56	1616	22	0	400	1097	457.91	2.63	9.50	5.35	0.01	0.01	3.30
KDSP05	3.4	151.40	47	1597	0	1320	400	1151	40.79	15.10	10.95	3.19	10.06	8.08	150.67
KDSP06	5.0	197.70	66	1974	0	190	200	1362	466.28	7.47	10.33	5.21	0.20	1.35	22.42
KDSP08	5.0	201.00	72	2004	0	160	4	1322	528.52	10.01	10.24	5.43	0.10	2.34	24.51
KDSP10	6.4	28.30	10	26	4	6	20	23	0.80	0.24	5.25	1.67	0.12	0.01	0.17
KDSP11	5.0	201.00	67	2031	0	184	200	1388	471.98	8.65	8.07	4.66	2.09	1.83	19.95
KDSP15	5.0	204.80	65	2002	0	144	4	1409	473.23	8.07	7.39	4.20	0.22	1.77	15.65
KDSP16	5.0	206.70	72	2035	0	118	2	1350	548.21	10.68	8.38	4.67	0.01	2.42	13.99
KDSP17	6.6	101.60	18	727	14	8	4	590	198.11	9.79	6.11	2.14	0.01	0.01	0.03
KDSP19	6.4	21.90	9	111	8	0	2	42	0.48	0.16	4.89	1.06	0.01	0.01	0.07
KDSP20	4.6	74.90	108	556	0	18	6	457	129.46	5.24	8.28	4.72	0.01	0.68	0.82
KDSP23	5.0	38.91	16	256	0	6	4	229	52.95	4.93	7.36	3.13	0.01	0.43	0.31
KDSP24	5.8	20.60	11	12	6	14	2	53	0.39	0.01	3.64	0.33	0.01	0.01	0.04
KDSP25	6.6	11.09	75	77	4	6	6	90	4.65	2.55	7.86	1.26	0.17	0.01	0.56
KDSP26	4.7	141.50	17	1231	0	64	6	891	298.09	11.29	7.59	4.31	0.01	1.59	0.03
KDSP29	6.2	49.20	498	45	28	30	4	24	7.33	4.62	7.96	2.97	6.86	0.01	0.05
KDSP30	3.9	231.40	83	2274	0	144	8	1595	500.21	15.52	8.96	5.54	0.02	4.14	15.73
KDSP32	Dry							Dry							Dry
KDSP33	4.4	232.00	60	2368	0	90	6	1591	527.45	25.76	9.95	3.14	0.01	2.82	10.36
KDSP34	4.2	238.00	1487	2371	0	88	10	1460	552.72	16.86	10.18	11.53	0.01	4.60	15.60
KDSP36	5.8	55.40	2295	48	4	20	6	34	2.03	0.09	10.33	2.44	0.48	0.06	0.04
KDSP37	4.3	163.50	31	1518	0	66	6	1045	381.04	13.50	10.05	5.43	0.01	2.14	7.61

Table C 10 Water Laboratory Data 27/07/1999 (Laboratory -ACCL)

Site	pH	EC	S.S	TDS	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	3.1	254.00	88	3331	0	1552	56	2095	104.45	34.22	11.45	5.78	84.49	14.65	239.87
KDSP02	3.4	256.30	108	2465	0	1616	20	2200	110.02	32.49	9.04	3.53	108.69	12.19	247.95
KDSP03	3.2	259.00	79	3484	0	1172	50	2134	104.37	32.80	9.71	4.46	92.60	13.38	242.00
KDSP04	8.9	236.00	104	2325	4	0	2	1542	708.06	4.43	7.75	3.47	0.10	0.01	3.01
KDSP05	3.2	143.00	56	1798	0	852	50	1150	40.07	14.93	10.87	3.71	9.67	8.41	149.94
KDSP06	4.6	271.00	87	2797	0	108	2	1745	720.84	8.57	8.05	3.97	14.51	0.95	12.89
KDSP08	4.6	268.20	83	2797	0	138	50	1793	745.95	9.45	8.45	3.94	15.13	1.34	18.59
KDSP10	6.3	5.00	2	36	4	6	2	28	0.97	0.01	3.81	1.10	0.17	0.01	0.10
KDSP11	4.6	267.00	93	2815	0	128	4	1805	643.63	8.43	8.32	3.80	10.95	1.10	17.52
KDSP15	6.7	260.00	86	2638	78	24	2	1628	764.89	16.84	10.81	4.57	0.63	2.22	0.06
KDSP16	5.1	239.00	71	2524	4	26	2	1594	751.66	13.01	7.99	3.81	1.06	3.30	1.78
KDSP17	6.5	107.00	48	907	10	6	2	571	265.60	11.19	7.33	2.19	0.19	0.03	0.03
KDSP19	6.3	3.00	11	28	6	8	2	7	1.87	0.01	4.53	1.20	0.21	0.01	0.09
KDSP20	4.2	198.00	60	1862	0	58	2	1207	584.85	16.20	8.08	3.76	0.32	3.77	7.94
KDSP23	4.7	98.10	39	2749	0	32	2	457	178.96	6.10	6.85	2.85	0.69	1.27	1.47
KDSP24	5.6	3.20	21	707	4	6	2	20	1.73	0.17	3.95	0.40	0.15	0.01	0.08
KDSP25	6.5	6.10	5	32	6	6	2	28	2.63	1.19	6.92	0.77	0.52	0.01	0.22
KDSP26	4.0	206.00	58	1985	0	60	4	1288	580.45	19.66	7.83	3.94	0.26	4.59	9.87
KDSP29	5.6	4.00	7	59	6	8	2	9	1.47	0.17	4.55	0.41	0.15	0.01	0.06
KDSP30	4.0	250.00	81	66	0	76	4	1609	667.75	21.26	8.59	4.08	0.31	5.03	10.34
KDSP32	Dry							Dry							Dry
KDSP33	4.3	263.00	109	2549	0	100	20	1702	709.77	34.04	14.24	3.98	0.61	4.37	12.93
KDSP34	4.1	235.30	95	2300	0	52	2	1496	701.10	20.14	7.57	3.32	0.81	3.87	4.01
KDSP36	5.7	4.00	9	45	8	18	10	4	1.67	0.01	6.93	1.18	0.60	0.01	0.11
KDSP37	4.2	225.00	134	2213	0	80	6	1420	696.45	24.07	11.91	5.89	8.12	4.93	6.45

Table C 11 Water Laboratory Data 23/08/1999 (Laboratory - ACCL) (Wetland samples not collected. Access to it was denied by farmer who owns the land at its edge).

Site	pH	EC	S.S	TDS	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP01	3.1	240.30	119	3184	0	1870	100	2170	107.24	36.12	15.62	6.13	98.25	15.77	235.09
KDSP02	3.2	245.20	111	3311	0	297	50	2311	114.50	34.38	12.25	3.71	82.42	12.39	252.94
KDSP03	3.1	253.00	128	3248	0	326	100	2219	115.27	36.91	14.72	5.17	103.22	14.78	251.18
KDSP04	9.9	167.30	65	1600	4	0	2	1096	522.25	2.06	13.09	4.12	0.01	0.01	3.03
KDSP05	3.2	247.10	117	3323	0	1945	100	2318	124.55	36.87	14.45	4.38	75.85	13.89	254.65
KDSP06	7.3	111.30	131	920	12	30	4	657	286.77	1.58	11.68	2.92	0.10	0.28	0.28
KDSP08	7.0	106.80	192	913	8	28	2	717	290.06	1.80	10.97	2.92	0.06	0.40	0.12
KDSP10	5.7	42.80	7	10	4	32	2	63	0.18	0.01	4.14	0.31	0.05	0.01	0.05
KDSP11	4.5	126.00	145	1102	0	92	4	751	287.23	5.49	10.78	3.42	0.05	1.83	8.57
KDSP15	4.6	123.80	156	1093	0	96	2	776	299.83	5.86	11.50	3.51	0.04	1.99	8.60
KDSP16	4.8	1926.00	467	1822	0	62	2	1211	548.81	20.07	12.40	5.22	0.19	5.69	3.80
KDSP17	6.6	105.50	31	882	12	12	2	598	258.97	12.39	12.05	2.44	0.14	0.05	0.06
KDSP19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
KDSP20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
KDSP23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
KDSP24	5.7	2.97	4	27	4	10	2	51	0.85	0.37	4.95	0.47	0.11	0.01	0.07
KDSP25	6.6	99.10	28	872	12	14	4	580	255.21	11.85	11.21	2.25	0.14	0.02	0.03
KDSP26	4.0	182.50	68	1726	0	72	2	1180	544.34	19.02	11.40	3.74	0.20	3.45	6.93
KDSP29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
KDSP30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
KDSP32	Dry							Dry							Dry
KDSP33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
KDSP34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
KDSP36	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
KDSP37	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table C 12 Water Laboratory Data (Average Values)

Site	pH	EC	SS	TDS	T-Alk	Acidity	Chloride	Sulphate	Ca	Mg	Na	K	Fe	Mn	Al
KDSP 01	3.73	459.73	224.36	3416.50	0.00	1550.36	47.45	2141.27	119.06	36.58	15.47	6.18	40.57	13.40	217.75
KDSP 02	3.62	432.86	177.18	2875.50	0.00	1244.82	88.73	1975.18	101.57	33.68	15.64	5.21	49.21	13.73	222.30
KDSP 03	3.67	455.00	190.09	3144.50	0.00	1210.91	68.18	2082.73	152.82	35.61	15.00	5.71	53.45	12.97	197.70
KDSP 04	8.67	464.88	69.30	1939.70	14.18	160.60	9.20	1359.00	586.57	15.41	15.09	11.43	32.92	0.93	2.45
KDSP 05	3.57	278.86	174.64	1936.20	0.00	1000.10	124.27	1256.46	51.68	18.93	16.65	3.51	16.04	9.49	148.04
KDSP 06	4.62	535.63	138.82	2450.50	1.09	277.09	14.91	1626.18	532.42	22.83	12.65	6.03	7.44	3.26	34.57
KDSP 08	4.68	221.78	118.18	2384.90	0.73	217.45	4.27	1589.73	540.04	19.76	14.59	5.95	6.35	3.03	25.86
KDSP 10	6.13	34.73	121.45	54.90	4.00	8.00	4.91	43.09	0.99	0.28	9.74	1.32	0.07	0.01	0.10
KDSP 11	4.65	229.82	114.27	2150.38	0.00	196.55	4.16	1628.82	537.98	193.16	14.64	4.82	10.64	4.30	49.16
KDSP 15	4.84	220.17	127.45	2348.50	7.09	113.64	7.82	1595.45	570.92	21.73	14.74	6.21	0.74	3.59	15.75
KDSP 16	5.42	372.91	2961.00	2399.20	6.18	107.45	10.55	1360.45	549.17	29.38	13.47	5.35	0.16	4.60	11.31
KDSP 17	6.65	97.32	20.18	776.00	28.73	7.09	3.82	485.08	205.52	10.24	12.76	2.30	0.07	0.02	0.17
KDSP 19	7.70	44.07	2745.60	71.11	15.20	16.00	4.40	158.70	3.21	1.62	11.90	2.11	0.75	0.11	0.15
KDSP 20	5.83	119.78	42.90	1142.22	0.00	31.80	4.60	8.34	334.70	11.15	13.53	2.94	0.08	1.41	3.86
KDSP 23	5.59	110.84	98.10	1156.44	0.40	35.40	4.50	598.50	286.10	9.27	14.26	2.87	0.16	1.21	3.42
KDSP 24	6.96	33.21	60.45	216.60	3.45	10.18	4.00	94.09	24.16	1.44	10.69	0.65	0.09	0.17	0.59
KDSP 25	6.74	33.43	118.73	150.40	9.27	8.91	7.09	42.00	26.81	2.95	12.47	1.42	0.42	0.01	0.18
KDSP 26	4.48	167.20	36.64	1732.90	0.00	68.72	7.63	1534.54	476.61	17.16	14.42	3.83	0.24	33.63	7.59
KDSP 29	7.98	32.33	3669.78	68.13	19.50	8.22	4.25	23.38	4.31	1.66	11.09	2.36	5.45	0.02	0.12
KDSP 30	4.78	229.01	126.40	1627.00	0.00	106.20	6.00	1608.00	559.47	20.97	14.75	5.23	0.33	3.76	16.29
KDSP 33	5.96	232.76	57.00	2101.10	0.00	48.36	8.20	1574.20	671.05	20.27	15.83	3.79	0.12	2.78	6.81
KDSP 34	4.11	234.39	221.90	2176.70	0.00	84.00	5.20	1611.20	634.50	21.37	14.62	6.35	0.40	4.68	15.00
KDSP 36	6.49	67.47	1510.30	298.30	7.00	15.80	5.00	201.50	40.53	3.12	12.62	1.38	1.02	0.66	0.53
KDSP 37	4.89	183.84	1226.70	1519.60	1.20	83.00	5.70	1173.60	507.95	18.60	15.33	4.21	7.71	3.13	7.06

APPENDIX D - RAINFALL DATA
(Agricultural Research Council, Pretoria)

Table D 1 Daily Values of Rain (mm) 1998 (Bethal Station)

Date	Jan	Feb	March	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	21.0
2	2.5	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	0.0
6	44.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	2.0	0.0	30.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	0.0	0.0
8	0.0	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.5
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.5	0.0	12.5	9.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.5	19.0	7.5
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	6.5	16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.0	7.5
19	0.0	11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0	0.0
20	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	18.5	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0
23	43.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	38.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	16.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	22.0	0.0
26	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.0	0.0	20.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	0.0	0.0	9.0
28	4.0	7.0	0.0	0.0	0.0	0.0	0.0	0.0	33.0	0.0	0.0	33.0
29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	22.5
31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0
TOTAL	**185.5**	**36.5**	**58.5**	**2.0**	**0.0**	**0.0**	**0.0**	**0.0**	**100.0**	**61.5**	**171.5**	**178.5**
Ave	**6.0**	**1.3**	**1.9**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**3.3**	**2.0**	**5.7**	**5.7**
High	**44.0**	**16.5**	**30.0**	**2.0**	**0.0**	**0.0**	**0.0**	**0.0**	**33.0**	**25.5**	**23.0**	**33.0**
Low	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**

Table D 2 Daily values of rain (mm) 1999 (Bethal Station)

Date	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	4.0	14.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
4	30.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
12	0.0	0.0	41.5	0.0	0.0	0.0	0.0	0.0	-	-	-	-
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	-	-	-	-
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
15	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
16	0.0	0.0	15.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
17	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	-	-	-	-
18	0.0	0.0	0.0	0.0	0.0	11.0	0.0	0.0	-	-	-	-
19	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	-	-	-	-
20	0.0	11.5	0.0	0.0	14.0	0.0	0.0	0.0	-	-	-	-
21	11.0	0.0	0.0	5.5	0.0	0.0	0.0	0.0	-	-	-	-
22	0.0	0.0	16.5	15.5	0.0	0.0	0.0	0.0	-	-	-	-
23	5.0	0.0	6.5	0.0	0.0	0.0	0.0	0.0	-	-	-	-
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
29	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
30	0.0	-	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-
31	0.0	-	0.0	-	0.0	-	0.0	0.0	-	-	-	-
Total	**50.0**	**25.5**	**82.5**	**21.0**	**25.5**	**11.0**	**0.0**	**0.5**	-	-	-	-
Ave	**1.6**	**0.9**	**2.7**	**0.7**	**0.8**	**0.4**	**0.0**	**0.0**	-	-	-	-
High	**30.0**	**14.0**	**41.5**	**15.5**	**14.0**	**11.0**	**0.0**	**0.5**	-	-	-	-
Low	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	-	-	-	-

Table D 3 Longterm Summary of rain (mm) for 16 years ending 1999 (Bethal Station)

Date	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1.5	4.9	1.5	0.2	0.0	0.1	0.0	0.0	0.0	3.6	2.0	3.2
2	4.9	2.5	3.7	1.1	1.2	0.0	0.0	0.0	1.7	0.2	2.3	3.7
3	6.3	0.5	6.7	0.0	0.9	0.5	0.1	0.0	0.3	0.6	2.9	3.4
4	4.1	3.0	8.4	0.7	0.0	2.2	0.0	1.6	0.0	0.8	2.4	5.4
5	0.6	0.5	3.8	0.6	0.2	0.0	0.0	0.4	0.0	1.1	5.6	7.4
6	5.8	1.0	2.1	0.0	0.1	0.0	0.4	0.0	0.0	1.6	5.5	2.9
7	3.4	4.5	4.2	0.1	0.2	0.8	0.3	0.0	1.6	1.6	1.7	2.1
8	9.0	4.4	4.2	0.2	0.0	0.0	0.0	0.3	0.7	4.4	3.4	8.4
9	3.6	0.8	0.7	1.5	0.3	0.0	0.0	0.0	0.2	2.1	2.2	3.5
10	4.6	4.6	0.0	0.0	0.9	0.5	0.9	0.0	0.6	1.6	3.4	6.4
11	5.1	8.8	0.3	3.3	0.6	0.0	0.0	0.0	1.4	2.0	1.8	9.6
12	1.7	3.1	6.0	1.3	0.6	0.0	0.0	0.0	0.0	1.4	4.3	3.5
13	1.3	11.5	2.9	2.3	0.5	0.0	0.0	0.0	0.7	3.7	4.1	3.7
14	1.1	2.2	2.3	0.5	0.5	0.0	0.0	0.8	0.0	7.1	2.0	8.5
15	3.6	1.3	2.3	0.2	0.0	0.0	0.0	0.0	1.3	2.7	2.8	4.4
16	2.2	3.0	1.4	4.6	0.8	0.0	0.0	0.3	1.2	2.0	1.1	3.9
17	2.6	2.8	2.8	0.1	0.7	0.0	0.0	0.1	0.2	2.4	7.4	3.7
18	2.0	1.2	1.7	0.1	0.0	0.8	0.0	0.2	0.5	3.6	2.8	5.3
19	4.1	1.2	1.1	0.1	0.6	0.5	0.0	0.0	0.1	4.7	4.7	1.8
20	1.8	4.5	1.4	1.4	0.8	0.4	0.0	0.3	0.0	4.9	4.3	2.5
21	2.6	4.1	2.0	0.9	0.0	0.7	0.0	0.0	0.6	3.6	2.3	6.3
22	7.9	4.9	2.2	2.7	0.0	0.0	0.0	0.0	0.1	6.3	2.0	6.2
23	6.3	5.4	6.2	0.0	0.5	0.0	0.1	0.0	0.2	4.6	2.9	5.5
24	8.2	2.3	2.3	0.4	1.2	0.3	0.0	0.4	0.0	2.4	1.5	5.0
25	4.3	2.0	4.0	1.2	1.7	0.5	0.0	1.7	0.9	4.7	5.6	0.7
26	1.7	3.5	0.7	0.1	0.7	0.1	0.0	0.4	2.1	1.3	5.4	6.0
27	0.2	1.2	1.8	0.9	0.0	0.2	0.2	0.0	5.1	1.9	2.1	2.0
28	2.7	3.8	2.8	3.6	0.7	0.7	0.0	0.0	3.7	4.7	5.6	8.5
29	0.7	0.0	0.6	0.7	0.0	0.0	0.0	0.1	2.1	2.6	6.9	4.7
30	1.9		2.2	0.9	0.0	0.0	0.0	0.7	3.5	3.5	5.3	5.3
31	0.1		0.5		0.0		0.0	1.1		2.4		1.7
Total	**105.9**	**93.5**	**82.8**	**29.7**	**13.7**	**9.3**	**2.0**	**8.4**	**28.8**	**90.1**	**106.3**	**145.2**
Ave	**3.4**	**3.2**	**2.7**	**1.0**	**0.4**	**0.3**	**0.1**	**0.3**	**1.0**	**2.9**	**3.5**	**4.7**
High	**9.0**	**11.5**	**8.4**	**4.6**	**1.7**	**2.2**	**0.9**	**1.7**	**5.1**	**7.1**	**7.4**	**9.6**
Low	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.2**	**1.1**	**0.7**

APPENDIX E – SOIL SITES

Table E 1 Geographical positions of the soil sites

Site	Latitude	Longitude	Description
KDS01A KSA01B	25°46' 36.47 "S	29°25' 04.39"E	Mine area
KDS02A KDS02B	25°46' 24.17 "S	29°25' 44.47"E	Seepage area at the Liming Plant
KDS03A KDS03B	25°46' 32.52 "S	29°25' 40.11"E	Liming Plant Stream
KDS04A	25°46' 40.00"S	29°25' 38.18"E	Central Seepage Area
KDS05A	25°46' 28.14 "S	29°25' 24.58"E	Liming Plant Stream
KDS06A	25°46' 21.12 "S	29°25' 57.83"E	Liming Plant Stream
KDS07A KDS07B	25°46' 29.04"S	29°25' 40.40"E	Area opposite the seepage area at the evaporation ponds
KDS08A KDS08B	25°46' 37.39"S	29°25' 20.99"E	Beginning of the wetland
KDS09A KDS09B	25°46' 47.09"S	29°25' 43.43"E	Wetland Sample
KDS10A KDS10B	25°46' 33.46"S	29°25' 22.74"E	Spring Area below the farmhouse.
KDS11A KDS11B	25°46' 14.09"S	29°25' 36.03"E	Seepage area below the evaporation ponds.
KDS12A KDS12B	25°46' 00.47"S	29°25' 35.54"E	Evaporation ponds.
KDS13A KDS13B	25°46' 47.07"S	29°25' 55.75"E	Wetland Sample
KDS14A KDS14B	25°46' 47.08"S	29°25' 36.34"E	Wetland Sample
KDS15A KDS15B	25°46' 40.40"S	29°25' 20.32"E	Wetland Sample
KDS16A KDS16B	25°46' 43.55"S	29°25' 14.68"E	Wetland Sample

The geographical positions were located using a Geographic Positioning System (GPS).

APPENDIX F – SOIL DATA

Table F 1 Soil Data September 1998 - Winter (Lab - Agricultural Research Council, Pretoria)

Site	pH	EC (mS/m)	Anion (me/l)	Cations (me/l)	SAR	Saturation (%)	F (mg/l)	Cl (mg/l)	SO_4^{2-}(mg/l)	NO_3(mg/l)	Ca^{2+}(mg/l)	Mg^{2+}(mg/l)	Na^{2+}(mg/l)	K^{+}(mg/l)
KDS01A	4.57	21	1.00	0.88	0.28	32.70	0.17	2.27	38.55	7.91	9.70	2.34	3.60	1.80
KDS01B	4.84	10	1.65	0.53	0.74	33.14	0.08	1.45	72.82	5.63	3.30	1.10	5.90	0.84
KDS02A	3.85	253	52.52	17.11	0.22	33.92	0.07	23.46	2490.74	0.00	267.00	37.51	14.30	3.30
KDS02B	3.71	65	8.58	2.01	0.23	36.87	0.56	6.86	400.00	1.83	24.00	5.97	4.90	2.85
KDS03A	3.98	319	72.64	23.04	0.11	42.91	0.11	21.40	3459.80	0.00	365.00	51.30	8.70	9.00
KDS03B	4.06	250	49.56	19.51	0.10	40.52	0.13	17.99	2355.42	0.00	308.00	42.72	6.80	13.03
KDS04A	3.98	60	6.24	2.77	0.35	44.27	0.54	8.40	284.40	3.33	24.00	6.81	7.50	26.64
KDS05A	6.96	253	40.83	32.49	0.04	24.23	0.23	8.89	1924.32	31.50	553.00	56.60	3.70	2.98
KDS06A	4.90	122	14.06	11.65	0.07	24.46	0.21	4.75	668.37	0.00	205.00	13.09	4.00	6.62
KDS07A	4.83	13	0.53	0.55	0.26	31.06	0.13	3.98	16.82	2.48	5.30	1.30	2.60	2.89
KDS07B	4.76	11	0.52	0.44	0.14	30.34	0.12	2.32	16.69	5.50	4.70	1.49	1.40	1.33
KDS08A	4.33	464	85.11	70.82	0.74	40.02	0.65	25.10	4052.37	0.00	441.00	504.70	95.70	122.50
KDS08B	4.71	140	16.95	14.11	0.28	33.73	0.30	4.92	803.71	3.57	158.00	63.90	16.60	9.91
KDS09A	5.10	35	2.75	2.48	0.44	40.86	0.16	4.77	124.24	1.19	31.20	4.74	9.90	3.82
KDS09B	4.83	24	1.37	1.73	0.58	29.58	0.17	2.30	60.77	1.62	14.60	5.55	10.40	3.67
KDS10A	5.26	23	0.95	1.24	1.26	69.81	0.11	21.63	14.83	1.28	5.00	2.40	13.90	7.61
KDS10B	5.16	14	0.24	0.87	0.77	46.66	0.18	6.14	1.69	1.15	5.00	1.99	8.00	4.12
KDS11A	3.44	389	80.75	40.59	0.27	40.24	0.29	123.48	3703.02	9.19	536.00	146.80	27.60	21.78
KDS11B	4.36	202	30.23	21.96	0.10	41.54	3.10	12.26	1427.35	0.00	363.00	39.17	7.30	11.99
KDS12A	4.00	263	41.25	28.82	0.08	35.76	0.98	6.17	1970.88	0.00	500.00	40.84	6.80	8.33
KDS12B	5.44	217	30.41	26.29	0.05	34.87	0.12	8.62	1430.41	23.42	492.00	17.57	4.00	4.78
KDS13A	4.89	19	0.72	1.08	0.53	38.98	0.15	3.52	27.55	2.38	10.70	1.91	7.10	3.05
KDS13B	5.14	5	0.13	0.24	0.65	46.42	0.09	1.45	3.27	1.23	1.30	0.20	3.00	1.31
KDS14A	4.63	60	3.48	4.11	0.33	65.07	0.51	6.80	156.74	0.00	54.60	9.46	10.20	6.49
KDS14B	4.71	16	0.24	0.80	0.44	32.61	0.31	1.79	5.98	2.96	5.70	2.52	5.10	3.45
KDS15A	4.46	206	28.19	23.17	0.15	82.87	0.99	20.39	1323.52	0.00	393.00	35.54	11.50	5.65
KDS15B	4.56	47	3.41	3.62	0.37	42.64	0.47	4.18	155.73	2.15	42.50	10.85	10.60	5.99
KDS16A	5.24	117	11.10	12.03	1.91	63.86	0.19	10.39	515.27	4.17	92.60	42.57	88.20	2.92
KDS16B	5.57	56	3.39	4.22	3.13	40.66	0.17	7.72	148.71	3.96	15.20	8.90	62.10	1.18

Table F 2 Soil Data March 1999 - Summer (Laboratory - Agricultural Research Council, Pretoria)

Site	pH	EC (mS/m)	Anion (me/l)	Cations (me/l)	SAR	Saturation (%)	F (mg/l)	Cl (mg/l)	SO_4^{2-}(mg/l)	NO_3(mg/l)	Ca^{2+}(mg/l)	Mg^{2+}(mg/l)	Na^{2+}(mg/l)	K^{+}(mg/l)
KDS01A	4.36	34	2.55	1.90	0.11	30.80	1.35	6.46	96.47	18.19	23.20	5.51	2.40	7.52
KDS01B	4.35	24	1.44	1.40	0.24	26.00	0.53	13.53	44.46	5.94	12.20	4.77	3.90	9.05
KDS02A	3.80	254	50.85	11.35	0.13	28.72	1.47	9.29	2426.24	0.00	150.00	410.91	7.20	3.86
KDS02B	3.64	442	121.49	22.38	0.14	34.39	2.76	8.29	5816.82	0.00	264.00	105.40	10.40	3.64
KDS03A	4.47	249	40.98	31.04	0.07	37.47	1.80	7.77	1953.37	0.00	567.00	27.70	6.30	7.81
KDS03B	4.34	312	60.39	34.46	0.10	33.94	18.38	0.00	2854.18	0.00	577.00	61.10	9.20	9.19
KDS04A	3.83	130	21.04	4.56	0.19	25.00	1.43	4.45	993.16	9.43	60.90	13.70	6.20	4.88
KDS05A	4.33	226	36.61	31.71	0.06	26.29	0.00	0.00	1758.36	0.00	610.00	11.26	5.10	4.76
KDS06A	5.18	219	32.68	31.34	0.05	22.14	0.00	0.00	1569.73	0.00	583.00	23.81	4.10	4.18
KDS07A	4.88	14	0.84	0.71	0.07	31.19	0.72	5.12	29.81	2.32	7.40	2.44	0.90	3.93
KDS07B	4.70	9	0.53	0.43	0.08	30.91	0.39	3.57	17.56	2.54	3.40	1.33	0.70	4.71
KDS08A	4.27	223	32.84	26.28	0.15	32.74	0.00	9.91	1563.69	0.00	423.00	54.05	12.30	6.93
KDS08B	4.46	174	25.43	18.92	0.11	32.00	0.00	5.57	1203.73	13.21	317.00	31.11	7.80	7.88
KDS09A	5.51	33	2.15	2.71	0.63	31.50	4.56	9.36	79.05	0.00	17.60	11.91	14.00	9.50
KDS09B	5.33	11	0.31	0.68	0.29	25.86	0.26	2.98	9.29	1.91	5.30	2.39	3.30	3.20
KDS10A	4.89	14	0.73	0.97	1.26	57.41	1.78	11.43	14.71	0.67	3.70	2.38	12.70	1.52
KDS10B	4.93	10	0.39	1.11	1.00	53.73	3.65	3.91	3.64	0.88	2.30	1.47	7.90	21.30
KDS11A	4.27	265	40.10	34.05	0.53	44.53	5.56	9.48	1899.18	0.00	290.00	190.50	47.20	72.90
KDS11B	4.51	249	36.90	32.35	0.63	38.23	4.48	0.00	1760.65	0.00	287.00	172.00	54.30	59.50
KDS12A	4.10	163	24.57	18.74	0.02	41.36	1.06	3.19	1168.54	5.84	360.00	6.82	1.50	5.99
KDS12B	4.38	177	26.67	22.00	0.05	35.88	0.85	0.00	1267.25	15.37	410.00	15.41	3.70	4.12
KDS13A	4.64	26	1.49	2.16	0.54	63.68	11.63	6.87	33.37	0.00	18.90	7.61	11.00	4.47
KDS13B	4.91	19	0.98	1.75	0.42	38.63	12.47	6.24	5.25	1.74	12.50	7.69	7.50	6.53
KDS14A	4.86	67	6.86	7.00	0.31	51.29	16.19	5.63	281.05	0.00	78.30	24.13	12.50	22.04
KDS14B	4.84	99	11.76	10.65	0.32	47.77	15.01	5.60	519.35	0.00	131.00	36.70	15.80	15.56
KDS15A	4.16	215	30.48	29.16	0.22	53.33	17.05	8.39	1409.10	0.00	512.00	29.96	19.10	12.70
KDS15B	5.14	132	17.43	15.81	0.18	31.86	12.65	8.30	782.39	14.95	265.00	21.92	11.50	11.38
KDS16A	4.86	174	24.40	21.42	0.50	41.57	1.52	3.86	1152.23	13.69	271.00	74.90	36.40	6.22
KDS16B	5.44	174	25.24	20.39	0.26	31.26	8.55	4.07	1185.22	0.00	317.00	44.16	18.40	5.41

REFERENCES

Amcoal Colliery and Industrial Operations Ltd., (1993), *The Environmental Management Programme Report for Landau Colliery*, A Section of South African Coal Estates, Unpubl.

AMD Chemistry, (01/03/1999), http://www.mines.edu/fs_home/jhoran/ch126/amd.htm; Environmental Chemistry in Colorado, Toxic Mine Drainage Chemistry and Treatment; AMD Chemistry.

Batchelor, A. L. & Murray (1994) *Interpreting Evidence from Field Results and Determining the Feasibility of Restoring Wetlands,* Watertek, CSIR, 21 pp (unpublished).

Batchelor, A. L. (1992) *A Scoping Study on the Structure and Function of the Landau Wetland, South African Coal Estates*, Report on the Results of a Research Project Commissioned by AMCOAL, 29pp (unpublished).

Batchelor, A. L. (1994) *Preliminary Assessment and Review of the Need for Integrated Passive Water Treatment Systems for Mine Effluent Streams*, Report to the Water Commission, February, 1994 134 pp (unpublished).

Berti, W.R., & Cunningham, S. D. (1993). *Remediating soil pH with Green Plants*. Presented at the International Conference of the Society for environmental Geochemistry and Health, New Orleans, USA. 10 pp.

Bervoets, L, Baillieul, M. Blust, R & Verhagen, R (1996). *Evaluation of Effluent toxicity and Ambient Toxicity in a Polluted lowland River*. Environmental Pollution, **91**, No.3. pp333 – 341.

Betti, W. R., Cunningham, S. D. & Jacobs, L. W. (1995). *Sequential chemical extraction of trace elements: development and use in remediating contaminated soils.* Proceedings

of the Third International Conference on the Biogeochemistry of Trace Elements, Paris France.

Billet, M. F. & Cresser, M. S. (1992). *Predicting Stream-water quality using catchment and soil chemical characteristics*. Environmental Pollution **77**. pp 263 – 268.

Boham-Carter, G. F (1994), 1st ed., *Geographic Information Systems For Geoscientists. Modelling with GIS*. Pergamon (Elsevier Science Ltd.) Publications, U.S.A, 398pp.

Boult, S., Collins, D. N. White, K. N. & Curtis, C. D. (1994). *Metal Transport In a Stream Polluted By Acid Mine Drainage* – The AFONGOCH, ANGLESEY, UK. Environmental Pollution **84**. No.1 p279 – 284.

Brodie, G. A., Hammer, D. A. & Tomlijanovich (1988a) *Constructed wetlands for acid damage control in the Tennessee Valley,* Proceedings of a Conference Sponsored by The American Society for Surface Mining and Reclamation, US Bureau of Mines Information Circular 9183, p 325 – 331.

Brodie, G. A., Hammer, D. A. & Tomlijanovich (1988b) *An evaluation of substrate types in constructed wetlands acid drainage treatment systems,* Proceedings of a Conference Sponsored by The American Society for Surface Mining and Reclamation, US Bureau of Mines Information Circular 9183, pp 389 – 393.

Butler, A (1993), *Wetlands – Perfect answer To Acid Mine Drainage Problems*; Mine Safety Digest.

Butler, P. A. (Ed), (1992). *Passive Treatment of Coal Mine Drainage*. Course Notes for Jennings Environmental Center. RAMP Program Workshop. Compiled by Robert L. Kleinmann, Robert S. Hedin, Robert, W. Nairn, David Hyman, Greg Brodie. 43pp.

Clark, I., (1999) *Statistical Evaluation*, Course Notes for Graduate Diploma in Engineering (GDE) ; Statitisical Valuation of Ore Reserves, The University of the Witwatersrand.

Conley, A. H. (1987), *Some Views of the Department of Water Affairs on Wetlands.* Symposium, 1987.

Ctcnet.net, (16/11/1998), http://www.ctnet.net/scrip/hillman.htm; Acid Mine Remediation Project; Thomas Mills, Somerset County; SCRIP.

Cunningham, S. D & Berti, W. R. (1993), *Remediation of contaminated soils with green plants: an overview.* In Vitro Cell Developmental Biology, 29P, pp 207-212.

Cunningham, S. D & Lee, C.R. (1994). *Phytoremediation: plant-based remediation of contaminated soil and sediments.* Soil Science of America Journal, based on a Symposium held in Chicago, November 1993, 16pp.

Dalton, R., Abrahams, L. & Morkel, G (Eds) (1998a), *Jutas Statutes of South Africa; Electricity, Energy & Mining: Labour, Transport.* Volume 4, 8th Edition.

Dalton, R., Abrahams, L. & Morkel, G (Eds) (1998b), *Jutas Statutes Of South Africa; Agriculture, Fisheries, Forests & Water: Property.* Volume 6, 8th Edition.

De Villiers, J. M. & W. Z. Heathman (1991) *Pre – Mining S oil Inventory and Land Capability Assessment of Kromdraai Surface Mining Rights Area, in the Witbank Area of Transvaal,* a report submitted to AMCOAL Colliery and Industrial Operations Ltd., South African Coal Estates Division, November, 1991.

De Villiers, M. (1991), Kromdraai Opencast Rehabilitation Report, December 1991 (unpublished).

Doyle, W. S. (1976) *Strip Mining of Coal – Environmental Solutions.* Pollution Technology Review No.27, Noyles Data Corporation, New Jersey, pp141 – 222.

DWAF (Department of Water Affairs and Forestry), (1996), *Groundwater Harvest Potential of the Republic of South Africa*

Environment: SSG, (18/05/1999), http://www.environment.gov.au/ssg/pubs/amdintro; Managing Sulphidic Mine Wastes and Acid Mine Drainage: Supervising Scientist Group: Environment Australia.

Fourie, A. B., Laubscher, I. & Batchelor, A. (1996) *Improving the Ability of Constructed Wetlands to treat Acid Mine Drainage,* Second Conference On Environmental Management Technology and Development, 7 & 8 October, 1996.

Fourie, A.B., Rogers, K. H., Truby, R. & Truby, S. (1992*) Contaminant Removal In An Experimental Wetland*, Environmental Issues and Waste Management in Energy and Minerals Production, Balkema, Rotterdam, pp 771 – 777.

Friend, J. F. C & Loewental, R. E. (1992), *Chemical Conditioning of Low-And Medium-Salinity Waters. STASOFT Version 3.0. ;* Prepared for the Water research Commission, Pretoria.

Hedin, R. S. & Hyman, D. M. (1989). *Treatment Of Coal Mine Drainage With Constructed Wetlands, Biotechnology in Minerals and Metals Processings*, ed. B. J. Scheiner, F. M. Doyle & S. K. Kawarta, Society of Mining Engineers Inc., Colorado, pp 113 – 120.

Hedin, R. S., Narin, R. W. & Kleinmann, R. L. P (1994). *Passive Treatment of Coal Mine Drainage,* US Bureau if Mines Information Circular 9389, 34pp.

Hem, J. D., (1985), 3rd ed., *A Study and Interpretation of the Chemical Characteristics of Natural Water,* Dept. of the Interior, U.S. Geological Survey, 263pp.

Hesse, P. R., (1971). *A Textbook of Soil Chemical Analysis*. John Murry (Publishers) Ltd, Great Britain. 520pp.

Hodgson, F. (1992). *Report On Surface Water Quality At Kromdraai Colliery*. Surface Water Quality – Kromdraai Colliery. 2 October 1992.

Hodgson, F. (1999). *An Investigation Into Water Quality in the Olifants Catchment.* Opencast Mining.

Hodgson, F. D. I. & Krantz, R. M. (1995). *Investigation Into Groundwater Quality Deterioration In the Olifants River Catchment Above The Loskop Dam With Specialized Investigation In the Witbank Dam Sub – Catchment.* Report to the Water Research Commission. WRC Report No. XXX/X/95.

Howard, J. L & Shu, J (1996). *Sequential Extraction Analysis of Heavy Metals using a Chelating Agent (NTA) to counteract Resorption.* Environmental Pollution, **91**. No 21 p89 – 96.

Lieven, B., Baillieul, M., Blust, R. & Verheyen, R. (1996). *Evaluation of Effluent Toxicity and Ambient Toxicity in a Polluted Lowland River*. Environmental Pollution.

Lillesand, T. M. & Keifer, R. W., 3rd ed, (1994), *Remote Sensing and Image Interpretation*. John Wiley & Sons, Inc. Canada, 749pp.

Limpitlaw, D & Fabbri, A.G. (in press). *Map representation of Indicators for assessing environmental impacts of mining in the Zambian Copper belt,* in Geoenvironmental Mapping Method, Theory and Practice, ed. P. Bobrowsky, Balkema Scientific Publishers.

Limpitlaw, D., (1998), *Environmental Impact Assessment Of Mining By Integration Of Remotely Sensed Data With Historical Data*, Proceedings of the Second International

Symposium on Mine Environmental Engineering, Brunel University, West London, United Kingdom, 28 –31 July.

Limpitlaw. D (1995) *The Assimilative Capacity of the Kromdraaispruit Wetland*, MSc Thesis, University of the Witwatersrand, Johannesburg, South Africa. 125 pp.

Long, R. (1986), *The Availability and Cost of Coal in South Africa*. IEA Coal Research, London, 74pp.

Mandaokar, S. S., Dharmadhikari, D. M. & Dara, S. S. (1993). *Retrieval of Heavy Metal Ions from Solution Via Ferritisation.* Environmental Pollution, **83**, No 1&2. pp 277 – 282.

Map 2528 PRETORIA, Geological Series 1: 250 000, Dept . Of Mines, South Africa.

Map 2528 PRETORIA, (1976), 1:250 000 Land Type Series, South Africa.

Map 2529 WITBANK, (1996), 1: 50 000, Topocadastral Series, South Africa.

McBride, M. B., (1994), *Environmental Chemistry of Soils*. Oxford University Press, Inc.New York, 406 pp.

Mehliss, A. T. M. (1990), *Operating and Developing Coal Mines in the Republic of South Africa;* 12th Ed., Department of Mineral and Energy Affairs, 58pp.

Miller, R. W. & Donahue, R. L., 6th Ed., (1990), *SOILS, An Introduction to Soils and Plant Growth.* Practice Hall, Inc. New Jersey. 768pp.

Miningwatch, (28/01/1999), http://emcbc.miningwatch.org/library/acid.htm: Acid Mine Drainage – Perpetual Pollution Machine .

Mitsch, W.J. & Gosselink, J. G., (1993), 2nd ed., *Wetlands*, Van Nostrabd Reinhold Publishers, United States, 722pp.

Moolman, J., Quibell, G. & Hohls, B (1999); Chapter 3 *A Qualitative (GIS BASED) Model Of Nonpoint Source Areas (Modelling Suspended Sediment in the Olifants River Catchment)* in the Water Research Commission Report: Development of A Nonopoint Sources Assessment Guide & ndash; Test CASE STUDIES; WRC Report No: (in press); http://wwwdwaf.pwv.gov.za/IWQS/reports/slopes_olifants

Murray, K. & Jooste, M. M. (1993), *JESS investigation into the Functioning of the Landau Wetland, Witbank.* 13 December 1993 Project Number: WM751 6800 6930, 88pp (unpublished).

Norrstrom, A. C. (1993). *Retention And Chemistry of Aluminum in groundwater Discharge Areas.* Environmental Pollution, **81**, pp269 – 275.

Patrono, A., (1995), *Theory and Practice in Landscape Analysis for Environmental Impact Assessment (EIA).* Prepared for; MSc Degree Course, " Environmental Systems Analysis and Monitoring", International Institute for Aerospace Survey and Earth Sciences, Enschede, The Netherlands, 144pp.

Peverill , K. I., Sparrow, L. A. & Reuter, D. J. (Eds) (1999), *Soil Analysis an Interpretation Manual.* CSIRO Publishing, Australia. 369 pp.

Rogers, F. E. J, Rogers, K. H., & Buzer, J. S., (1985), *Wetlands For wastewater Treatment with Special Reference to Municipal Wastewaters,* Witwatersrand University Press, Johannesburg, p 1 – 20.

Ross, S. M. (1994) (ed.) *Toxic Metals in Soil-plant Systems.* Wiley, Chicester, 469pp.

Russell, C. (1990); *Coal Mining – Custodian or Culprit?* Case Study Reference, pp 7 – 14.

Singer, M. J & Munns, D. N., 2nd ed. (1992), SOILS, *An Introduction*. Macmillan Publ. Company, New York. 474pp.

Skinner, E.M.W. (1992) Use of Limestone Limited for Acid Mine Drainage Neutralization. Phase 1: Mechanical Suitability of a Design Concept. AARL PROJECT No. SP12/030. REPORT AARL (Pty).

Smith, D. A. M. & Whittaker, R. R. L. G. (1986): *The Springs-Witbank Coalfield*; In Mineral Deposits of Southern Africa. 1969 – 1984p.

Soil Classification Working Group, (1991), *Soil Classification, A Taxonomic System for South Africa,* Memoirs on the Agricultural Natural Resources of South Africa No. 15. Dept of Agricultural Development, Pretoria. 257pp.

Soil Science Society of South Africa (1990). *Handbook of standard soil testing methods for advisory purposes.* Compiled by the Non- Affiliated Soil Analysis Working Group, Pretoria.

South African Coal Report cc, (2000), *South African Coal Statistics 2000* , South African Marketing Manual, South African Coal Report publ. 148pp.

Steffen, Robertson & Kirsten (1989) *BC AMD Task Force, Draft Technical Report Guide,* Volume 1.

Steffen, Robertson & Kirsten (1990) *Acid Mine Drainage – Short Course*, Course Notes, 4 – 5 October 1990.

Tedder, H. A. (1989) *Water Management In Mining*, Environmental Engineering in South African Mines, The Mine Ventilation Society of South Africa, Anikem (Pty) Ltd. pp 893 – 900.

The Non-Affiliated Soil Analysis Work Committee (1990), *Handbook of Standard Soil Testing Methods for Advisory Purposes.*The Agricultural Reasaerch Council, Pretoria, South Africa.

US Bureau of Mines Research Update (1987), *Remote Methane Detection, Fire Suppression System, Improved Bit Design, Wetland Ecosystems for Acid Mine Drainage, Coal Bump Studies;* Mining Engineering; 39, No.8, pp 788 - 790.

USGS; Mine Drainage, (1105/1999), http://geology.er.usgs.gov/eastern/enviroment/drainage.html, FAQ (Frequently Asked Questions) About the Environment 2 – Mine Drainage (USGS).

Vorster, H. (1994). *Extensive Water Pollution Controls proposed for Witbank and Ermelo.* Mining Mirror, March 1994, pp 5-8.

Water Resource Commission (1997), *Neutralising Acid Mine Water with Limestone - Underground.*South Africa (SA) Waterbulletin **23,** No. 4, July/August 1997.

Wates, Meiring & Bernard (1992), Report On Conceptual Water Pollution Control Plan, Witbank *Water Quality Management Strategy*. Report No. 1648/490/1/W.

Wells, J.D., Van Meurs, L. H. & Rabie (1992) *Terrestrial Minerals, in Environmental Management in South Africa* ed. R. F. Fuggle & M. A. Rabie, Juta & Co. Ltd., CapeTown, pp 351 – 357.

White, K (1997*). Remote Sensing. Progress* in Physical Geography **21**, No.2 pp 297 – 305.

Wood, A. (1994) Natural Wastewater treatment – with specific reference to constructed wetlands, *Water, Sewage and Effluent*, **14**, No. 1, March 1994, pp16 – 21.

Yaron, B., Calvet, R. & Prost, R. (1996), *Soil Pollution, Processes and Dynamics*. Springer – Verlag Berlin, 313pp.

BIBLIOGRAPHY

Athey, D. W., (1992), (unpubl.), *Environmental Impact of Shallow Defunct Coal Mines in the Witbank Area*, Project, University of the Witwatersrand

Bertsch. P. M., (1990). *The hydrolytic products Of Aluminium and their Biological Significance.* Environmental Geochemistry & Health, **12**, No 112, pp 7 – 13

Brodie, G. A., (1990). Workshop on Design, Construction and operation of Wetlands systems to treat acid mine drainage. Proceedings: 12th Annual NAAMLP Conference: *Returning Mined Land to Beneficial Use* Breckinridge, Colorado, September 16 – 20, 1990.

Burrows, J. (Ed) (1989). *Environmental Engineering in South African Mines.* CTP Book Printers, Cape, 987pp.

Cohen, B. (1992) *A Preliminary investigation into the Structure and Functioning of the Landau Wetland,* a report submitted to AMCOAL Colliery and Industrial operations Ltd., South African Coal Estates Division, unpublished internal report, January 1992, 56pp.

Crites, R. W., Günther, D.C., Krunzic, A. P. & Tchobanoglou, G. (1991) *Design Manual – Constructed Wetlands & Aquatic Plant Systems for Municipal Wastewater Treatment*, USEPA, Office of Research & Development, Cincinnati, OH, 84pp.

Crites, R.W., Gunther, D. C., Kruzic, A.P., Pelz, J. D. & Tchobanoglous, G. (1991), *Constructed Wetlands and Aquatic Plant Systems for Muncipal Wastewater Treatment.* Environmental Protection Agency, 84pp.

Dietz. J. M. & Unz, R. F (1988), *Effects of Sphagnum Peat on The Quality Of A Synthetic acidic Mine Drainage,* Proceedings of a Conference Sponsored by The American Society for Surface Mining and Reclamation, US Bureau of Mines Information Circular 9183, pp 310 – 316.

Dillard, C.R. & Goldberg, D. E. (1971) *Chemistry – Reactions, Structure and Properties,* Second Edition, Macmillan Publishing Co., New York.

Dingemans, D. R. W. & Hodgson, F. D. I. (1986) *The In-Pit Water Quality Management During and after Mining Operations in Pits 1 and 3N at Kriel Colliery,* unpublished internal report, January, 1986, 50pp.

Driscoll, C.T. & Schecher (1990) *The Chemistry of Al in the environment,* Environmental Geochemistry and Health, 12, No ½, March 1990, p 28 – 47.

Eger, P., Wagner, J. R., Kassa Z & Melchert, G. D. (1994) *Metal removal in wetland treatment systems.* Proceedings of the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 23-29, 1994, pp 80 – 88.

Grundon, N. J. & Bell, L. C. (Eds) (1995). *Proceedings of the Second Australian ACID MINE DRAINAGE Workshop,* Charters Towers, Queensland. 28 – 31 March 1995. Australian Centre for Mine site Rehabilitation Research: Brisbane, Australia.

Hynes, T. P and Blanchette, M. C. (Eds) (1995), *Proceedings of Sandbury '95 – mining and the Environment.* May 28 – June 1, 1995, Sudbury, Ontario, Canada. 3 volumes. CANMET, Ottawa.

Institute for Groundwater Studies, (1993) *An Investigation into Water Quality in the Olifants Catchment – Opencast Mining*, a Report Submitted to the WRC Steering Committee, 27 April, 1993.

Johnston, A. E., Mott, C. J. B., Goulding, K. W. T. & Blake. L.; *Changes in Soil Chemistry accompanying more than 100 year under woodland and grass at Rothamsted Experimental Station, UK.* European Journal of Soil Science, **50**, pp 401 – 412.

Lillesand, T. M. and Kiefer, R. W. (1994). *Remote Sensing and Image Interpretation.* 3rd Eds. John Wiley & Sons Inc. USA.750pp.

Madden, B. J. & Canbulat, I. (1996), *Rock Engineering's Role in the Mining of Coal Reserves in the 21st Century;* CSIR Division of Mining & Technology; in Coal Mining 2000 and Beyond, Colloquium; The South African Institute of Mining and Metallurgy.

Mittsch, W. J and Gosselink, J. G. (1993). *Wetlands*.2nd ed. Van Nostrand Reinhold, New York. 722pp.

Patrono, A. (1995), *Theory and Practice In Landscape Analysis For Environmental Impact Assessment (EIA).* Enschede, 144pp.

Resource Recovery: *Striving to make Today's Pollution Tomorrow's Product*; http://ctnet.net/sac/virahein.h ,98/11/16.

Smith, D. A. M. & Whittaker, R. I. G. (1986) The Springs – Witbank Coalfield, Mineral Deposits Of Southern Africa, **1 & 2**, pp 1969 – 1984

University Research Benefits Industry (1993), *Coal,* March 1993, pp 45 – 51.

Weider, R. K., Heston, K. P., O'Hare, E. M., Lang, G. E., Whitehouse, A. E. & Hett, A. E. (1988*). Aluminium Retention In Man-Made sphagnum Wetland. Water, Air and Soil pollution* 37, pp 177-191. Klluwer Academic Publisers.