THE IMPACT OF IRRIGATION WITH COAL MINE WATER ON GROUNDWATER RESOURCES

by

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THESIS

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Be not afraid of going slowly; be afraid only of standing still.

Chinese Proverb

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1 INTRODUCTION

1.1 Overview

South Africa is a country blessed with an abundance of minerals, and is the fourth largest coal producer in the world. Coal is the main source of energy; the Energy Information Administration (EIA, 2000) stated that in 1997, 68% of the energy consumption of South Africa was coal-based.

Coal resources in South Africa are contained in 19 coalfields (Erasmus *et al.*, 1981). The most important coalfields in the Mpumalanga province are the Springs-Witbank Coalfield and the Highveld (Eastern Transvaal) Coalfield. A map of the coalfields in South Africa is shown in Figure 1-1.

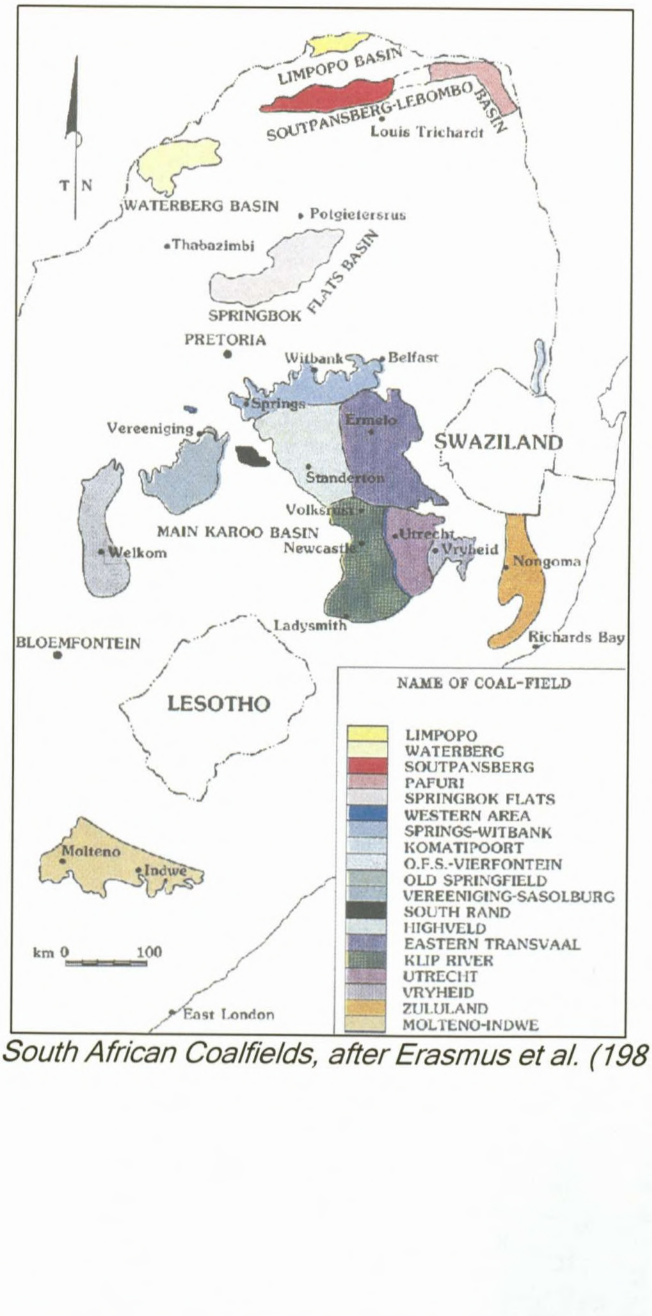


Figure 1-1: The South African Coalfields, after Erasmus et al. (1981).

The aerial extent and the period of mining operations that altered the hydrogeological environment of the coalfields impact on the operational life of the mines for several years after mining has ceased.

Large volumes of acid mine drainage produced in the Mpumalanga coalfields are mostly neutralised by seepage through neutralising strata, or artificially by the addition of lime. Mine drainage is, therefore, often saturated with gypsum ($CaSO_4.2H_2O$). When released into the surface water environment, the associated high salinities are frequently responsible for unacceptable water quality degradation.

South Africa is a water-scarce country, and therefore a significant impact on the environment has been forecast, as early as 1983 (Funke, 1983). However, in recent years, many mines have been striving to ensure that the negative impacts of their mining operations are kept within acceptable limits, also in terms of the water qualities.

1.2 The problem of mine closure

After mineable coal has been removed, mines are left to fill with water and seepage takes place into adjacent, polluting aquifers and rivers.

The National Water Act requires mines to separate clean and dirty water and to contain, and treat if necessary dirty water, so as to prevent impacts on the surface and groundwater resources. The Minerals Act of 1991 was the first that forced mining operations towards sustainable land management instead of just beautifying disturbances. This Act, Act 50 of 1991, stated that the mine remained the property of the owner until a closure certificate had been issued. The law allowed authorities to gain insight into and control mining activities that could adversely affect the water environment. This law was substituted by the Mineral and Petroleum Resources Development Act, Act 28 of 2002. This Act states that no closure certificate may be issued unless the management of potential pollution to water resources has been addressed. The MPRDA requires all mines to make financial provision for closure, and now goes as far as making sure mines have the necessary funding to cover current liabilities (in the event of bankruptcy).

The government has turned down many applications for mine closure, because of the concern of possible uncontrolled pollution of water resources in the vicinity of the mines. The government's reluctance to grant closure certificates has forced the industry to investigate other ways of managing the water pollution problem. One of the ways forward is to look at natural passive options, e.g. filling up of mines with water to decrease the ingress of oxygen and intermine flow. The Institute for Groundwater Studies at the University of the Free State has done a large amount of research in this regard over the years (Hodgson and Krantz, 1998; Hodgson *et al.*, 2001; Grobbelaar, 2001; Hough, 2002; Havenga, 2002 and Vermeulen, 2003).

1.3 Irrigation with gypsiferous water

Irrigation provides a novel approach to the utilization and disposal of gypsum-rich water. The potential for use of gypsiferous mine water for crop irrigation in South Africa was first evaluated by Du Plessis (1983). Research at scales ranging from experimental to semi-commercial over a period of more than ten years has demonstrated the potential to successfully use this water for the irrigation of a range of crops and significantly reduce the salt load emanating from mine drainage, by precipitating gypsum within the soil. Jovanovic *et al.* (1998) proved that irrigation with this water should not present a soil salinity or crop production problem within the relatively short time period of three years, provided that careful fertilisation management is applied. An evaluation of the feasibility and sustainability of this practice from agricultural and environmental perspectives was the subject of a WRC project by Annandale *et al.* (2006). The researchers simulated the long-term soil-water and salt balance, as well as the impact to soil and groundwater resources. The journal Water SA (Jovanovic *et al.,* 2002) stated that the disposal of mine wastewater is a worldwide problem wherever operating coal and goldmines, as well as closed underground and open-cast workings are found (Pulles et al., 1995).

The type of water emanating from mines depends largely on the geological properties of the coal and other geological material with which waters come into contact. The concentrations of salts and other constituents frequently render such waters unsuitable for direct discharge to the river systems, except in periods of high rainfall when an adequate dilution capacity is present and controlled release permitted. DWAF permits mines to discharge polluted mine water as part of the Controlled Release Scheme. The objective is to allow mines to release some of their excess water, but in such a way that the rivers and dams, as well as aquatic organisms, are not negatively impacted upon.

As large volumes of water in underground and opencast collieries are not utilised, the use of available water resources iun a water-scarce country like South Africa should be optimised. Gypsiferous mine water can thus be regarded either as one of the greatest problems associated with mining, or as a potential asset.

Large amounts of wastewater could be possibly available to the farming community for the irrigation of highly productive soils nearby the coalfields of the Mpumalanga Province where available water resources are scarce. The concentration of the gypsiferous mine water through evapotranspiration, thereby precipitating gypsum in the soil profile, may reduce environmental pollution by eliminating these salts from the water system (Annandale *et al.*, 2002). The aluminium toxicity, often occurring in these soils, could be reduced by irrigation with gypsiferous mine water (Barnard *et al.,* 1998). A surplus water problem of the coal-mining industry could also be significantly reduced by the irrigation option with gypsiferous mine water during dry periods; this could release the aluminum toxicity into river systems during rainy periods.

Irrigation with mine water is thus currently one of the potential uses of excess mine water. However, there is continuing concern from especially the regulatory authorities regarding the long-term impact that larger-scale implementation of this practice may have on water-resource (specifically groundwater) quality and quantity. The sections, which follow, will address these concerns.

1.4 Objectives

Sufficient detail does not exist regarding the subsurface behaviour and long-term impact of the use of mine water for irrigation. The thesis provides the following research studies needed to fill that gap. The research investigated:

- The determination of hydraulic interaction of irrigated mine water with the underlying aquifers
- The assessment of the effect of irrigation on water quality and quantity at rehabilitated opencast colliery spoils and on virgin areas.
- The determination of salt migration and attenuation from irrigated areas under natural and spoils conditions.
- The establishment of criteria for site selection/operation, monitoring, determination of impacts and mitigation methods for mine water irrigation areas as part of integrated mine water management.

1.5 Method of Investigation

Irrigation with mine water has been ongoing for several years at the sites as indicated in the next paragraph. The sites of the studied areas have not yielded significant indications of deterioration of groundwater quality monitoring. Methodologies for monitoring and predicting impacts therefore had to be adapted to provide meaningful estimates of expected salt loads for the long term and for more intensive irrigation. Thus, detailed groundwater monitoring throughout the duration of the project was an important objective.

Research was done at five irrigation sites (Figure 1-2):

- Two pivots at Kleinkopje Colliery near Witbank, i.e. Kleinkopje 1 (Major) and Kleinkopje 4
- Syferfontein Colliery between Kriel and Trichardt
- Optimum Colliery (rehabilitated opencast) between Witbank and Hendrina
- New Vaal Colliery near Vereeniging

In Figure 1-3 the position of the collieries in Mpumalanga where the research was conducted, can be seen.

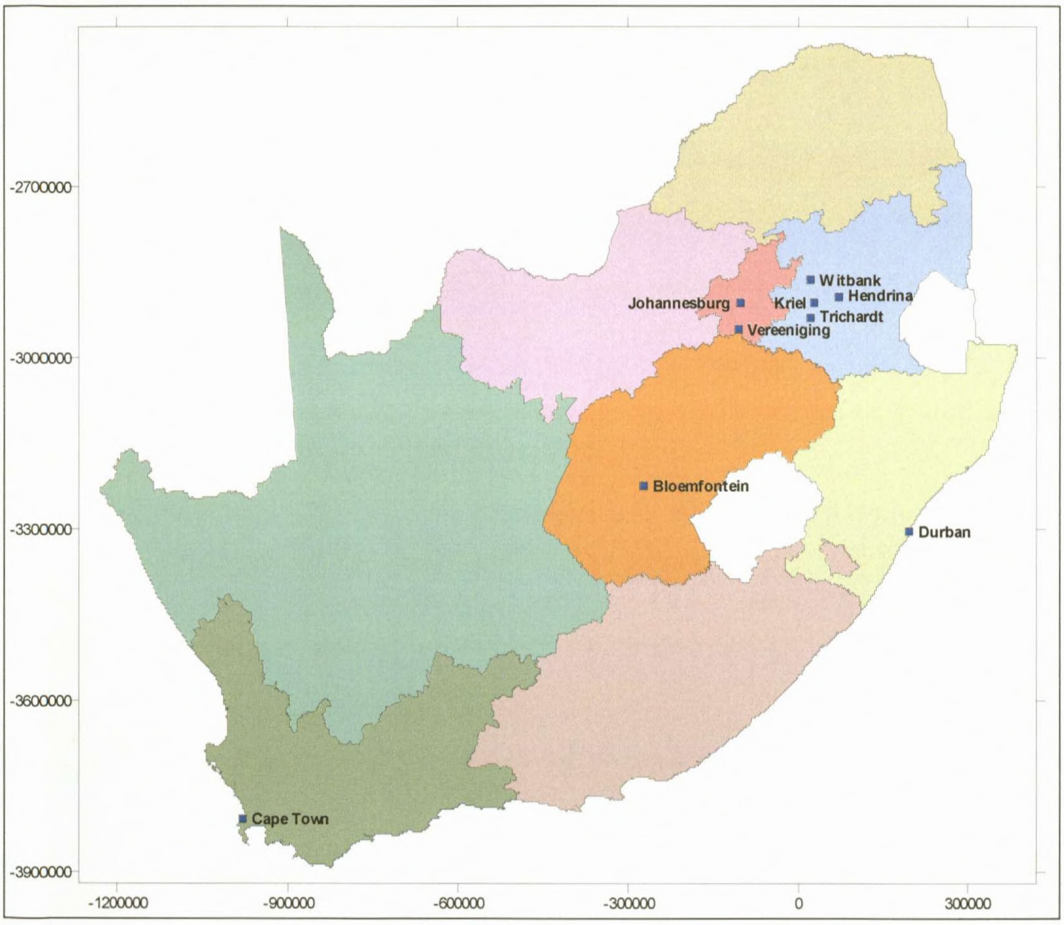


Figure 1-2: South African Map with the towns near to the irrigation sites.

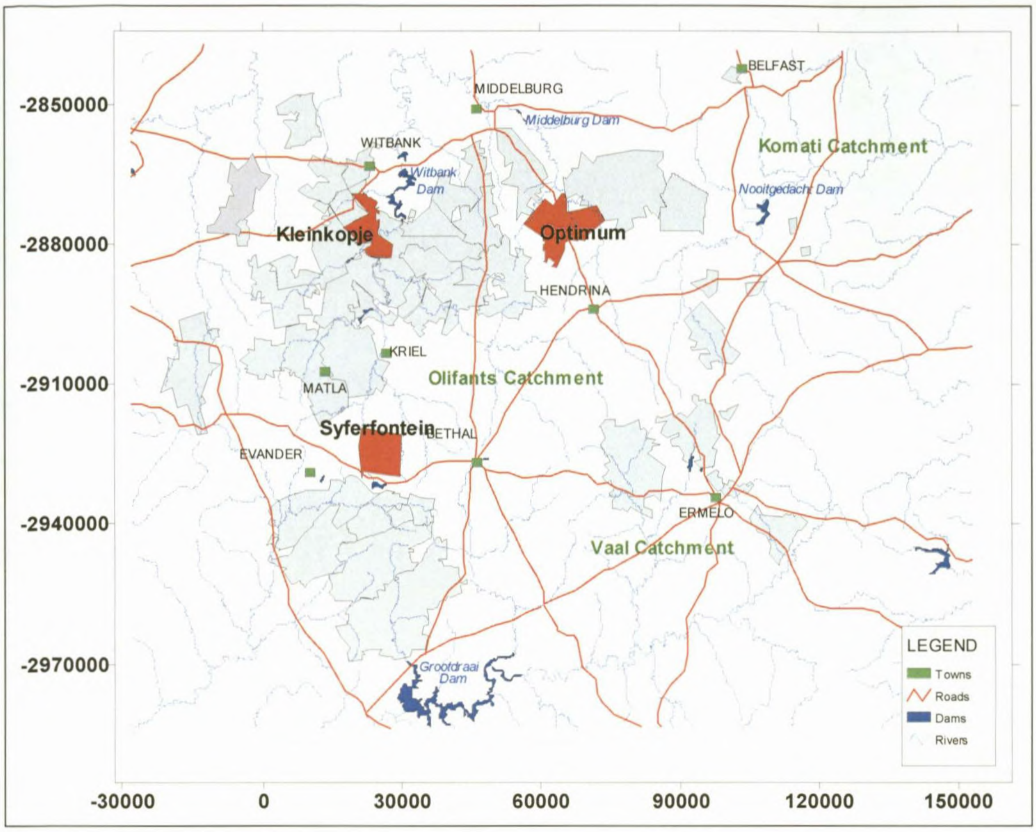


Figure 1-3: Colliery map of Mpumalanga, illustrating the collieries with irrigation sites investigated in this research. (Map courtesy of Grobbelaar et al., 2002).

To achieve the project aims, the following methodologies were applied:

1. Determination of hydraulic interaction of irrigated mine water with the underlying aquifers.
    - Seasonal water level measurement within and down gradient of irrigation pivots
    - Soil moisture and salt migration measurement using aspects such as porous cups, augur drilling, and borehole drilling in the spoils/aquifer.
    - Pumping tests and point dilution tests

2. Assessment of the effect of irrigation on the hydrology and water quality at opencast spoils and on virgin areas.
    - Installation of porous cups/lysimeters to collect moisture at various depths in soil and spoil profiles
    - Installation of water interception systems (columns) within unirrigated spoils to measure water quality and volumes response over time.
    - Installation of monitoring boreholes within the areas of irrigation (virgin soil and spoils) and in adjacent non-irrigated areas.

- Trenching in the irrigated areas (spoils and natural) to determine hydrochemical and hydraulic interactions through direct observation.
- Leaching columns and humidity cells
- Simplified geochemical modelling

3. Determination of salt migration and attenuation from irrigated areas under virgin and spoils conditions.

- Obtaining soil and overburden samples through direct access methods such as trenches, drilling and auguring. The profiles obtained in this way were tested through techniques such as water leaching/extraction and mineralogical determination by means of XRF/XRD.
- Laboratory column leachate experiments to observe variation in attenuation or salt migration for different media or conditions.
- Installation of monitoring boreholes within areas of irrigation and in adjacent non-irrigated spoils.
- Groundwater monitoring results

4. The establishment of criteria for site selection/operation, monitoring, determination of impacts and mitigation methods for mine water irrigation areas. The lessons learnt are synthesised into clear guidelines regarding the site selection, groundwater monitoring, and impact determination for irrigating with mine water in South African conditions. This provides a suggested best practice for mine water irrigation in South Africa.

1.6 Thesis Structure

The thesis is structured as follows:

- Chapter 1 is an introduction.
- Chapter 2 deals with coal mine water irrigation.
- Chapter 3 provides a general site description.
- Chapter 4 is a discussion of hydraulic characteristics and hydrochemical impacts of irrigation on soil and spoils, and an initial conceptual model of the interaction between irrigation and water resources.
- Chapter 5 describes the methodologies used in the investigation
- Chapter 6 gives a detailed characterisation of virgin soil irrigation sites

- Chapter 7 deals with irrigation at opencast collieries (rehabilitated coal spoils).
- Chapter 8 describes the consolidated models of mine water irrigation for virgin soil irrigation
- Chapter 9 deals with operation and monitoring guidelines and provides details of a tool (GIMI) to facilitate irrigation site selection.
- Chapter 10 gives the overall conclusions, and deals with feasibility and recommendations.
- The Appendices (**on the attached CD**) contain all the data gathered during the investigation, calculation sheets, and chapters on:

1. Coal mining in South Africa
2. Irrigation in agriculture - an overview
3. Gypsum in soils.

2 IRRIGATION WITH COAL MINE WATER

2.1 Introduction

The mining industry in South Africa has historically been plagued by the accumulation of excess water (see Appendix A for detail on coal mining and water related issues). When the mining void is filled, whether opencast or underground, the result is often that water eventually decants at the surface, or seeps along the strata. As the workings fill up, mine water is forced out at the lowest interconnection between the mine and the surface. South Africa is a relatively dry country, and seepage towards, or decant into the rivers, can have a significant impact on the overall state of the rivers and underground aquifers. This is particularly relevant in the coal mining industry. Stream water monitoring shows that the water quality has deteriorated over the last 20 years (Grobbelaar *et al.,* 2000).

For the sake of current and future generations it is neccessary to safeguard the purity and quantity against pollution by irresponsible mineral development operations.

The rehabilitation of new mine sites should ideally be planned before starting any mining, including a future water management plan. This plan should also include the management of the mine water and groundwater after mine closure. In particular, the data should include physical, chemical, hydrological and geotechnical properties of the ore (coal), and adjacent country rocks to develop an EMPR (Taylor, 2000). This is also necessary for operational mines to ensure that the best result is achieved and that the community and regulatory authorities are satisfied.

While there have been improvements in mining practices in recent years, it still has significant negative impacts on the environment, which includes the disturbance of groundwater during mine construction. These impacts depend on a variety of factors, such as the sensitivity of the local terrain, the composition of minerals being mined, the type of technology employed, the skill, knowledge and environmental commitment of the company, and finally, the ability to monitor and enforce compliance with environmental regulations. Water pollution from mine waste rock and tailings may need to be managed for decades, if not centuries, after closure.

One of the problems is that mining has become increasingly mechanised and therefore able to handle more rock and ore material than ever before. Consequently, mine waste and therefore also polluted mine water, has increased enormously. As mine technologies are developed to make it more profitable to mine low-grade ore, even more waste will be generated in the future. This trend requires the mining industry to adopt and consistently apply practices that minimise the environmental impacts of this waste production.

Once a mine is in operation, water protection must remain the highest goal of the company, even if it means reduced mineral productivity. Adopting this common-sense ethic is the only way we can ensure that the golden dreams of mining do not turn into the nightmare of poisoned streams (www.miningwatch.org). In the right place, and with conscientious companies, new technologies and good planning, many of the potential impacts are avoidable.

Not all mine waters are bad news. Some mine waters do have a positive impact on the water environment. Banks *et al.* (1996) state that a considerable number of mine waters are of a good quality and can thus be used for potable supplies. Furthermore, a substantial amount of mine water is of good enough quality to be utilised in industries and for irrigation (Reddy *et al.*, 2000). Careful management is however necessary to avoid over-utilising such water (Younger, 1993a; 1998b). If the collieries are excessively dewatered, it can result in:

- The decrease of stream flows and wetlands
- Lowering of the water table near water supplies and irrigation wells
- Land subsidence

2.2 Water volumes available for irrigation

Previous work (Hodgson and Krantz, 1998; Grobbelaar *et al.*, 2000; Hodgson *et al.*, 2001 and Vermeulen, 2003) has stressed that the likely time-scales should not be ignored. The time for the workings to fill with water, for example, is relatively short. The rise in water levels in opencast mining is in the order of 1 m per annum. Depending on the pit geometry, decanting usually occurs within ten years after mining has ceased. Depending on the recharge coefficient, underground mining could take longer to fill/decant. Many of the operating underground mines are already 20 - 40% filled with water. Often at closure, only small areas of these mines remain to be filled by water influx. Decanting at many locations is therefore predicted within the next 40 - 60 years. Some seepage into the weathered zone will also occur, but due to the relatively low hydraulic conductivity of the weathered strata, the seepage component will be relatively small. However, in many of the deeper mines where the cavities fill up, no decanting will occur due to the absence of any significant piesometric head differences in the groundwater regimes.

Grobbelaar *et al.* (2000) provided projections of future water volumes to decant from the coal mines. In total, about 360 ML/d will eventually decant from all the coal mines in combination. On a catchment basis, this amounts to (in ML/d):

Wilge/Klip	Olifants	Klein Olifants	Vaal	Komati
23	170	45	120	2

This demonstrates the anticipated future scale of the water that the industry will have to deal with. However, an investigation currently undertaken by Hodgson for the coal mining fraternity indicates that more than half of the available water will be treated for human consumption, and will not be available for irrigation.

To put these figures in perspective and determine the volumes to be available for irrigation, the following figures can be considered:

Opencast: The void space in spoils is 20%, which implies that 2000 m^3 of water will be in storage per hectare for every meter of depth in the spoils. The average annual rainfall for the Mpumalanga region is 680 - 750 mm.

Approximately 75 000 ha of opencast will eventually be rehabilitated in the Mpumalanga region, according to the Kraai van Niekerk report (Schoeman, 2001). If it is assumed that the recharge to the rehabilitated opencasts will be in the order of 20% of MAP (Vermeulen, 2003), and that the annual irrigation water for 1 ha is 5 000 m^3, then in excess of 20000 ha could be irrigated for a single crop. This assumes that all the water can be collected and that sufficient appropriate areas are available for irrigation.

Underground: The average void space for bord-and-pillar mining is 65%. At an average mining height of 3m, 19500 m^3 of water will be in storage when filled for every hectare mined.

Calculated according the average rainfall, shallow mines with a recharge of 5-10% of MAP will annually have an amount of 350 - 700 m^3 /ha available annually for irrigation. This means that every 7-14 ha will provide enough water to irrigate one hectare. These values are also applicable to stooped areas. For deep underground bord-and-pillar areas with a recharge of 4%, 18 hectares will provide enough water for one hectare of irrigation.

2.3 Composition of coal mine waters

2.3.1 *Introduction*

Large amounts of wastewater could possibly be made available to the farming community and utilised for the irrigation of highly productive soils in the coal-fields of the Mpumalanga Province in South Africa. Concentrating the gypsiferous soil solution through evapotranspiration, and precipitating gypsum in the soil profile, may reduce environmental pollution as these salts are removed from the water system (Annandale *et al.*, 2002). The surplus water problem for the coal-mining industry could also be significantly reduced by the irrigation option (mine water utilisation during dry spells), which could complement the controlled release into river systems during rainy spells.

2.3.2 *Acid Mine Drainage*

Acid Mine Drainage is a widespread phenomenon in the mining industry worldwide, and also affects the water quality of the collieries in South Africa. With the new mine closure law applicable in South Africa, it is important to find ways of curbing, or at least slowing down the process of water acidification, in order to attain mine closure certificates. Industry, labour, government and environmentalists unanimously agree on the issue of AMD as the number one environmental problem facing the mining industry (Domville *et al.,* 1994).

In the coal mining industry the pyrite in the coal is roughly three times as high as in the surrounding rock (Usher, 2002-personal communication). This result in the generation of sulphate, heavy metals and acidity, and can have numerous environmental consequences (Usher *et al.,* 2003), for the following reasons:

- It devastates fish and aquatic habitat
- It is virtually impossible to reverse with existing technology
- Once started, can costs millions to treat
- Is very complex to control and treat (Lawrence and Day, 1997)

According to Seif (2002), as early as 1978, many variations of AMD passive treatment systems have been studied by numerous organizations on the laboratory bench-testing level. During the last 15 years, passive treatment systems have been implemented on full-scale sites throughout the USA with promising results. The concept behind passive treatment is to allow the naturally occurring chemical and biological reactions that aid in AMD treatment to occur.

It is therefore of the utmost importance for the mining industry to know the characteristics/capacity of waste rock, overburden, pit walls, pit floor and tailings, to forecast if it will produce Acid Mine Drainage or not (Usher *et al.,* 2003).

AMD is primarily a function of the geology, geohydrology and mining technology employed at the mine site (Seif, 2002). AMD is the result of a series of complex geochemical and microbial reactions that occur when water comes in contact with pyrite in coal, refuse or the overburden of a mining operation. AMD occurs by the oxidation of the sulphide minerals (mostly pyrite) in the country rock (coal and surrounding rocks) as a result of exposure to moisture and oxygen. This results in the generation of sulphates, metals and acidity. Pyrite (FeS_2) is the most important sulphide found in South African coal mines. When exposed to water and oxygen, pyrite can react to form sulphuric acid (H_2SO_4). The resulting water is usually high in acidity and dissolved metals such as lead, copper, zinc, arsenic, selenium, mercury and cadmium (Hadley and Snow, 1974). These heavy metals are fatal, because they prevent the energy production that is essential for life, by combining with -SH groups (Stevenson, 1997). Certain naturally occurring bacteria can significantly increase the oxidation rate. The contaminated water is often reddish brown in color, indicating high levels of oxidised iron (Hadley and Snow, 1974). Bright orange-colored water and stained rocks are usually telltale signs of AMD (Usher *et al.,* 2001). The dissolved metals remain in solution until the pH rises to a level where the iron oxidizes and precipitation occurs. The precipitates can be harmful to aquatic life, as the clumps reduce the amount of light that can penetrate the water, affecting photosynthesis and the vision of animals. When the precipitate settles on the streambed, it smothers the bottom-dwellers and their food resources.

There are four commonly accepted chemical reactions that represent the chemistry of pyrite weathering to form AMD. An overall summary reaction is as follows (Seif, 2002):

↓

$$4\ FeS_2 + 15\ O_2 + 14\ H_2O \longrightarrow 4\ Fe(OH)_3 + 8\ H_2SO_4$$

Pyrite + Oxygen + Water → "Yellowboy" + Sulphuric acid

The first reaction in the weathering of pyrite includes the oxidation of pyrite by oxygen. Sulfur is oxidized to sulphate and ferrous iron is released. This reaction generates two moles of acidity for each mole of pyrite oxidised.

1). $2\ FeS_2 + 7\ O_2 + 2\ H_2O \longrightarrow 2\ Fe^{2+} + 4\ SO_4^{2-} + 4\ H^+$

Pyrite + Oxygen + Water → Ferrous iron + Sulphate + Acidity

The second reaction involves the conversion of ferrous iron to ferric iron. This process consumes one mole of acidity. Certain bacteria increase the rate of oxidation from ferrous to ferric iron. This reaction is pH dependent with the reaction proceeding slowly under acidic conditions (pH 2-3) without the presence of bacteria, and several orders of magnitude faster at pH values near 5. The oxidation for pyrite by Fe^{3+}*(aq)* is 2 - 3 orders of magnitude faster than that by oxygen (Appelo and Postma, 1993), and is more rapid than the oxidation of dissolved Fe^{2+} to Fe^{3+}. This process rapidly consumes all Fe^{3+} and pyrite oxidation will cease unless Fe^{3+} is replenished in the oxidation process of Fe^{2+} by oxygen. It is thus important to know the oxidation rate for ferrous to ferric iron according to Equation 2. Numerous studies on the ferrous iron oxidation rate show that, under acid conditions, the rate becomes very slow (in the pH range of 3, the half life is in the order of 100 days). Such rates are considerably slower than the oxidation rate of pyrite by Fe^{3+} *(aq)*. Therefore this reaction would be referred to as the "rate limiting step" in the overall acid-generating sequence, were it not for the catalytic effect of bacteria.

2). $4\ Fe^{2+} + O_2 + 4\ H^+ \longrightarrow 4\ Fe^{3+} + 2\ H_2O$

Ferrous iron + Oxygen + Acidity ⟶ Ferric iron + Water

The third possible reaction is the hydrolysis of iron. Hydrolysis is a reaction that splits the water molecule. Three moles of acidity are generated as a byproduct. Many metals are capable of undergoing hydrolysis. The formation of ferric precipitate (solid) is pH dependant. Solids form at a pH-value above about 3.5, whereas little or no solids will precipitate below this value.

$$\downarrow$$

3). $4\ Fe^{3+} + 12\ H_2O \longrightarrow 4\ Fe(OH)_3 + 12\ H^+$

Ferric iron + Water ⟶ Ferric Hydroxide (yellow boy) + Acidity

The fourth reaction is the oxidation of additional pyrite by ferric iron. The ferric iron is generated in Reaction Steps 1 and 2. This is the cyclic and self-propagating part of the overall reaction and takes place very rapidly. The cycle continues until either the ferric iron or pyrite is depleted. Note that in this reaction iron, and not oxygen, is the oxidizing agent.

4). $FeS_2 + 14\ Fe^{3+} + 8\ H_2O \longrightarrow 15\ Fe^{2} + 2\ SO_4^{2-} + 16\ H^+$

Pyrite + Ferric iron + water ⟶ Ferrous iron + Sulphate + Acidity

Although these equations yield a correct picture, in that oxygen is the ultimate driving force for the oxidation of pyrite, with the final products being an insoluble form of oxidized iron and an aqueous sulphuric acid solution, this is an oversimplification of the problem (Azzie, 2002). However, the equation do not explain the geochemical mechanisms or rates and it does not reflect the slow oxidation of aqueous ferrous iron in acid solutions that often results in high ferrous concentrations in acid mine waters. Furthermore, factors such as microbial catalysts, neutralization reactions, sorption reactions, and climatic effects have an important influence on pyrite weathering, but are not considered in the above equations (Nordstrom and Alpers, 1999a). The problem is multi-faceted and it must be emphasized that Acid Mine Drainage occurs within a complex system for which several factors need to be considered by the disciplines of inorganic and organic chemistry, geology and mineralogy, hydrology and microbiology. During the initiation of pyrite oxidation, these are complex chemical and microbiological processes occurring in microenvironments (Williams *et al.,* 1982). The existence of these environments is well illustrated by the formation of Jarosite ($KFe_3(SO_4)2(OH)^6$), a mineral that can only form under acid conditions, but has been found by Carson *et al.,* (1982) in soil waters of near neutral pH-value.

Micro-organisms are abundant in natural waters containing AMD, and in many cases they are the only life form under such conditions (Azzie, 2002). As early as 1919, Powell and Parr suggested that bacteria might catalyze pyrite oxidation. Iron oxidizing bacteria can accelerate the rate of Fe^{2+} oxidation by a factor of 10^6. The two acidophyllic bacteria, *Thiobacillus thiooxidans* and *Thiobacillus ferrooxidans*, play an important role in the microbial degradation of pyrite, and thus are an important factor in producing acid mine waters. The nutritional requirements of *Thiobacillus* are ubiquitous. Nitrogen and carbon dioxide are available in the atmosphere, sulphur is available in the mine waters, and only phosphorus is needed. These bacteria have several adaptive techniques that also permit them to tolerate low pH, and high metal concentrations (Tuovinen *et al,* 1971).

Thiobacillus thiooxidans oxidises elemental sulphur but not iron, *T. ferrooxidans*, oxidizes both iron and sulphur compounds. A third species *Leptospirillum ferrooxidans*, metabolically behaves like *T. ferrooxidans* although it has a different morphology, which was first described by Markosyan (Azzie, 2002). Other bacteria that play a role in these processes are *Thiomicrospira* and *Sulfolobus*.

Stages in the development of AMD.

Under natural conditions, the availability of oxygen acts as a limiting factor for oxidation to occur. Rainwater, the natural source of recharge into the aquifers and into the mines, contains an average of 8 mg/L of oxygen, which is available for reactions with natural substances in the soil, such as organic material and sulphur-bearing minerals, including pyrite (FeS_2), chalcopyrite (FeS.CuS) and pyrrhotite (FeS). This oxidation process can yield at most an equivalent amount of sulphate, which is 32 mg/L (Drever, 1997).

A complex combination of organic and inorganic processes and reactions are involved in AMD. To produce severe AMD where the pH drops below 3, the sulphide minerals should create an optimum environment for rapid oxidation in the system. This oxidation must continue for a sufficiently long time to exhaust all of the neutralizing potential of the rock. The potential of a sulphide-bearing rock to generate acid, is therefore strongly related to the amount of alkaline material present in the rock (Usher *et al.,* 2003). When this sulphide-bearing rock is exposed to moisture and oxygen, sulphide oxidation and acid generation start. Calcium-based carbonates in the surrounding rock will immediately neutralise the acidity, and neutral to alkaline conditions will be maintained in the water that passes over the rock (Broughton *et al.,* 1992). As this neutralizing agent becomes depleted, the water will start to acidify. Consequently, the pH decreases, which in turn creates favorable conditions for further acid generation.

As this process progresses, the rate of acid generation accelerates, and the pH progressively decreases in a step-like manner (Figure 2-1). Each plateau of relatively steady pH represents the dissolution of a neutralising mineral that becomes soluble at each specific pH. Eventually, if the acid generation process removes all the neutralizing potential from the surrounding rock, the pH will drop below 3, and AMD will become severe.

These stages can last for indefinite periods of time even centuries, until the sulphide minerals are completely oxidised and the rock becomes inert, or until special waste management and AMD control actions are taken (Durkin and Herrmann, 1996).

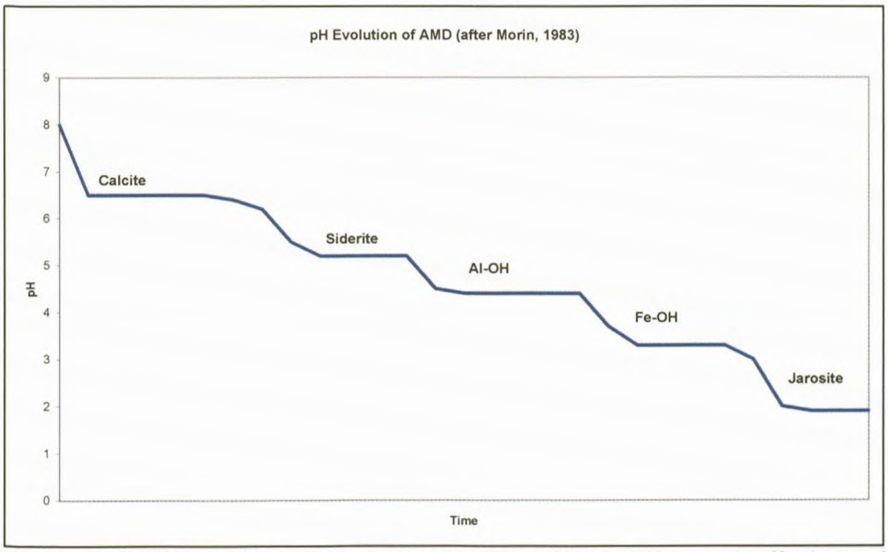


Figure 2-1. Stages in pH evolution as a result of different buffering minerals (after Morin, 1983 and Usher et al., 2001).

2.3.3 *Gypsiferous Waters*

The general trend in the Mpumalanga and Kwazulu-Natal Coalfields is that the southern and western coalfield waters are richer in sodium water than the northern and eastern areas. The table below illustrates the average to highest values for a number of mines in these coalfields. The western and southern coalfields i.e. Kilbarchan/Roy Point, ZAC and Syferfontein, have a much higher sodium content than the eastern collieries, but a much lower calcium and magnesium content in general. This implies that for this research project, Syferfontein was irrigated with sodium-sulphate water (Table 2-2), whilst the irrigation water of the Kleinkopje pivots were calcium - sulphate rich (gypsiferous type). The New Vaal irrigation water is also calcium-sulphate rich, but at a far lower concentration than those of Kleinkopje. The opencast waters at Optimum are also calcium - sulphate rich (gypsiferous type).

Table 2-1: Water quality changes over the coalfields (mg/L).

Mine	**Area**	**Ca**	**Mg**	**Na**	**SO4**
Roy Point/Kilbarchan	South	324-377	81-291	411-1482	1841-4863
ZAC	South	62-298	30-220	300-900	200-1423
Syferfontein	South	35-41	84-91	664-879	1220-1232
Khutala	North	82-416	42-174	32-103	360-2119
Optimum	Northeast	197-534	77-355	83-152	1249-2750
Ermelo	East	170-571	120-360	26-50	600-2805
New Largo	Northwest	163-473	27-84	15-66	885-1860
Schoongezicht	North	275-555	105-223	52-71	1199-2685
TNC	Central	345-367	184-208	54-73	865-1634
Minnaar	North	220-543	15-555	14-45	1230-1760
Kleinkopje Pivot 1	North	553-751	372-473	104-138	2917-3447
Kleinkopje Pivot 4	North	503-697	195-278	37-65	1935-2650
New Vaal	West	68-122	24-94	16-87	172-737

In South African coalfields, co-existing carbonates such as calcite and dolomite can neutralise acidity (Usher, 2003). Alternatively, the acidity can be neutralised by lime addition.

From the overall reaction of calcite as buffering mineral, it is evident that calcium and sulphate will increase in concentration:

$$FeS_2 + 2CaCO_3 + 3,75O_2 + 1,5H_2O \Leftrightarrow Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 2CO_2$$

This increase in Ca^{2+} and SO_4^{2-} can only occur to a certain extent, to a point where the aqueous solubility of these ions is limited by the solubility of gypsum ($CaSO_4.2H_2O$). Using the PHREEQC geochemical model (Parkhurst and Appello, 1999), the saturation state of the neutralised mine water used to irrigate at Kleinkopje's Pivot No1's was determined (Figure 2-2). The results show that the gypsum approached saturation (SI=0) for most of the values.

The implication of this is that when irrigation takes place, a small amount of evaporation, together with the selective uptake of essential nutrients, will result in gypsum precipitation.

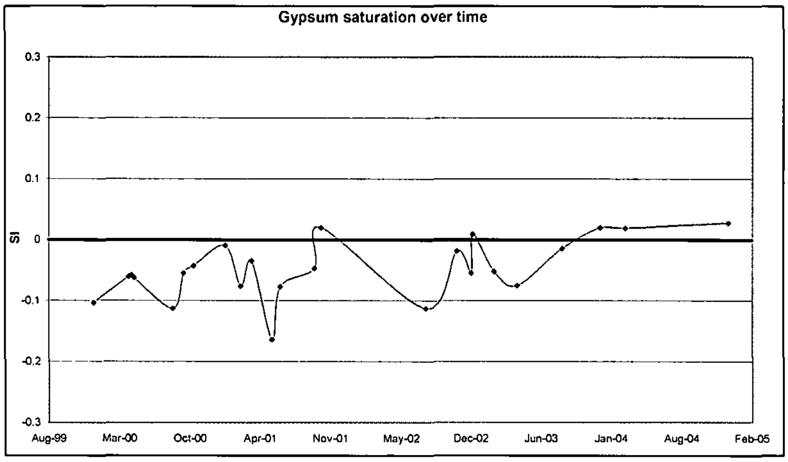


Figure 2-2: Gypsum saturation (SI) in neutralised mine water used to irrigate at Kleinkopje Pivot1.

Gypsum is a partially soluble salt. The concentration of the gypsiferous soil solution through crop evapotranspiration precipitates gypsum in the soil section and may remove it from the water system (see Table 2-2 for irrigation water quality at the different pivots investigated), reducing potential pollution in the process (Annandale *et al*, 2002).

Table 2-2: Irrigation water qualities (February 2004).

SiteName	ph	EC	Ca	Mg	Na	K	Alkalinity	Cl	SO4	Al	Fe	Mn
		mS/m	mg/L	mg/L	mg/L	mg/L	as mg/L CaCO3	mg/L	mg/L	mg/L	mg/L	mg/L
Kleinkopje Pivot 1	5.41	306	697	278	55	14	12	12	2453	0.03	0.01	1.52
Kleinkopje Pivot 4	8.31	505	751	473	138	41	114	94	3447	0	0.06	0.42
Syferfontein	8.84	381	35	91	789	10	621	30	1220	0.08	0.05	0
New Vaal	7.57	166	188	69	138	9	246	17	694	0.01	0.02	0.05
Optimum	7.41	311	438	339	113	39	297	36	2440	0.01	0.3	0.01

To further investigate this, Usher (2003) made use of PHREEQC to analise almost 8000 samples from over the entirety of the Witbank and Highveld Coalfields to ascertain the degree of saturation with gypsum (Figure 2-3). This figure shows the saturation state, represented by the saturation index (SI), which describes the state of any solution relative to the mineral being evaluated (Appelo and Postma, 1993). The maximum solubility of each mineral at equilibrium is given by its theoretical solubility (the K_{sp} value). The measured concentrations in solution are used to determine whether this condition is met.

A value of 1700 mg/L was used by Usher (2003) as a lower cut-off to ascertain solubility controls. From the 1071 samples in the obtained data set that exceeded 1700mg/L SO_4, almost half had SI values approaching equilibrium (a value of 0.1 was used as a cut-off). Therefore, although not all the values in the higher ranges are at, or approaching equilibrium, indications are that gypsum saturation is an important control on the upper limit of sulphate values that can be obtained.

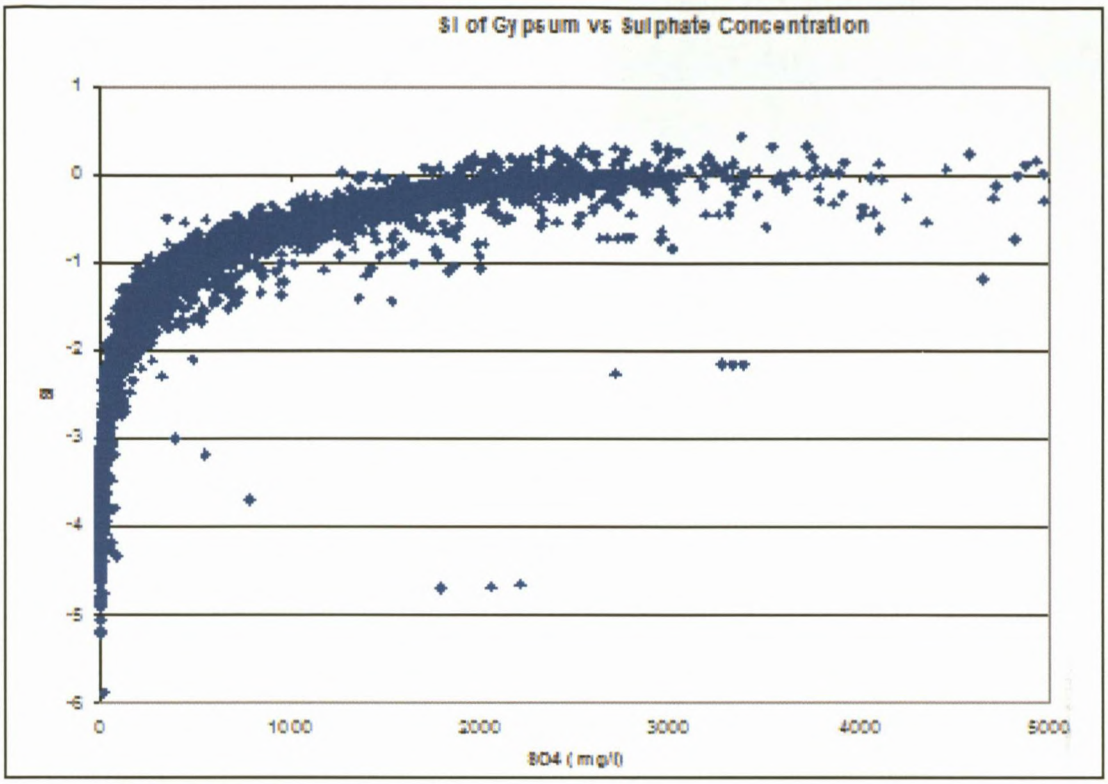


Figure 2-3: Saturation state of gypsum plotted against sulphate concentration (after Usher, 2003).

This observation by Usher (2003) has several implications:

- Determination of gypsum saturation should form part of any hydrogeochemical assessment in the coalfields.
- Calcium values should be measured on a regular basis so that these assessments can be made.
- The observed sulphate generation rates (Hodgson and Krantz, 1998) between 5 kg/ha/day and 10-kg/ha/day sulphate should be reported with an indication of possible gypsum saturation.

The last mentioned implication could be significant for the often generalised assessments, e.g. that rehabilitated opencast pits yield between 5 kg/ha/day and 10 kg/ha/day of sulphate (Hodgson and Krantz, 1998). This rate appears to be fairly constant, despite differences in degree of spoils saturation, age of spoils, or regional impacts. It is therefore possible that the observed rates, as derived from flow and concentration calibration, reflect a maximum sulphate concentration with a consistent recharge. The maximum sulphate concentration is determined by the gypsum solubility. In subsequent reports, Hodgson suggested that gypsum precipitation will play a role under low flow conditions.

Values from the water at Optimum Colliery clearly indicate the validity of this observation. In Figure 2-4, the sulphate concentration for the decant water over time, upon which previous determinations regarding the sulphate generation rate were based, is shown together with the relative saturation of gypsum.

The SI values indicate that the sulphate values are limited by gypsum precipitation, with values close to saturation as soon as concentrations rise. This could imply that the true sulphate generation rates are greater than those derived from flow and concentration measurements (Van Tonder *et al.*, 2003).

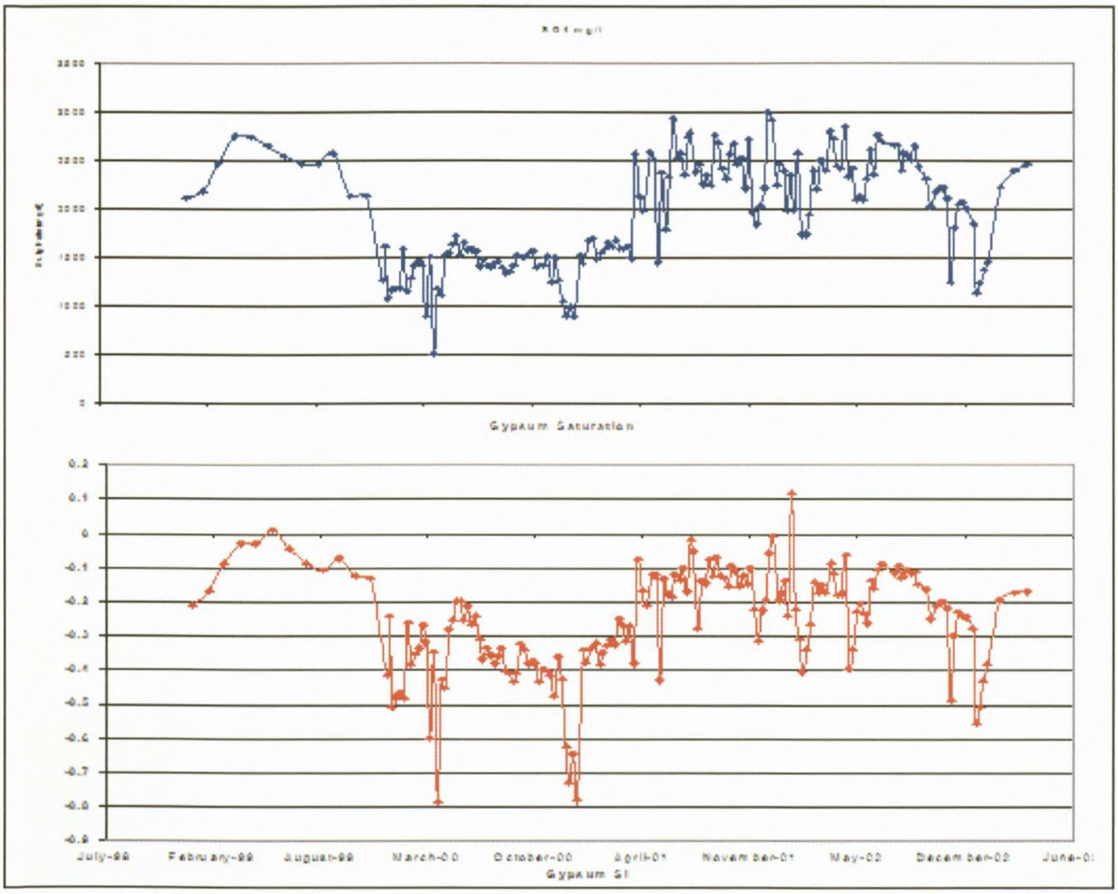


Figure 2-4: Sulphate concentration and gypsum saturation for decant water from Optimum Colliery.

The effect of secondary mineral formation is thus an important control on water quality in South African collieries.

2.4 Perception of the final fate of salts

On irrigated lands, irrigation water is the primary source of salts. At all the collieries except Syferfontein, this water is gypsiferous. In the case of Syferfontein, the water is sodium bicarbonate rich. The key concern relating to irrigating with these waters, focuses on what happens to the salts in the water.

The general belief is that the answer is simple–the salts go where the water goes, and they accumulate in soils where evapotranspiration (combined evaporation from soils and transpiration by plants) exceeds combined precipitation and irrigation (Cordy and Bouwer, 1999). Thellier *et* al. (1990) state that irrigation with saline water may result in the accumulation of dissolved mineral salts in the soil solution, in return resulting in increased soil salinity. The water returning to the atmosphere by evapotranspiration is essentially distilled water, leaving behind the salts in surficial soils and in the root zones of plants. To avoid salinity damage and possibly killing plants or crops, the salts brought in by irrigation water must be leached from the root zone by applying more irrigation water than can be evaporated. The leaching results in sustainable crop production and plant growth. If the amount of water leaching through the soil is too low to remove salts, the salt content in the soil increases and crop yields may decrease. In such situations, the soil is said to be salt-affected (Hoffman, 2004)

Generally, the leached water or deep percolation water continues to move downward through the saprolite soil of the unsaturated zone until it reaches the groundwater (saturated zone), and must eventually affect groundwater quality. Groundwater salinisation is more likely if the irrigation water itself is saline or soluble salts are present in the unsaturated zone (Suarez, 1989).

Proper irrigation management can slow down or stop salinisation. If crop fields are excessively watered or if large amounts of water are allowed to seep away from canals, the groundwater surface under the field and under the region can be raised (Sommerfeldt and Chang, 1980). If the groundwater surface rises to within 3 m (depending on soil type) of the surface, the upper portion of the saturated zone will experience evaporation, which will cause dissolved salts in the groundwater to become concentrated in the soil profile (Szabolcs, 1986). In arid areas, irrigation can cause the aquifer recharge rate to experience a forty-fold increase even with well-planned water conservation practices. The ability of the soil and bedrock to absorb and transport this increase without raising the water table will allow salts leaching through the soil profile to be carried away. If the soil has layers that possess low hydraulic conductivity, a perched water table could be created over the regional aquifer. If drainage is poor due to bedrock, soil or topography the water table will rise and water and salts will eventually reach and be concentrated in the root zone leading to the destruction of fertility (Schwartz et al., 1987).

According to Erie *et al.* (1982) all the water that is not evaporated or transpired, leaches salts from the root zone. This water contains almost all of the dissolved salts from the irrigation water. As an example consider cotton grown in south-central Arizona with an efficient irrigation system that applies 1.6 m of water per year, of which 1.3 m evaporates or transpires (Erie *et al.,* 1982), and about 0.3m leaches salts from the root zone. The leaching process produces 0.3 m of deep-percolation water per year. This moves down to the groundwater table; although this 0.3 m of water per year contains almost all of the dissolved salts from 1.6 m of irrigation water. As a result, salt concentrations in the deep-percolation water will be as much as five times higher (Bouwer, 1990) than those of the original irrigation water. **This research will determine the validity of all of these beliefs, and whether some of the salts are retained in the soil, if so at which quantities, and whether over-irrigation will leach these salts into the groundwater.**

3 GENERAL DESCRIPTION OF IRRIGATION SITES

3.1 Introduction

Five different irrigation sites were selected during research by the Dept. of Soil Science and Agronomy of the University of Pretoria to predict the environmental impact and sustainability of irrigation with gypsiferous mine water. These sites were used for the current research on the impact of irrigation with coal mine water on groundwater resources. Four of the sites are situated in the Mpumalanga province, and one (New Vaal) in the Free State province as stated in Section 1.5 and illustrated in Figure 1-2 and Figure 1-3.

3.2 Kleinkopje Colliery

Kleinkopje Colliery is part of Anglo Coal and is situated outside Witbank (Figure 3-1). Two of the irrigation sites are monitored i.e. Pivot 1(Major) and Pivot 4. They were selected because the soil at Pivot 4 is fairly homogeneous (Hutton soil), whilst that at Pivot 1 varies with depth (Bainsvlei and Clovelly soils).

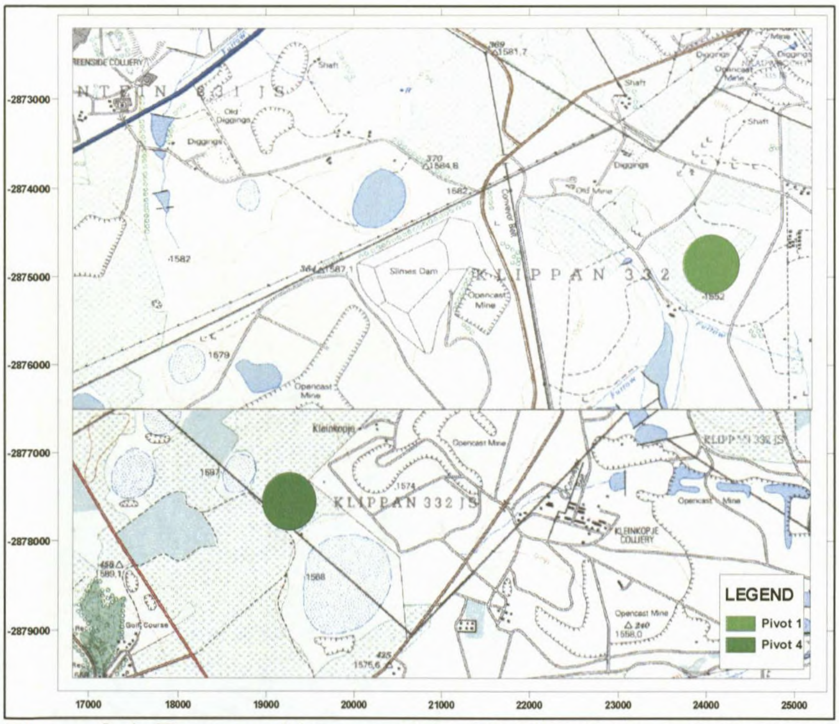


Figure 3-1: Topographic map of the Kleinkopje area, indicating the position of Pivot 1 and Pivot 4.

Irrigation at Pivot 1 started in 1999 and at Pivot 4 in 2001, and is currently still in operation. The crops planted were maize, wheat and potatoes.

3.2.1 *Surface Hydrology*

The annual average rainfall (MAP) for the greater catchment area B11G (368 ha) is 698 mm (SA Weather Service - Rainfall station Witbank no. 0515412-2). The mean annual evaporation (MAE) for the area is 1600 mm, and the mean annual runoff (MAR) 35.8 mm (Midgley *et al.*, 1994) under natural conditions.

3.2.2 *Geology*

3.2.2.1 Regional geology

Kleinkopje Colliery lies in the Springs-Witbank Coalfield and is flanked by the Highveld and Ermelo Coalfields. The coalfield extends over a distance of approximately 180 km from the Brakpan/Springs area in the west to Belfast in the east, and about 40 km in a north-south direction. It is currently the most important coalfield in the country.

3.2.2.2 Site -specific geology and hydrogeology

- Locally the strata encountered in Pivot1 consist largely of soils, sandstone and coal below this.
- No detail of the geology at Pivot 4 is available. However, trenches dug showed that the Hutton soil is deeper than the current water level and that no consolidated rock affects the downward movement of irrigation water towards the aquifer.

A fence diagram in Figure 3-2 provides a detailed cross-section of the strata indicating the different layers.

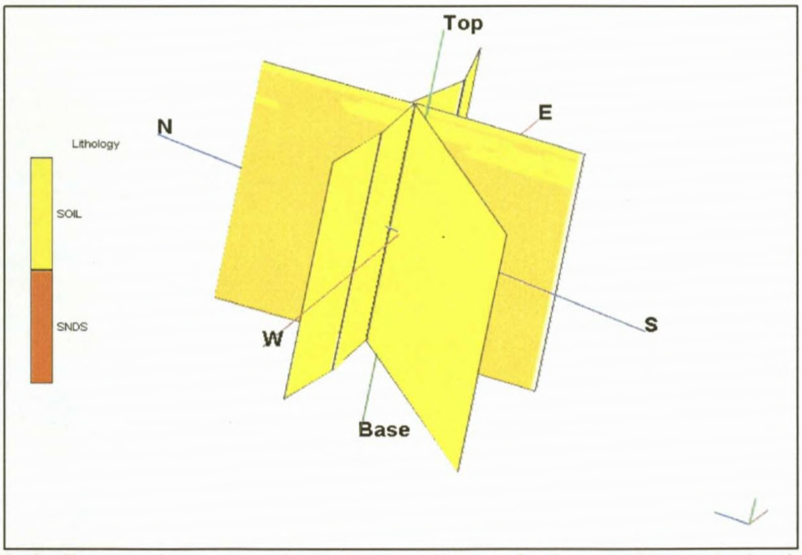


Figure 3-2: Fence diagram of geology at Pivot 1, drawn through the boreholes.

At Pivot 1 the hydraulic conductivity values (obtained from point dilution tests) in the weathered zone below can be as high as 140 m/d in specific zones or preferred pathways (Figure 3-3). This results in a flow zone above the solid rock. Pumping tests done at all the boreholes at this site indicated conductivity values for the aquifer itself as 0.001m/d. At Pivot 4 the highest conductivity values obtained in the weathered zone is 120 m/d (Figure 3-4), with the same values in the solid rock as at Pivot 1.

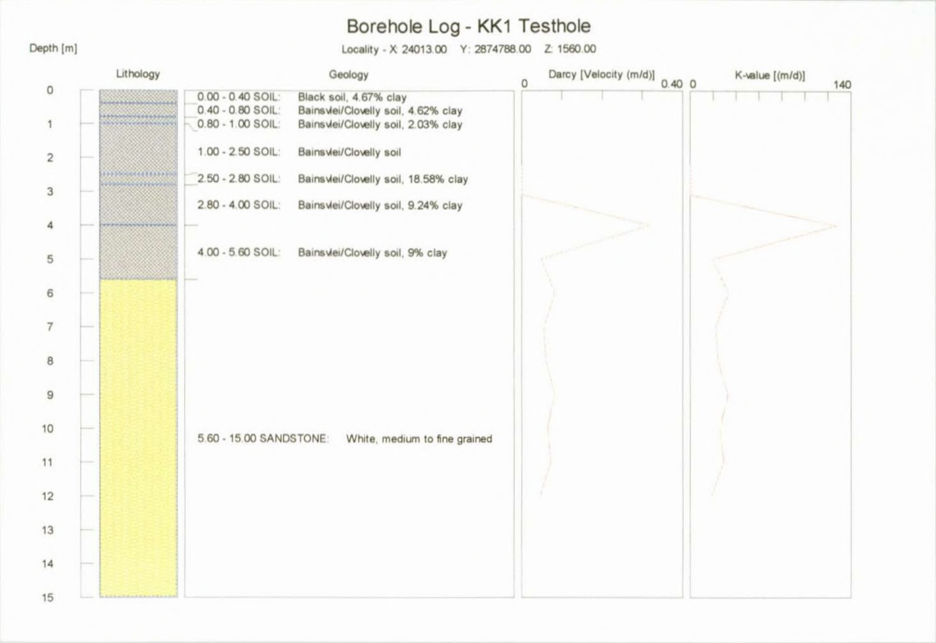


Figure 3-3: Geology and aquifer parameters at Pivot1.

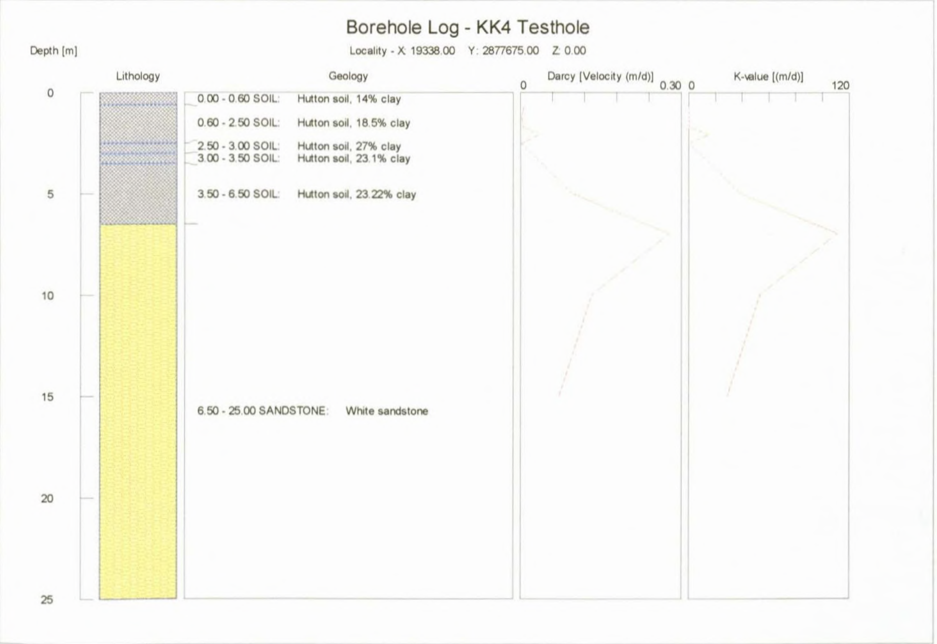


Figure 3-4: Geology and aquifer parameters at Pivot 4.

3.2.3 *Positioning of the monitoring boreholes*

Pivot1.

At this pivot, six of the ten boreholes were monitored regularly for water levels (Figure 3-5), but only five are used for hydrochemical profiling and water quality. The other boreholes were damaged due to agricultural activities and are inaccessible by samplers and probes.

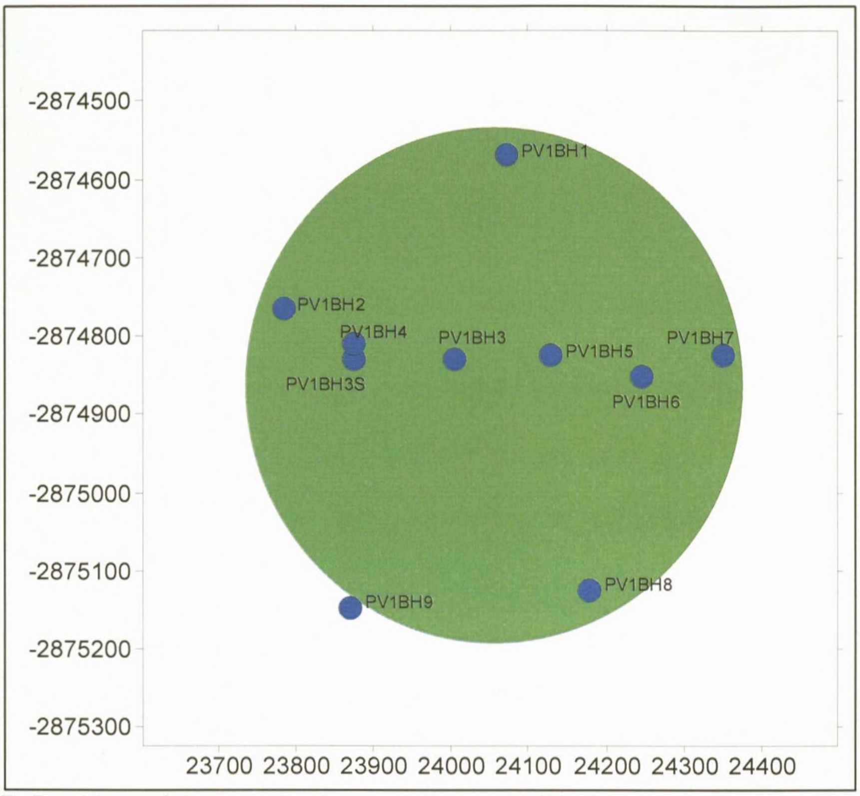


Figure 3-5: Position of the monitoring boreholes at Pivot1.

Pivot 4.

At this pivot six boreholes were monitored regularly for water levels, profiling and water quality (Figure 3-6).

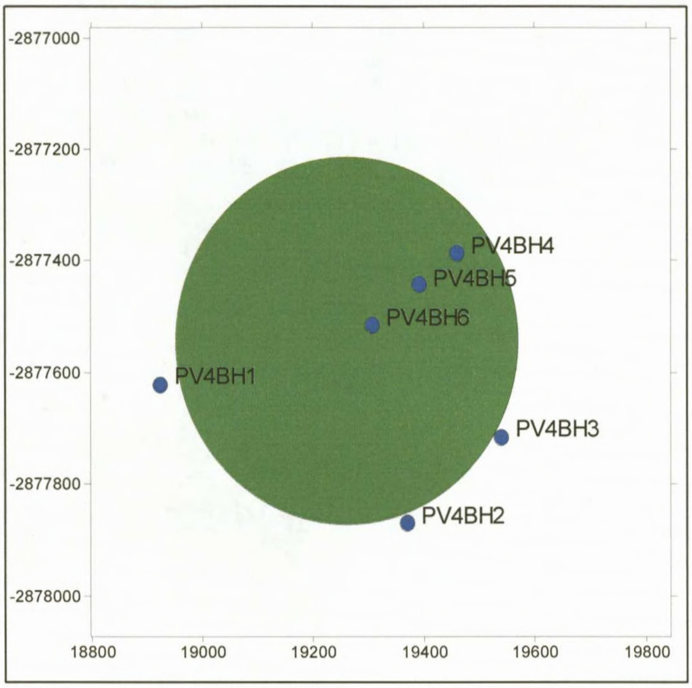


Figure 3-6: Position of the monitoring boreholes at Pivot 4.

3.2.3.1 Water levels

Pivot 1:

Figure 3-7 illustrates the groundwater levels at Pivot1. The water levels, as expected at an irrigation scheme, are very shallow.

- The time variation of the water levels indicates that the water levels fluctuate in correspondence with the seasons. Typically, the water level drops during the mid- to late winter months, and then recovers again during mid- to late summer.
- The rise in the water level during the early months of 2005 is due to high rainfall and excessive irrigation. Flooding was so great in this period that some of the boreholes (PV1BH-5, 6 and on occasion 7) could not be sampled at times.
- PV1BH-5 has a deeper water level than the other boreholes at the site. This borehole is drilled into the mine, and drains the groundwater in its vicinity into the mining cavity, resulting in the lower water level. This is a very important observation, as this influences the salt balance calculations in Chapter 6.

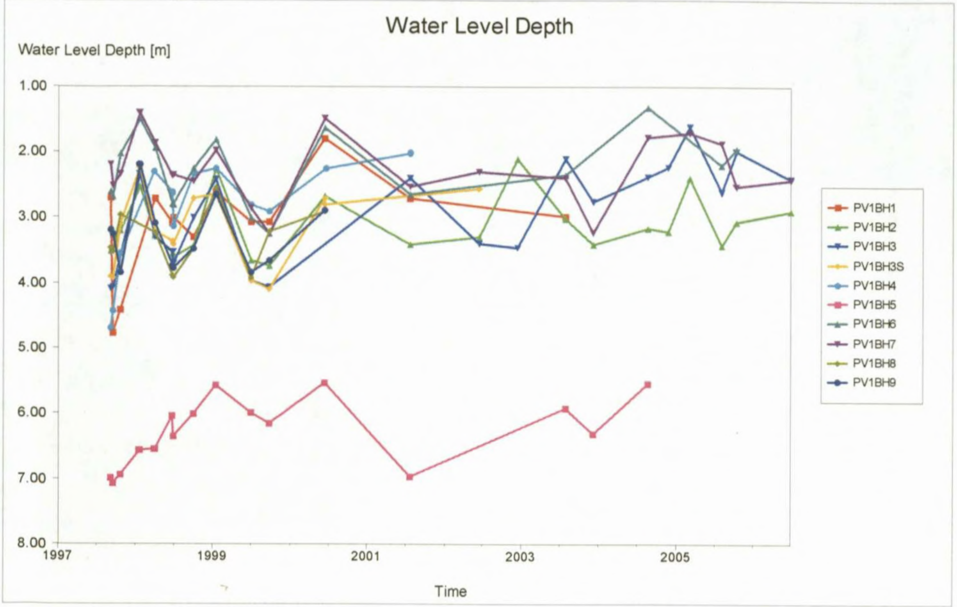


Figure 3-7: Water levels at Pivot1.

Pivot 4:

Figure 3-8 illustrates the groundwater levels at Pivot 4.

- The time variation of the water levels indicates that the water levels fluctuate in correspondence to the seasons. However, during early 2006 there was a rise in water levels due to the very high rainfall.
- Borehole PV4BH-1 and 2 have been destroyed since early 2005.

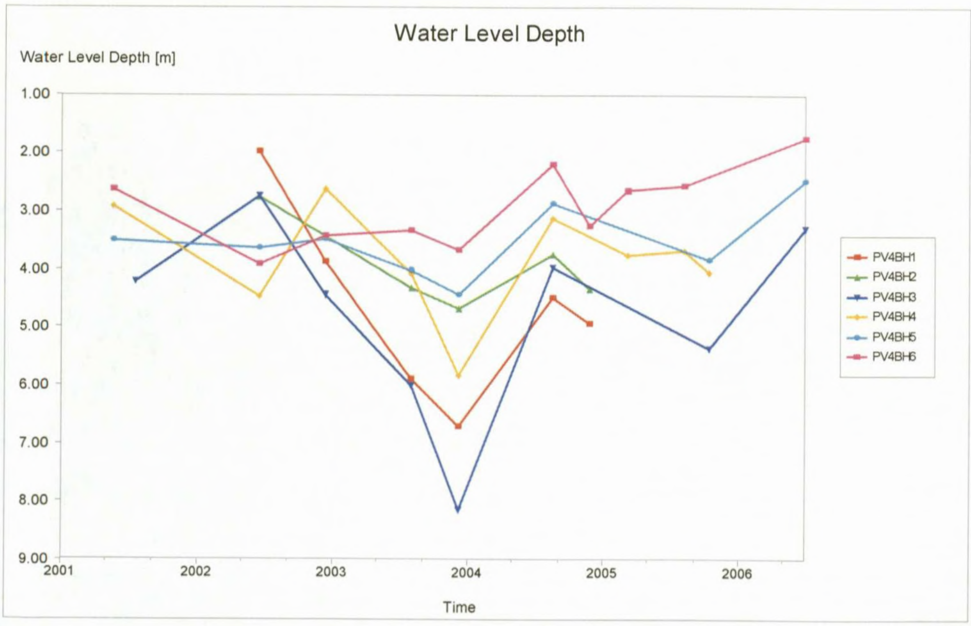


Figure 3-8: Water levels at Pivot 4.

3.2.3.2 Irrigation Water Quality

Pivot 1:

Irrigation is from water of the New Vleishaft dam adjacent to the pivot. This water is pumped from underground in the dewatering process ahead of mining. Table 3-1 depicts the average water quality of the irrigation water.

Table 3-1: (a) Average water quality over 4 years of the New Vleishaft dam at Pivot1 (from Annandale et al., 2006) with statistics on the water in table (b).

(a)

SiteName	pH	EC	TDS	Ca	Mg	Na	K
		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L
New Vleishaft dam	5.54	335	3313	581	242	51	12
SiteName	**PAlk**	**MAlk**	**Cl**	**SO4**	**Al**	**Fe**	**Mn**
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
New Vleishaft dam	20	21	13	2361	0.23	0.69	11.72

(b)

	pH	EC	Calcium	Sulphate
Minimum value	5.2	294	493	1935
Maximum value	6.2	408	697	2620
Standard deviation	0.43	45	87	277

The high TDS value is important. This is the total salinity that is being applied on the soil during irrigation. The pH value of 5.5 ensures that the metals stay in solution.

Pivot 4:

Irrigation is from a pan adjacent to the pivot. Water in the dam originates from the colliery. The water is Ca/Mg sulphate-rich, which is typical of water from Kleinkopje Colliery. The chemical modelling program PHREEQC indicated that the water is in equilibrium with gypsum, and saturated with dolomite and calcite. Table 3-2 depicts the average water quality of the irrigation dam. As is the case at Pivot 1, the TDS is very high.

Table 3-2: (a) Water quality of the Irrigation dam at Pivot4, with statistics on the water in table (b).

(a)

SiteName	pH	EC	TDS	Ca	Mg	Na
		mS/m	mg/L	mg/L	mg/L	mg/L
Irrigation dam	7.79	347	3585	448	266	88
SiteName	**K**	**PAlk**	**MAlk**	**Cl**	**SO4**	**NO3(N)**
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Irrigation dam	17	19	93	43	2192	0.08

(b)

	pH	EC	Calcium	Sulphate
Minimum value	6.4	271	293	1270
Maximum value	8.6	505	818	4392
Standard deviation	0.61	56	122	617

3.2.3.3 Multi-parameter Profiling Pivot1 (see Appendix D for Monitoring data).

In-situ measurements of water qualities were done at five localities at Pivot1.

- There is a slight increase in EC in the down-gradient boreholes BH5 and BH2 at 10m, which may be the result of the rock composition at that depth (Figure 3-9).
- There is no variation in any parameters in the higher lying boreholes BH6 and BH7.

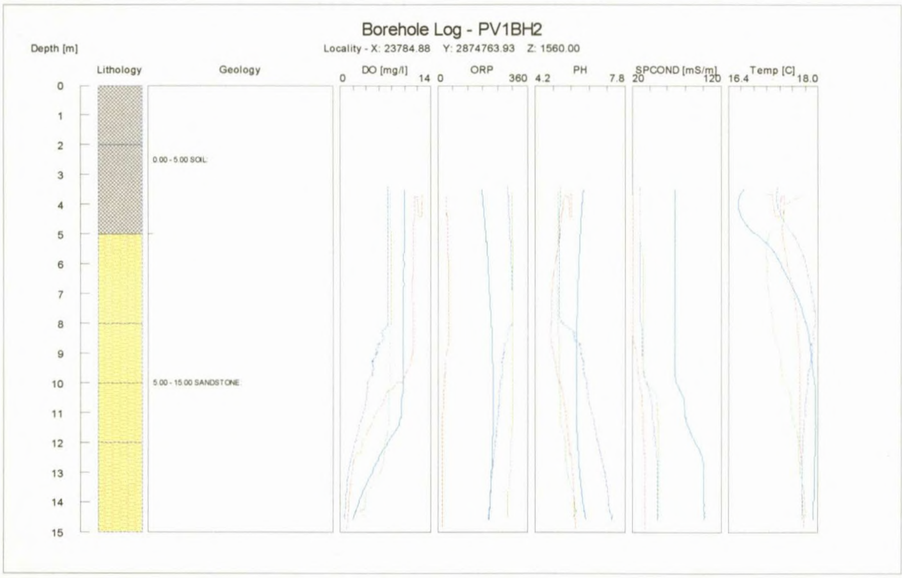


Figure 3-9: Multiparameter profiling at PV1BH2.

3.2.3.4 Multi-parameter Profiling Pivot 4. (see Appendix D for Monitoring data).

In-situ measurements of water qualities were done at six localities at Pivot 4.

- No significant variations occur with depth in any of the boreholes.
- EC values are very low.

3.3 New Vaal Colliery

The New Vaal pivot is situated next to the Vaal River, close to the town of Vereeniging (Figure 3-10). Monitoring at this site started early 2001. Maize, wheat, beans and potatoes were planted at this site. Irrigation has ceased at this pivot in 2005 due to problems with ponding at the surface, resulting in very low yields of crops.

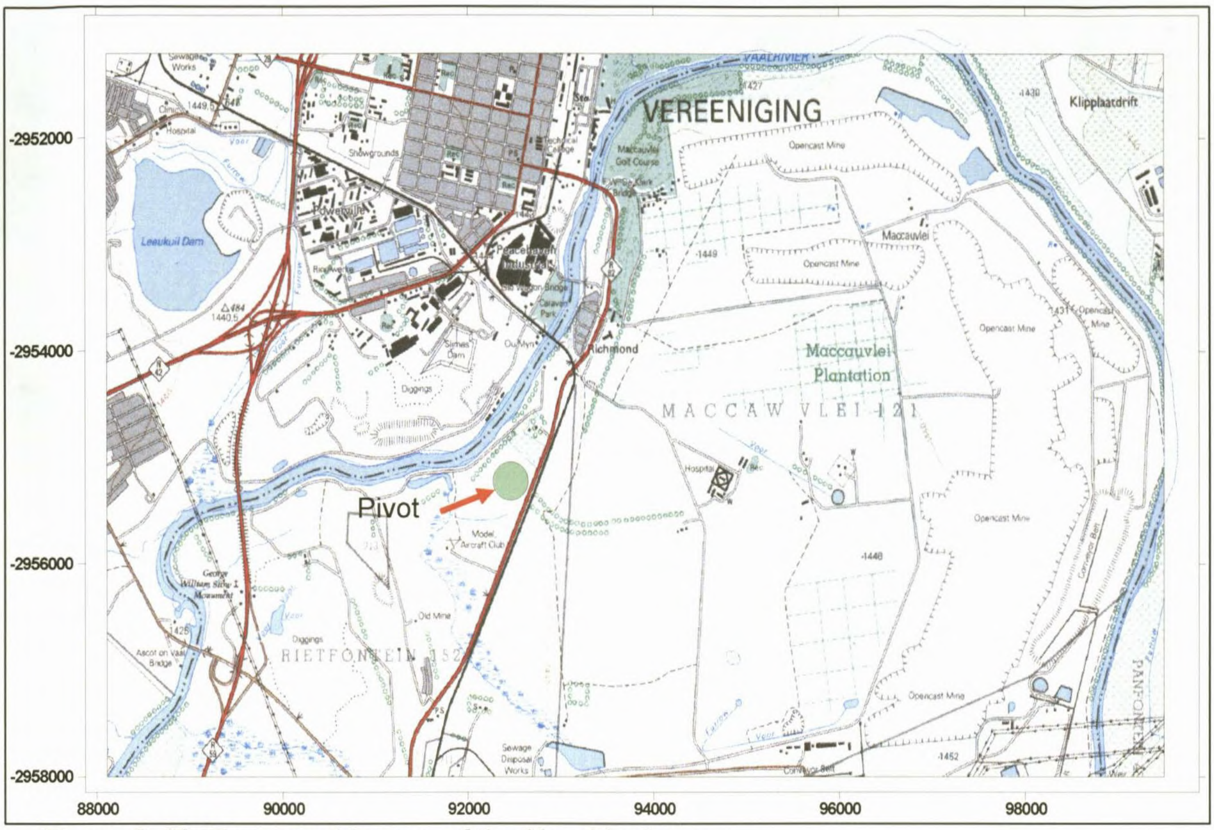


Figure 3-10: Topographic map of the New Vaal area.

3.3.1 *Surface Hydrology*

3.3.1.1 Rainfall

The annual rainfall (MAP) for the greater catchment area C22F (444 ha) is 643 mm (SA Weather Service - Rainfall station Vereeniging no. 0438784-3). The mean annual evaporation (MAE) for the area is 1650 mm, and the mean annual runoff (MAR) 24.3 mm (Midgley *et al.*, 1990).

3.3.1.2 Topography

The surface slope of the irrigation area is flat with a very slight dip towards the west and towards the river. The surface contours in Figure 3-11 illustrate this very clearly. Very little run-off will occur in this sandy area. All surface flow and expected groundwater flow is in a westerly direction towards the Vaal River.

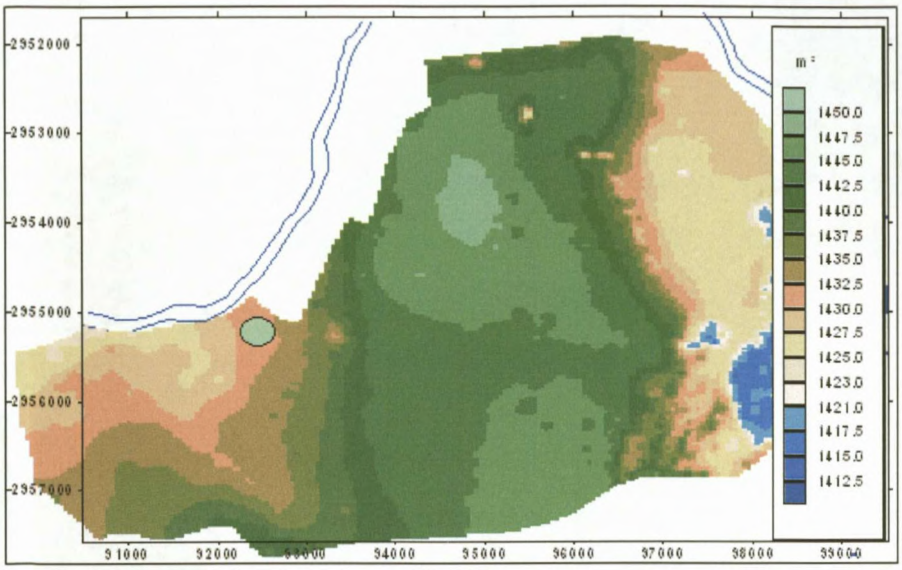


Figure 3-11: Surface contours for the New Vaal area.

3.3.2 *Geology*

3.3.2.1 Regional geology

New Vaal Colliery lies in the Sasolburg-Vereeniging Coalfield. The statigraphy of the coalfield is typical of the coal-bearing margins of the Karoo Sequence.

The succession consists of pre-Karoo rocks (dolomites of the Chuniespoort Group of the Transvaal Sequence) overlain by the Dwyka Formation (2-15 m thickness), followed by the Ecca Group sediments, of which the Vryheid Formation is the coal-bearing horizon. In some places the lava of the Ventersdorp Supergroup underlies the coal. The latter is present over the whole area and consists mainly of sandstone, shale and coal of varying thickness. An alluvium (sand) layer is present along the Vaal River. Dolerite intrusions in the form of dykes and sills are present over the entire coalfield and cause structural complications

3.3.2.2 Site-specific geology

Locally the encountered strata consist largely of soils, siltstones/shale and coal.

Figure 3-12 illustrates an integrated geological model for the underlying lithologies at the New Vaal pivot, based on the logs from the existing boreholes. A fence diagram in Figure 3-12 provides a more detailed cut through the model indicating the consistency of the different layers.

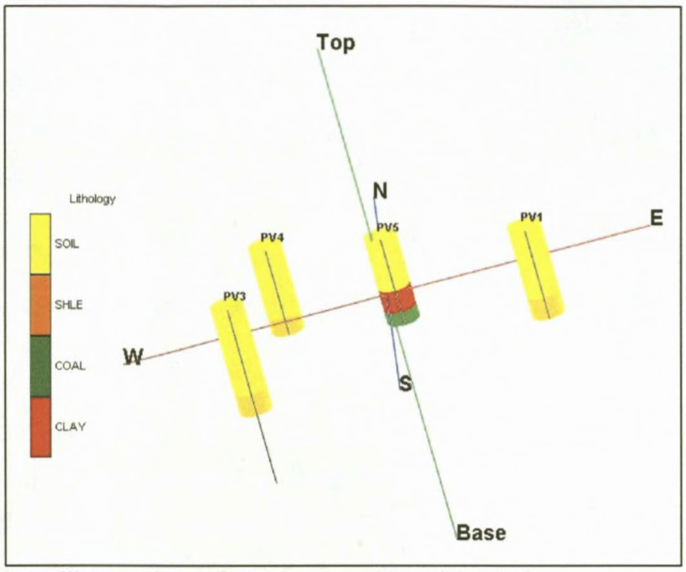


Figure 3-12: Log illustration of geology at New Vaal pivot.

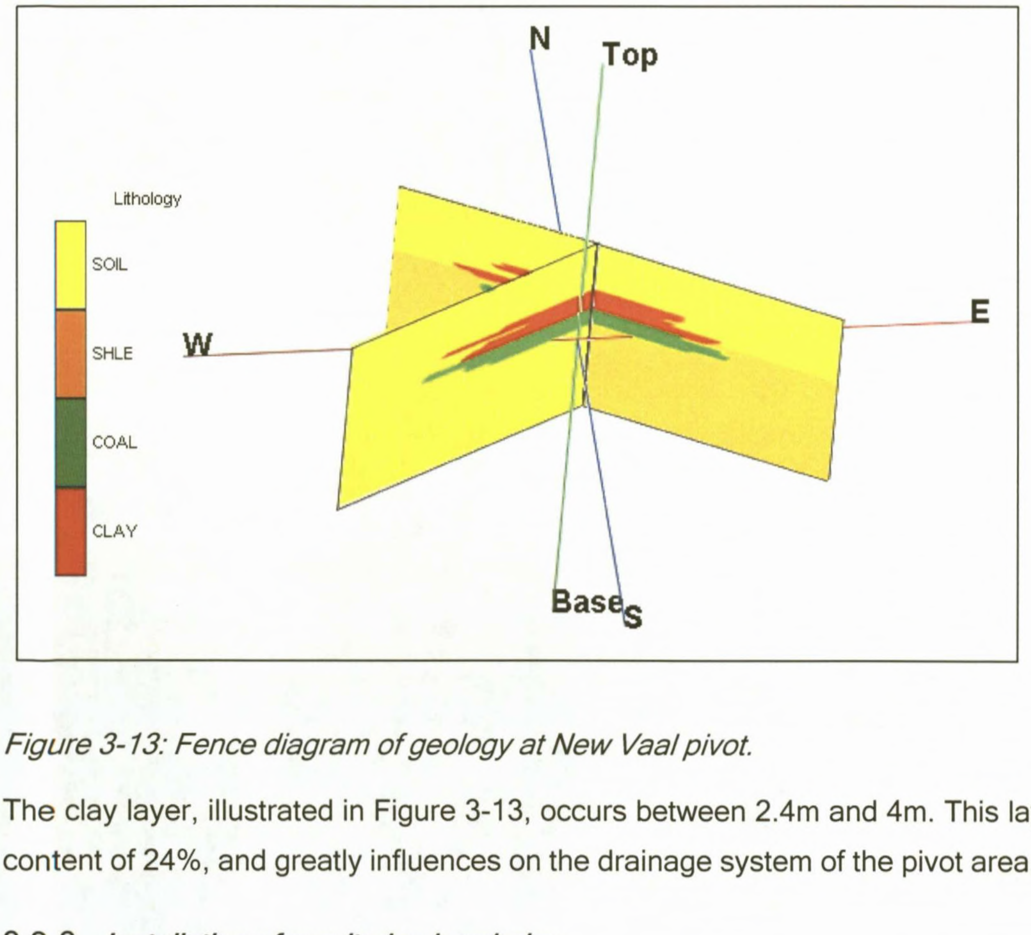


Figure 3-13: Fence diagram of geology at New Vaal pivot.

The clay layer, illustrated in Figure 3-13, occurs between 2.4m and 4m. This layer has a clay content of 24%, and greatly influences on the drainage system of the pivot area.

3.3.3 *Installation of monitoring boreholes*

Five monitoring boreholes were drilled at this site. These were spaced as indicated in Figure 3-14. These five boreholes were sited according to expected water flow. Boreholes NVPV1 and NVPV2 were placed for the purpose of obtaining background values. Boreholes NVPV3 and NVPV4 were located at the expected down-gradient side of the pivot, in order to obtain any irrigation water information, while Borehole NVPV5 was located in the centre of the pivot to obtain further water quality information on its expected path to the river.

All the boreholes were drilled to a depth of approximately 26 m. This depth was based on the on-site drilling, ensuring that the borehole was drilled approximately 10m into the geology below the alluvial system (Figure 3-14).

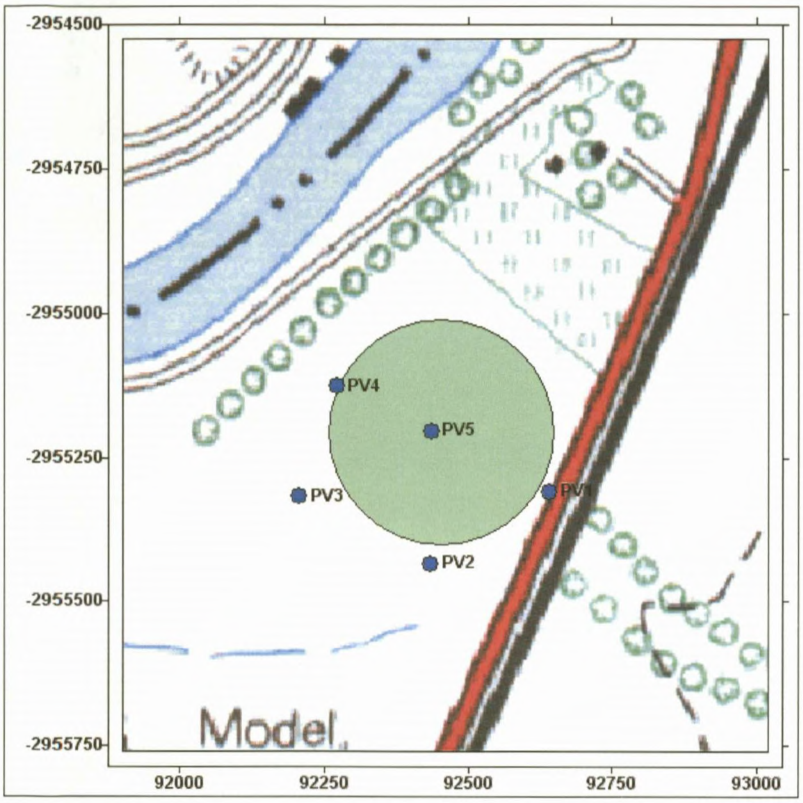


Figure 3-14: Position of the monitoring boreholes at the New Vaal Pivot.

3.3.4 *Water levels*

Figure 3-15 illustrates the groundwater levels at the New Vaal Pivot. The water levels are a little deeper than most other irrigation schemes. It was originally thought that this could be attributed to the high conductivity in the soils, resulting in rapid drainage towards the river. It appears, however, to be related to a clay layer at 2.4m - 4m that prevents most of the irrigation water from migrating downwards. This statement is supported by the water level of a short piezometer installed into the clay layer. The water level in the piesometer is less than 2m indicating the ponding of water above the clay layers identified during soil analysis (see Section 6.3.2). This was also observed when trenches were dug at this site. Over the course of the irrigation at New Vaal, areas of water logging were experienced due to the ponding in the soil.

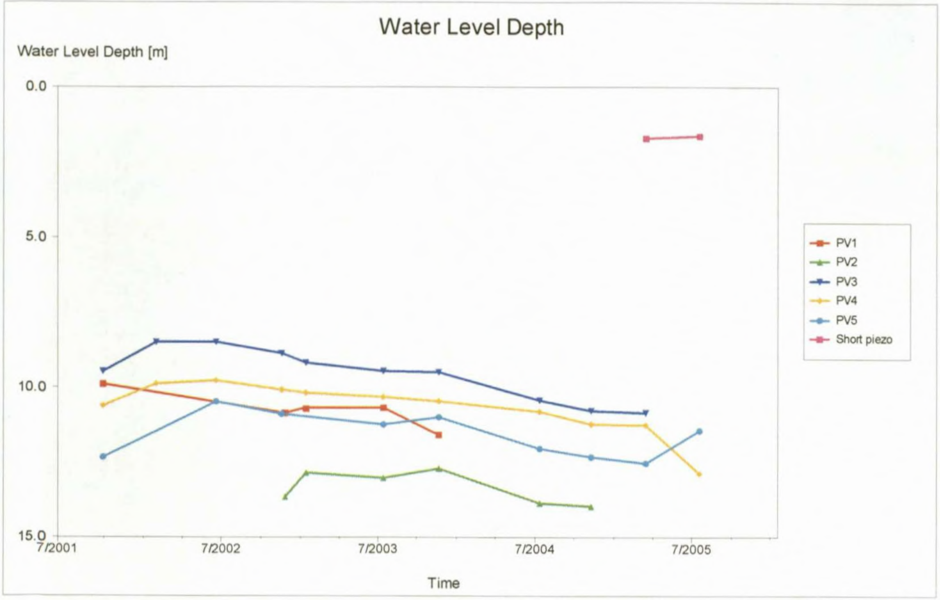


Figure 3-15: Water levels at New Vaal Pivot.

The water levels at New Vaal Pivot have varied very little over time, although a general decline in water levels is evident. The slight variations in water levels can be attributed to seasonal variation and associated rainfall. The water levels are relatively deep and different activities were undertaken to determine the reason for this, which will be discussed in chapter 6.

3.3.5 *Irrigation water analysis*

Irrigation occurs from Dam 595, adjacent to the irrigation site. Water in the dam originates from the colliery, as illustrated in the Durov diagram, showing the strong sulphate anion dominance, and with no specific cation dominance of the water in this dam (Figure 3-16).

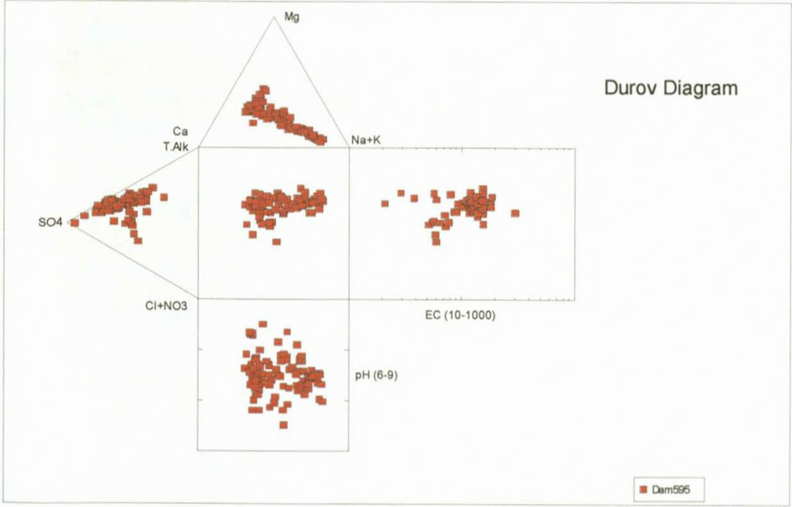


Figure 3-16: Durov diagram of the Irrigation Dam 595.

The illustration in the Durov diagram (Figure 3-16) and the water quality tables below depict calcium/magnesium/sodium sulphate water. Table 3-3 depicts the average water quality of the water sampled at the irrigation dam, with the standard deviation of 37 for EC. The quality of the water is of far better quality than at the Kleinkopje sites.

Table 3-3: Average water quality for the Irrigation dam 595.

SiteName	pH	EC	TDS	Ca	Mg	Na	K	PAlk
		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Dam595	7.5	125	904	86	31	124	5	29
SiteName	**MAlk**	**Cl**	**SO4**	**NO3(N)**	**PO4**	**Al**	**Fe**	**Mn**
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Dam595	242	44	410	0	2	0.16	0.30	0.08

3.3.6 *Multi-parameter profiling (see Appendix D for monitoring data).*

- The water quality in the groundwater was profiled with a multi-parameter probe. Multi-parameter logs ensure that water qualities are measured as they are in-situ, without disturbing the water column in the boreholes through sampling. Without such probing, sampling would be less precise and associated with greater uncertainity with regard to water quality variation.

In-situ measurements of water qualities were done at five localities in and around the pivot area at New Vaal. One such profile is illustrated in Figure 3-17.

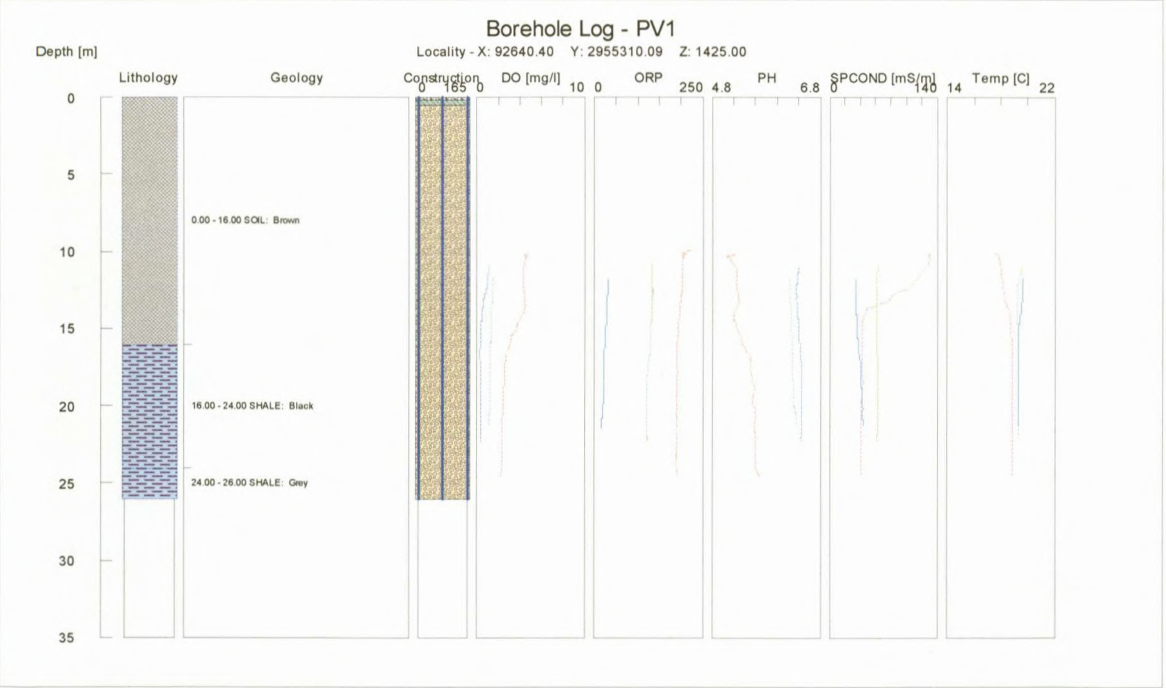


Figure 3-17: Multi-parameter profiling of PV1.

- PV1 is a background value with typical unpolluted aquifer parameters. The EC is low (46 mS/m) and the pH neutral.
- The measured values indicate clearly that the groundwater flow paths from the pivot do not intersect borehole PV4, as this borehole is unpolluted. A more westerly flow direction towards the Vaal River from the pivot is expected.
- PV5 is situated in the centre of the pivot. The measured values indicate clearly that the mine water used for irrigation has not impacted significantly on the water quality on the aquifer yet.
- The EC values in boreholes PV2 (above 300 mS/m) and PV3 are elevated (± 90-120 mS/m) compared to the previous three boreholes. These increases were influenced by spillage of water from the irrigation dam.

3.4 Syferfontein Colliery

Syferfontein Colliery is part of Sasol Mining and is situated between the towns of Trichardt and Kriel in Mpumalanga (Figure 3-18).

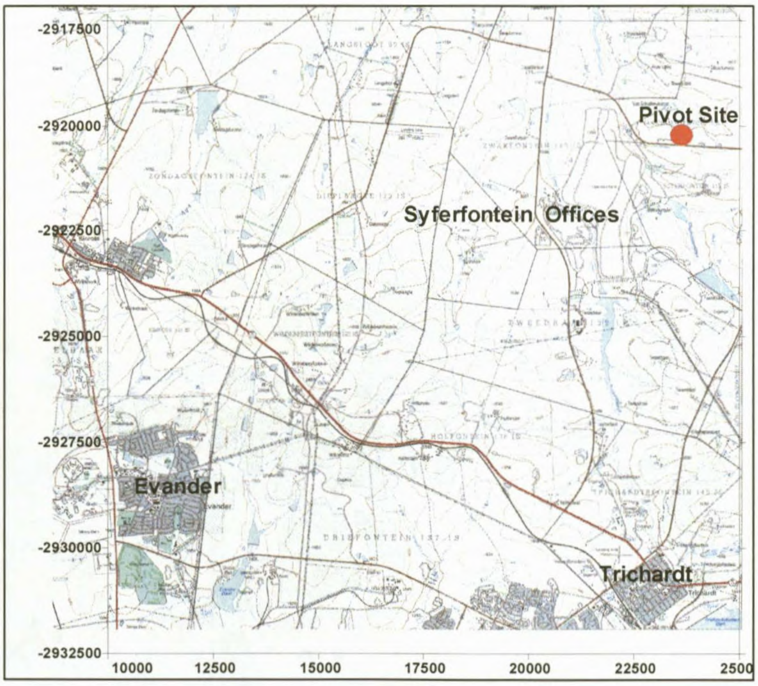


Figure 3-18: Regional setting of Syferfontein irrigation site.

Monitoring on a quarterly basis was performed till August 2004, when a conveyor that was constructed through part of the site (the grey strip in Figure 3-19), destroyed most of the monitoring holes. New boreholes OBH6 shallow and deep, 7 OBH and OBH 8 were constructed. Irrigation commenced again in October 2005. Since then a half circle was recommissioned. Only perennial grasses are being cultivated at this site.

3.4.1 *Surface Hydrology*

3.4.1.1 Rainfall

The annual rainfall (MAP) for the area at a 50% percentile is 708 mm (SA Weather Service - Rainfall Station: Secunda no. 047830-3). The mean annual evaporation (MAE) for the area is 1550 mm, and the mean annual runoff (MAR) 50 mm (Midgley *et al.*, 1990).

3.4.1.2 Topography

The surface slope through the irrigation area is to the north at an average gradient of 1:30. Boreholes were sited in such a way that any groundwater migration from the pivot would be intercepted by these boreholes (Figure 3-19). Borehole siting was done with consideration of the dyke positions and flow directions.

Borehole OBH3 was intended to monitor background water quality. The remaining boreholes are situated in the northeastern corner of the pivot adjacent to the test quadrant being researched by the University of Pretoria. An existing borehole, REGM-86, is also close enough to serve as a monitoring borehole and has therefore been included in the monitoring system.

Trenches were dug in 2001 to prevent the runoff water from the pivot area entering the boreholes from surface, thereby preventing skewing of the results.

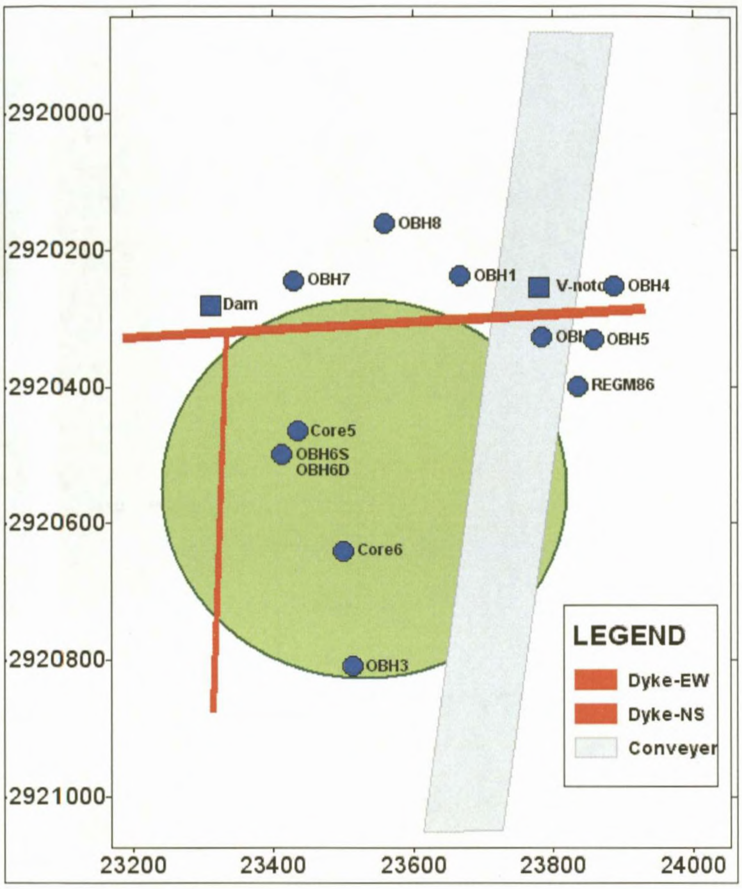


Figure 3-19: Pivot site showing the positions of the monitoring boreholes (with the positions of the dykes, provided by the mine's geologist).

3.4.2 *Geology*

Syferfontein lies in the Highveld Coalfield and is flanked by the Springs-Witbank and Ermelo Coalfields. The Karoo Sediments at Syferfontein comprise the Ecca Group (including the coal seams) and the Dwyka Formation. The total thickness of the Karoo Sediments ranges from 15 - 120 m. Regionally, the Ecca Sediments consist of sandstone, siltstone, shale, interbedded siltstone, mudstone and coal. Dolerite dykes and undulating sills are present.

The geology at Syferfontein is relatively homogeneous with the weathered sediments up to 10m deep. The strata mainly consist of 2 - 6 m soil, followed by dolerite to 10m, with a thin relatively impermeable layer of shale below the weathered zone. The shale is underlain by fresh sandstone with a white appearance. At the depth of 32-35 m the sandstone is again underlain by shale. Figure 3-20 illustrates an integrated geological model for the underlying lithologies at the Syferfontein pivot, based on logs from the existing boreholes. A fence diagram in Figure 3-21 provides a more detailed section of the model indicating the consistency of the different layers.

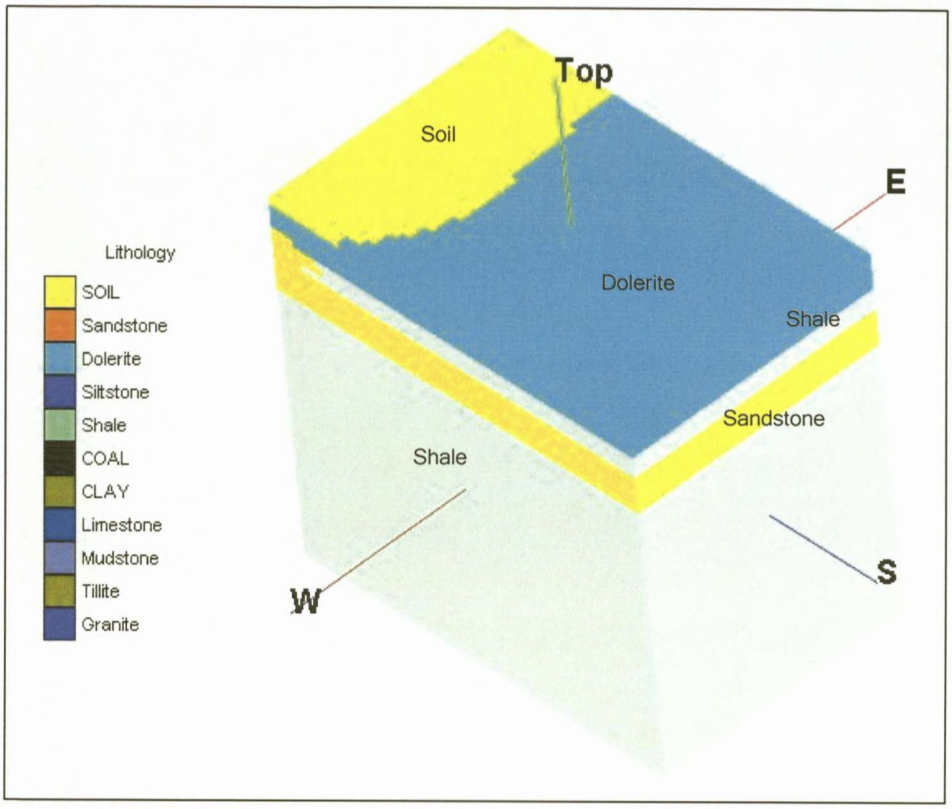


Figure 3-20: A model diagram of the geology at Syferfontein pivot, viewed from the south.

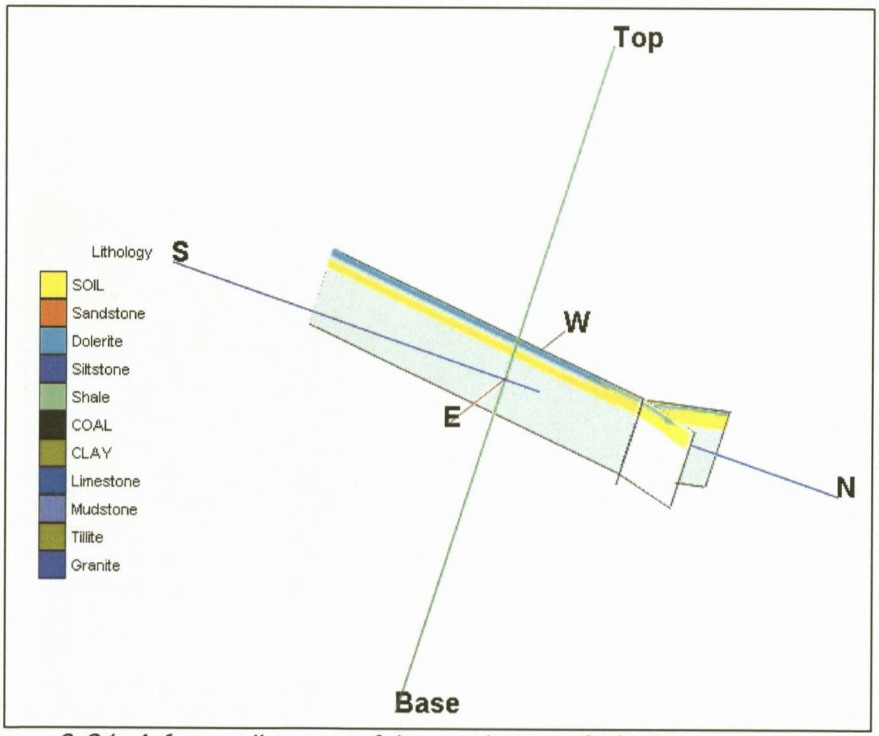


Figure 3-21: A fence diagram of the geology at Syferfontein pivot.

3.4.3 *Geohydrology at Syferfontein Pivot*

From the water strikes encountered in the drilling and from subsequent slug testing of the boreholes, it is clear that the underlying sediments have got very poor water-bearing properties. Generally the boreholes yielded little water during drilling, with minute quantities encountered above the shale layer lying at around 35 m.

Slug testing indicated that the sediments show a very poor response and a low hydraulic conductivity (0.001m/d) is inferred. In certain boreholes moisture (as opposed to definite water strikes) was associated with the shallower shale layer at approximately 15- 20 m. These shale layers can therefore be considered as barriers to vertical flow. Any water moving vertically from the irrigation should be impeded by this deeper lying shale layer. All the shallower layers show some signs of weathering and groundwater will be able to move vertically and laterally in these layers. This has been confirmed by point dilution tests performed, indicating conductivity values of as high as 50 m/d above the solid rock.

The low yields and aquifer parameters as obtained in the testing suggest that groundwater will migrate slowly from the pivot. Any degradation in quality due to the irrigation and fertilizer application will consequently be a largely localised phenomenon.

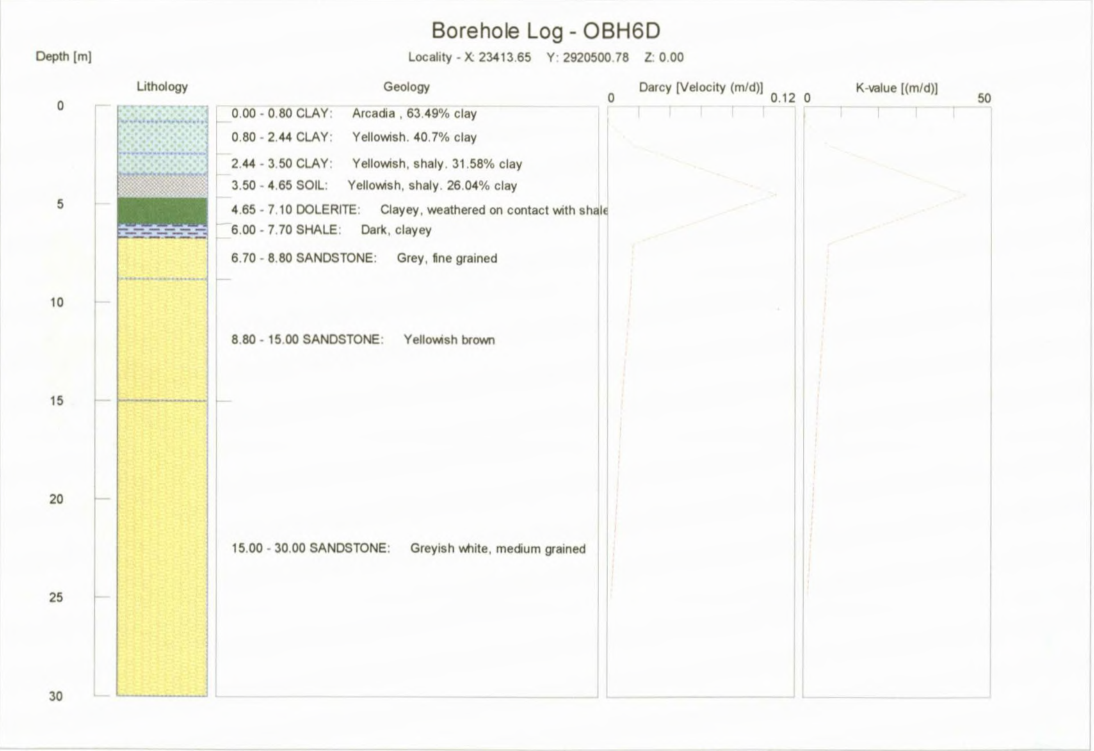


Figure 3-22: Geology and aquifer parameters at Syferfontein.

3.4.4 *Water levels*

Figure 3-23 illustrates the groundwater levels at the Syferfontein Pivot. The water levels, as expected at an irrigation scheme, are very shallow (3-5m below surface).

- All the water levels except those of OBH3 show a similar downward trend.
- The construction of the run-off trenches will also play part in the lower water levels.

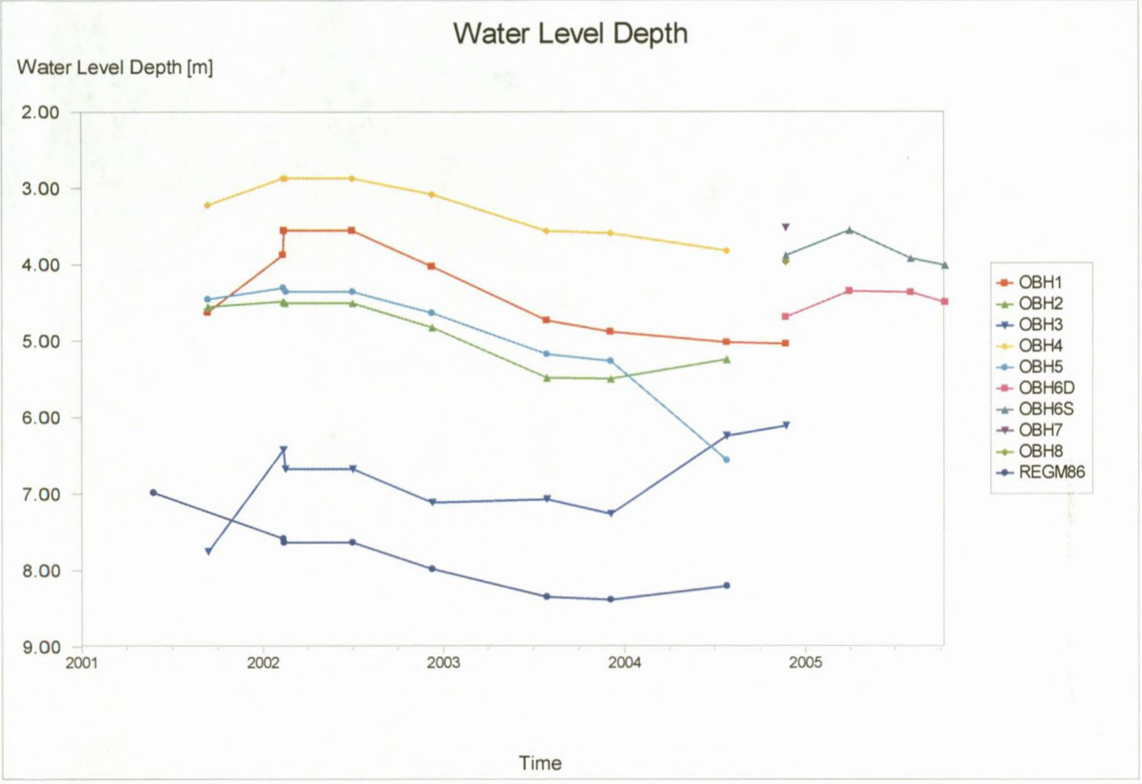


Figure 3-23: Groundwater levels for Syferfontein Colliery Pivot.

Of importance is the fact that the irrigation activities do not appear to have significantly affected the observed water levels, since these are at or below the levels measured when the boreholes were drilled in 2001.The dykes running though the area appear to be more important in delineating the different water level zones. It is important to note, however, that the two boreholes with deeper water levels are the upgradient boreholes OBH3 and REGM 86, which could both be considered to be less likely to be influenced by irrigation.

3.4.5 *Irrigation Water Quality*

Irrigation occurs from a dam adjacent to the pivot. Water in the dam originates from the colliery. The characteristics of this water are illustrated in the Durov diagram in Figure 3-24.

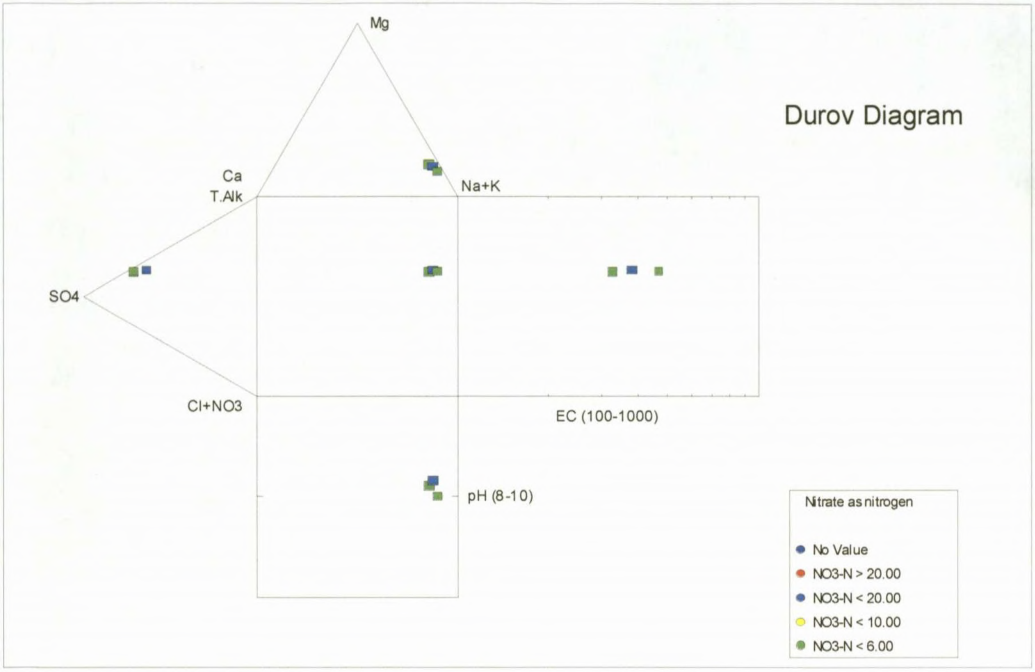


Figure 3-24: Durov diagram of the irrigation dam.

Table 3-4 depicts the average water quality of the water sampled at the irrigation dam with the standard deviation of 65 for EC. The water differs from that at the other irrigation sites in that it is sodium-rich.

Table 3-4: Water quality of the irrigation dam.

SiteName	pH	EC	TDS	Ca	Mg	Na	K	PAlk
		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Irrigation dam	9	335	2554	35	85	626	15	37
SiteName	**MAlk**	**Cl**	**SO4**	**F**	**B**	**Al**	**Fe**	**Mn**
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Irrigation dam	458	28	1372	1.03	1.11	0.032	0.059	0.015

3.4.6 *Groundwater Quality*

3.4.6.1 Multi-parameter profiling (see Appendix D for monitoring data).

In-situ measurements of water qualities were done at six localities in and around the pivot area at Syferfontein. As an example the in situ characterization of OBH1 is shown below in Figure 3-25.

Figure 3-25: Multi-parameter profiling of OBH1.

From Figure 3-25 it can be seen that there is very little variation in the different parameters with depth. Temperature increases slightly with depth. Dissolved oxygen shows the expected decrease of DO with depth as oxygen diffusion with depth decreases. The distinct shift in specific conductivity and pH in OBH1 during February 2002 (blue line) was the result of run-off water entering the borehole. The profiling indicates a two-year period before the water quality returned back to normal after the cut-off trenches were constructed.

3.5 Optimum Colliery

3.5.1 *Introduction*

Optimum Colliery is an opencast mine situated on the Mpumalanga Highveld between Middelburg and Hendrina, in the catchments of Woestalleen East, Woestalleen West and Zevenfontein Spruit, all tributaries of the Klein Olifants River, which discharges in the Middelburg Dam, upstream of the Loskop Dam (Figure 3-26).

The Optimum Colliery can be subdivided into four units: Optimus, Zevenfontein, Bothashoek and Pullenshope. The eastern Woestalleenspruit runs through the oldest pit, Optimus, and all the run-off from the pit ends up in the Fanies Dam and Lapa Dam (Hodgson, 1992). From there it flows through the Woestalleen Spruit and the Klein Olifants River to enter the

Middelburg Dam. The water in the pit is derived from groundwater, and recharged through the spoil from coal slurry disposal and surface run-off.

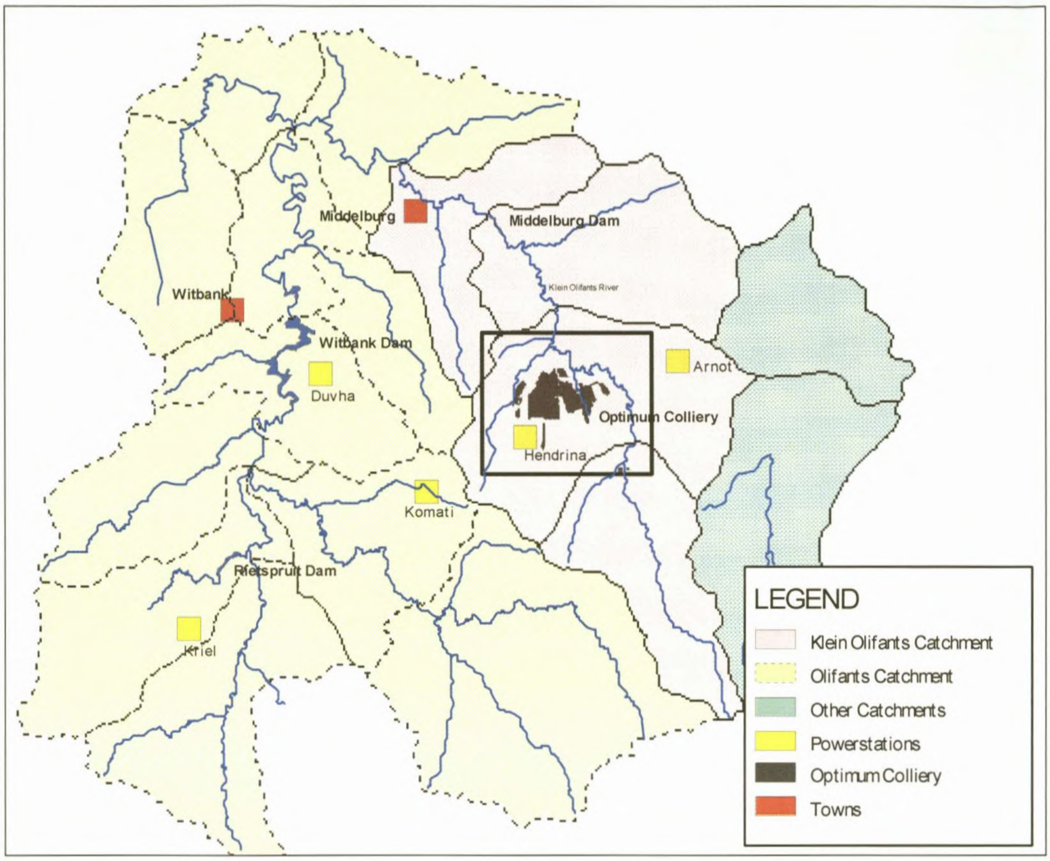


Figure 3-26: Locality plan of Optimum Colliery.

3.5.2 *Geology*

The area forms part of the Witbank Coalfield, which contains almost a fifth of South Africa's coal reserves (Cairncross *et al.*, 1990). The Karoo sandstones, mudstones, siltstones and coal seams of the Vryheid Formation are underlain by the Dwyka in the vicinity of the study area. Dolerite in the form of the Ogies Dyke strikes east to west through the study area and a small sill can be found on the eastern side of the Pullenshope section. Faults are rare in this area, but fractures are commonly found in the sandstone and coal (Krantz, 1993).

Mining results in the total topography disturbance. The mining depth varies from close to the surface to about 60m.

3.5.3 *Topography*

The pre-mining topography was reasonably flat, with pans situated on top of hills. The area has a mean elevation of 1600m above sea level. The drainage pattern is dendritic with all streams flowing into the Klein Olifants River in the north.

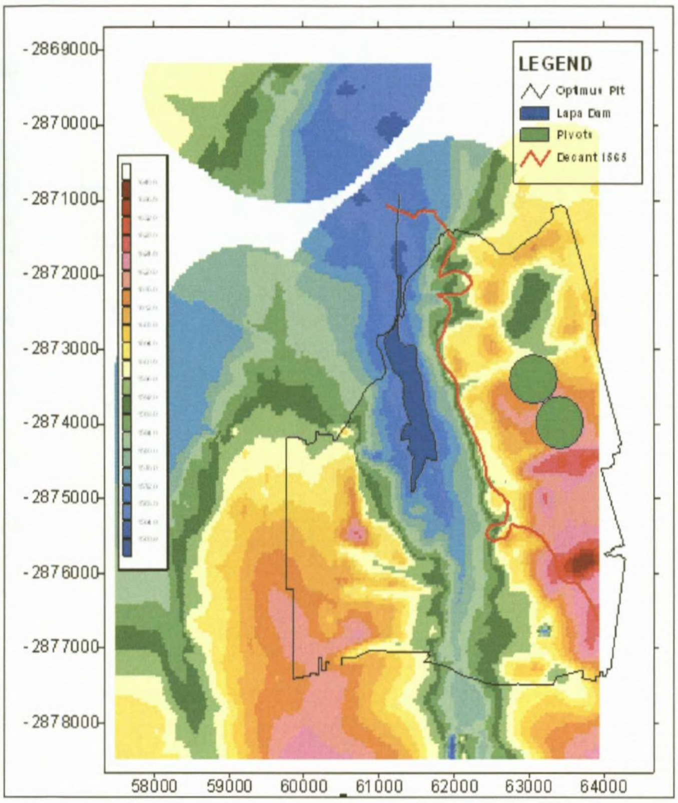


Figure 3-27: Surface contours in the area of Optimus Pit, indicating the position of the two irrigation pivots, as well as Lapa Dam.

3.5.4 *Geohydrology*

The two pivots are situated on the rehabilitated spoils of Optimus Pit, as indicated in Figure 3-27. The irrigation site is situated on a topographic high, with the flow directions towards the Lapa dam. The arrows in Figure 3-28 indicate the flow direction of the water in the spoils towards decanting in the Lapa Dam.

The decant value at the Optimus pit is at 1572 mamsl, where the water will stabilise in the pit. The floor of the pit below the irrigation site is higher than the decant point, resulting in all water in this area draining towards the Lapa Dam. The decant line is depicted in red in Figure 3-27. Therefore no borehole could be sampled in the vicinity of the irrigation, as the floor is always dry.

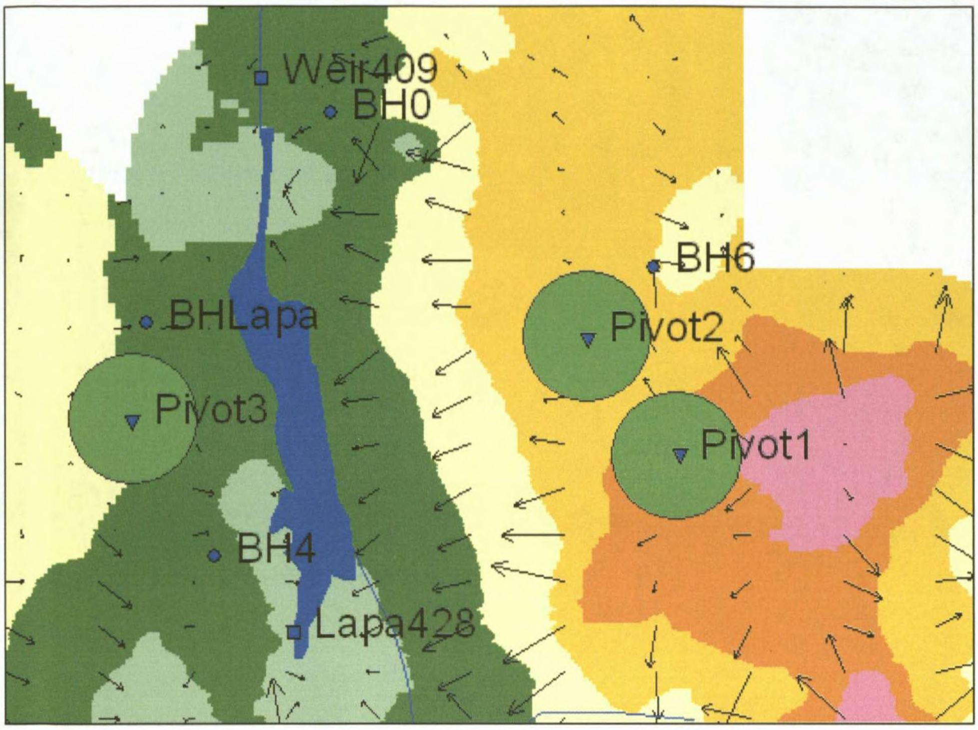


Figure 3-28: Floor contours, with flow directions indicated.

Irrigation water is pumped from the Lapa Dam. All excess water from irrigation will flow back through the spoils towards the decant level, and eventually end up in the Lapa Dam again. This will thus result in the circulation of irrigation water.

3.6 Summary

Each irrigation site differs from the others in either soil type, water quality and composition or mining methods. Therefore the approach regarding research at each site had to differ, as will be discussed in detail in the next chapters.

4 A REVIEW OF THE HYDRAULIC CHARACTERISTICS AND HYDROCHEMICAL IMPACTS OF IRRIGATION ON SOIL AND SPOILS

The main difference among the different research sites is the irrigation water quality and the type of soil on which the irrigation occurs. Of importance to the mining industry is the availability of soil for irrigation. Both virgin soil (in the natural state without any interference from mining activity) and rehabilitated spoils are important for future large-scale irrigation. The hydraulic and hydrochemical properties of these two options differ vastly.

4.1 Virgin soil irrigation

4.1.1 *The Unsaturated Zone (Vadose zone)*

The unsaturated zone (vadose zone) is the portion of the subsurface above the ground water table. It contains, at least some of the time, air as well as water in the pores. Its thickness can range from zero meters to hundreds of meters, as is common in arid regions.

Unsaturated flow represents an interesting challenge, namely the non-linear relation between degree of saturation, pressure and permeability.

Processes in the unsaturated zone.

- Water storage, plant nutrients, and other substances are present in the unsaturated zone (USGS, 2001). The unsaturated zone is not always considered a major storage component of the hydrologic cycle because it holds only a tiny fraction of the earth's fresh water, which is usually difficult to extract. It is however of great importance for storing water and nutrients in ways that are vital to the biosphere.
- Transmission of water and other substances occurs in the unsaturated zone. It is held by some hydrologic viewpoints as a zone that to a large degree controls the transmission of water to aquifers, as well as to the land surface, to water on the surface, and to the atmosphere. It may be a controlling factor in the amount of water that recharges an aquifer, or it may yield information that permits this replenishment to be quantified.
- The unsaturated zone contains natural and human-induced activity. Its constituents do not passively reside in place or pass through to the water table. The unsaturated zone experiences physical phenomena such as thermodynamic interactions, transport processes of various kinds, and chemical reactions. There are also chemical reactions involving both natural and artificial substances. There is the biological activity of plant roots, rodents, worms, microbiota, and other organisms. As a zone of

human activity, it is used all over the earth for the cultivation of plants, construction of buildings, and disposal of waste.

Water moves downwards through porous soils and sediments and, under favourable conditions, may preserve a record of weathering processes, climatic variations (in the Cl or isotopic signature), or human activities such as agriculture (NO_3) and acidification (H+). This record can be considered as the output from the soil zone and may reflect the properties or change in properties of soils.

The frequency of measurement suggested is 5-10 year intervals to confirm the movement of solutes towards the water table. Relatively homogeneous sediments are required where flow takes place uniformly (**diffusive flow**). In macro-pore media, possible by-pass flow (**preferred pathways**) needs to be taken into account, as when some contaminant travels relatively rapidly to the water table along fissures, root channels, mouse and mole holes, cracks in the soil, etc. The quality of groundwater reflects inputs from the atmosphere, from soil and water-rock reactions (weathering), as well as from pollutant sources such as mining, land clearance, agriculture, acid precipitation, domestic and industrial wastes. The relatively slow movement of water through the ground means that residence times in groundwater are generally orders of magnitude longer than in surface waters. Dispersion, reaction and mixing ensure that the addition of small amounts of contaminants is commonly difficult to detect. Below the water table, groundwater is not generally a good archive of past changes because of dispersion of the input signal.

4.1.2 *Unsaturated flow (matrix flow or diffusive flow)*

Even with the complexity of soil water flow, diffusive flow of water through soil will still occur. The rate of soil water flow is variable. Compacted soil layers that are so compact that they stop root growth will transmit water at slower rates, because of the smaller pore sizes. Irrigation water management must be tailored to account for rooting depths. If a compacted layer stops root growth, but not water movement, water and nutrients may move below the compacted zone and never be used by the crop.

In summary, waters flow through smaller pores partly due to gravitational forces, but also due to soil wetness or dryness. Water flows from wet to drier soil, but it flows more slowly in dry soil. The moisture content is dependent on the porosity and the permeability of the soil (de Marsily, 1986). Below a certain point the water content does not increase and the soil is said to be saturated, with all the pores filled. This water belongs to the **water table aquifer**.

Darcy's law and the concepts of hydraulic head and hydraulic conductivity have been developed with respect to a saturated porous medium where all the voids are filled with water.

$$Q = K\, A\, \Delta h/L$$

Where in the simplest form:

Q = Total discharge
$\Delta h/L$ = Hydraulic gradient **i**
K = Conductivity
A = cross-sectional area to flow

[Darcy's law is a simple mathematical statement which neatly summarises several familiar properties that groundwater flowing in aquifers exhibits (Wikipedia, the free encyclopedia, 2006), including:

- If there is no pressure gradient over a distance, no flow occurs
- It there is a pressure gradient, flow will occur from high pressure towards low pressure (opposite the direction of increasing gradient - hence the negative sign in Darcy's law
- The greater the pressure gradient (through the same formation material), the greater the discharge rate
- The discharge rate of fluid will often be different through different formation materials (or even through the same material if in a different direction)- even if the same pressure gradient exists in both cases].

However, soils are seldom saturated, especially near the surface. The voids are only partially filled with water, and the remainder of the pore space contains air. The flow under such conditions is called unsaturated flow. The water is subjected to the forces of gravity in the saturated zone, and to the capillary forces in the unsaturated zone. Water falling on the soil surface begins by moistening the upper few centimetres, and does not cause an immediate significant vertical flow. As rain or irrigation causes the water content to increase, the water spreads downward and moistens a deeper zone (Figure 4-1). If the wetting at surface continues long enough, the moistening will be progressively greater and eventually will cause infiltration into the aquifer.

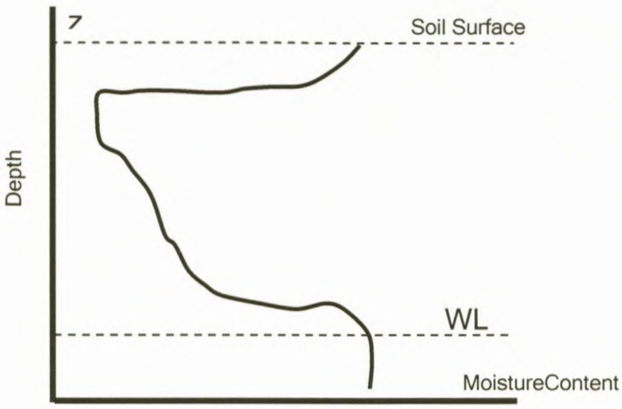
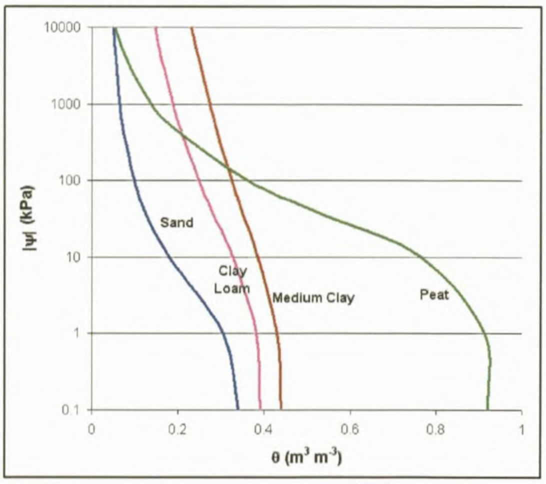


Figure 4-1: Typical moisture profile during rainstorm or irrigation (after De Marsily, 1986).

There are two characteristics that are critical to water movement, i.e. water content and hydraulic conductivity:

1. The most basic measure of the water in an unsaturated medium is **water content** θ or wetness, *defined as the volume of water per bulk volume of the medium.* Water is held in an unsaturated medium by forces whose effect is expressed in terms of the energy state or pressure of the water. Various types of pressure may be relevant in unsaturated hydrology, but one called the ***matric pressure or matric potential*** (arising from the interaction of water with the rigid matrix) is of unique interest, as it substantially influences the chief transport processes. *Matric pressure is the pressure of the water in a pore of the medium relative to the pressure of the air.* When a medium is unsaturated, the water is generally at lower pressure than the air, so the matric pressure is negative. The infiltration of water into the unsaturated zone can be considered mathematically in terms of both a gravity potential Z, and a moisture potential ψ (Childs, 1967). The moisture potential is at negative pressure due to the soil-water attraction. The moisture potential increases with decreasing amounts of soil moisture. Depending upon the soil-moisture content, either the moisture potential or the gravity potential dominates. At moisture contents close to the specific retention, the gravity potential is greater; but when the soil is very dry, the moisture potential may be several orders of magnitude greater than the gravity potential (Fetter, 2001).



Greater water content goes with greater matric pressure. Zero matric pressure is associated with high (saturated or nearly saturated) water content. As matric pressure decreases the water content decreases, but in a way that is nonlinear and hysteretic. The relation between soil moisture potential (matric pressure) and moisture content, called a moisture retention curve (right), is a characteristic of a porous medium that depends on the nature of its pores. This relation strongly influences the movement of water and other substances in unsaturated media.

2. The **hydraulic conductivity**, a measure of how easily water moves through the medium for a given driving force, is a second characteristic that is critical to water movement. The hydraulic conductivity has a highly sensitive and nonlinear dependence on the water content. Usually it is assumed that the flow rate of water is equal to the hydraulic conductivity times the driving force (typically gravity and pressure differences). This relation is known as Darcy's law. When the flow is steady, Darcy's law may suffice in itself for quantifying the flow. When the soil is not saturated, soil moisture flows downwards by gravity flow through interconnected pores that are filled with water and, to a lesser extent, as a film along particle surfaces in pores that also contain air. With increasing water content, more pores fill, and the rate of downward water movement increases. Darcy's law is valid for flow in the unsaturated zone, although the unsaturated hydraulic conductivity, $K(\theta_V)$ is not a constant. The unsaturated hydraulic conductivity is a function of the volumetric water content, θ_V. As θ_V increases, so does $K(\theta_V)$. The value of the moisture potential, ψ, is also a function of θ_V, often ranging over many orders of magnitude. The relationship between moisture potential and volumetric water content is determined experimentally for a given soil. The results are graphed as a soil-water retention curve. The total potential ϕ in unsaturated flow is the sum of the moisture potential $\psi(\theta_V)$ and the elevation head, Z:

$$\phi = \psi(\theta_V) + z$$

The water table is commonly regarded as the boundary between the unsaturated and saturated zone, but a saturated capillary fringe often exists above the water table. The water table is best defined as the surface on which the fluid pressure p in the pores of a porous medium is exactly atmospheric (Freeze and Cherry, 1979) or $p=0$. This implies that $\psi = 0$ and since $h = \psi + z$, the hydraulic head at any point on the water table must be equal to the elevation z of the water table at that point.

The relationship of unsaturated hydraulic conductivity and volumetric water content can be determined experimentally. A sample of rock is placed in a container. The water content is kept constant, and the rate at which water moves through the soil is measured. The value of $K(\theta_V)$ can be determined by Darcy's law.

Darcy's law in the unsaturated zone is given by:

$$q_Z = K(H)\frac{dH}{dz}$$

Where:

K (H) = unsaturated zone K, depending on moisture [water] content

θ = water content (degree of saturation)

H = total Head (m)

dH/dz = soil water gradient

H = h+z

h = matric potential (m) - or matric suction head

z = depth below surface (m)

Darcy's law was developed for saturated flow in porous media. To this Richards applied a continuity requirement suggested by Buckingham, and obtained a *general partial differential equation describing water movement in unsaturated non-swelling soils*. The transient state form of this flow equation is commonly known as Richards' equation and is a highly dynamic phenomenon. The equation may be represented quantitatively by a combination of Darcy's law and the continuity equation (Buckingham-Darcy flux equation). The Richards' equation (1931) combines both these laws in one formula:

Thus:

$$\frac{dH}{dz} = \frac{dh}{dz} + 1$$

And therefore:

$$q_Z = K(H)[\frac{dh}{dz} + 1]$$

Because of the hysteresis effect of *K(H)*, *K(θ)* is used instead which shows much less hysteresis:

$$q_Z = K(\theta)[\frac{dh}{dz} + 1]$$

with:

K = the hydraulic conductivity (m/s);

h = the pressure (matric) potential (m), i.e. soil water pressure head);

θ = the volumetric water content (m^3/m^3);

z = the gravitational potential or height above a reference level (m), i.e. the vertical distance taken positive upwards.

(For unsaturated conditions h is negative).

The use of measured or estimated hydraulic properties with formulations such as Darcy's law and Richards' equation can quantify the movement of water (matrix flow) in the unsaturated zone. The flow rate of water is often very directly of interest, for example in estimating how fast water moves down to the water table. It is also critical in the transport of contaminants, whether they are dissolved in the water or moving in a non-aqueous liquid or solid form. The usual first step in assessing the rate of contaminants spreading in the subsurface, is to assess the flow rate of water that to some degree moves the contaminant along with it.

Using of this formula requires the knowledge of two properties of the medium: the unsaturated hydraulic conductivity, and the differential water capacity, which can be directly calculated from the water retention curve.

For a wetting front (infiltration) the equation reduces to $q_z=K_s$ (because the gradient becomes 1 very quickly at saturation). To solve this equation, $K(\theta)$ and h must be known. The relation between θ and h is called the soil water retention curve, as discussed earlier in the section.

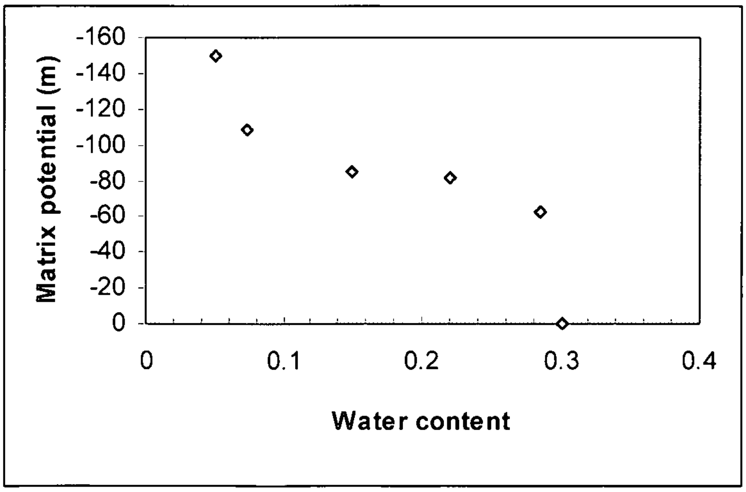


Figure 4-2: Soil water retention curve. Notice that the saturated porosity is equal to the water content where the matric potential = 0 m (i.e. 0.3 in this graph). In practice, no flow occurs if the matric potential is smaller than -10 m.

At saturation, the most conductive soils are those in which large and continuous pores constitute most of the overall pore volume (e.g. sand), while the least conductive are the soils in which the pore volume consists of numerous micropores (e.g. clay).The relation of K and suction (or wetness) can be derived from the well-known equation of Van Genuchten and can be illustrated in a very simple form (Botha, 1996) as:

$$K(\theta) = Ks(\frac{\theta - \theta_r}{\theta_s + \theta_r})^{5/2}$$

Where:

θ_r= residual moisture content

θ_S = moisture content

$K(\theta)$ = unsaturated K

Ks = saturated K

The unsaturated K for a specific moisture content and saturated K-value can thus be determined from a graph (Figure 4-3). The saturated K used can be estimated from the clay content of the soil (Kirchner *et al.,* 1991). This is discussed in more detail in Section 6.6.6 and illustrated in Appendix D Calculations "Unsaturated K", contained on the DVD.

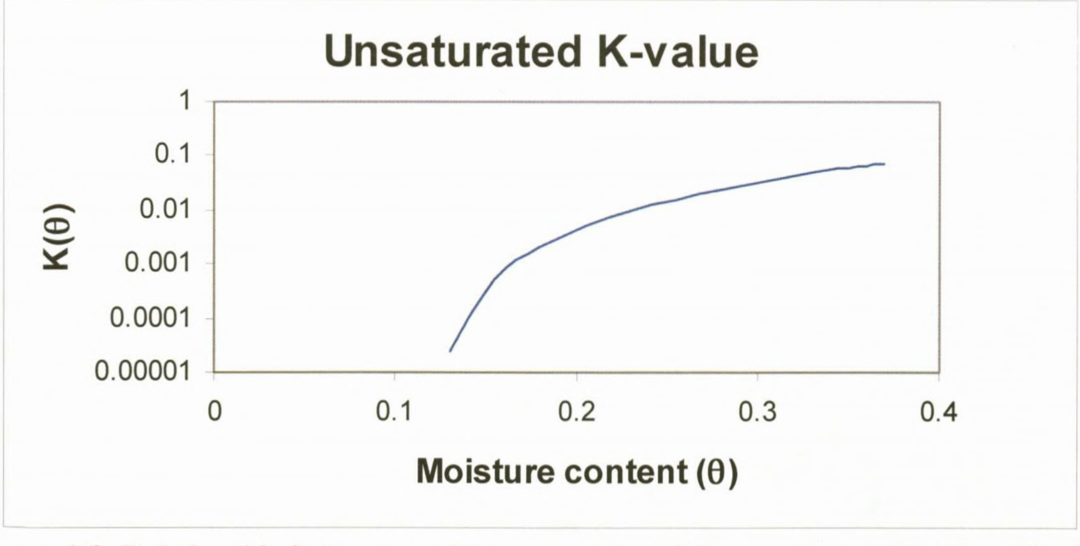


Figure 4-3: Relationship between moisture content and the unsaturated K-value. Note that the saturated K-value (i.e. K_s) is the value where the water content is equal to the saturated porosity (θ_s).

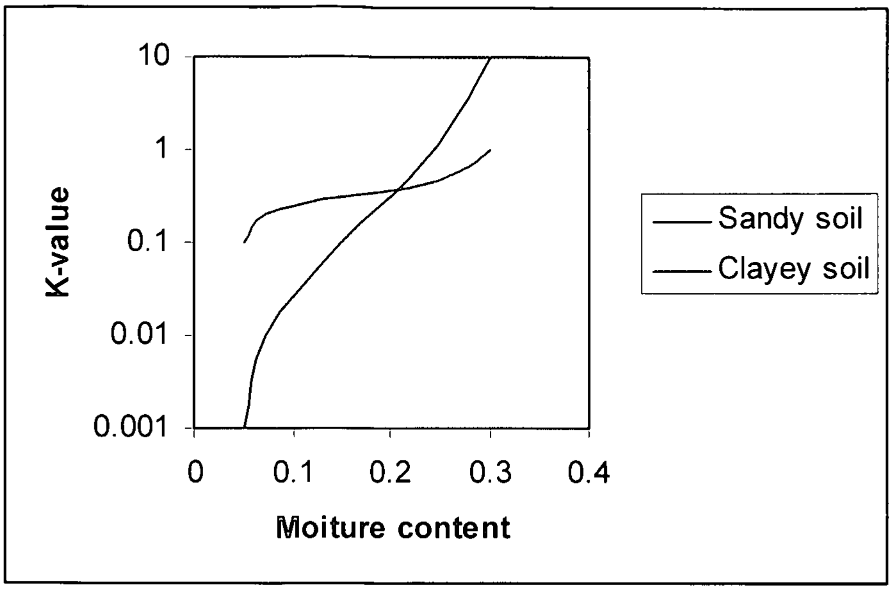


Figure 4-4: Example of K-value for sandy and clayey soil.

One important consideration in unsaturated flow is that at low volumetric content, the relations that hold true in saturated flow may be invalid (Fetter, 2001). The best example is the fact that for coarse materials such as sand and gravel, the pores are large and drain quickly. At lower volumetric moisture contents, there may be very few saturated pores. On the other hand, most of the pores in finer-grained soils may still be saturated. In a soil with large pores, these pores quickly empty and become nonconductive as suction develops, thus steeply decreasing the initially high conductivity. In a soil with small pores, on the other hand, many of the pores retain and conduct water even at appreciable suction, so that the hydraulic conductivity does not decrease as steeply and may actually be greater than that of a soil with large pores subjected to the same suction. Since the soil in the field is largely unsaturated, it often happens that flow is more appreciable and persists longer in clayey than in sandy soils. For this reason, the occurrence of a layer of sand in a fine-textured profile, far from enhancing flow, may actually impede unsaturated water movement until water accumulates above the sand and suction decreases sufficiently for water to enter the large pores. This simple principle is all too often misunderstood (Hillel, 1982).

Thus, at lower values of θ_V the unsaturated hydraulic conductivity of clay may be greater than that of sand. A layer of sand in a fine-textured, unsaturated soil may retard the downward movement of infiltrating water owing to its low unsaturated hydraulic conductivity. The ratio of surface area to volume of a particle is inversely proportional to its radius. The surface area of grains exposed to pores in a fine-grained porous medium is thus larger than in a coarse-grained porous medium. A fine-grained porous medium may therefore contain more fluid than a coarse-grained porous medium, but will also adsorb a much larger volume of fluid. This explains why a clayey formation, with its fine-grained matrix, forms a poor aquifer, although it may contain larger quantities of water than a corresponding coarse-grained sand aquifer. Less force will thus be needed to remove water from a pore with a large radius than from one with a small radius. Pores with large radii, therefore, will drain before pores with smaller radii in unsaturated flow.

4.1.3 *Preferential flow (macropore flux)*

4.1.3.1 Introduction

It is usually assumed on a macroscopic scale, water flow in soils obeys Darcy's law. This assumption is not valid in structured or aggregated soils in which varying flow velocities occur on a macroscopic scale (Hutson, 1983). Water applied to the soil surface initially moves rapidly through macropores and other pathways, but more slowly through finer matrix pores. By Poiseuilles law, the total flow rate of water through a capillary tube is proportional to the fourth power of the radius, while the flow rate per unit cross-sectional area of the tube is proportional to the square of the radius. A 1-mm-radius pore will thus conduct the same amount of water as 10 000 pores with a radius of 0.1 mm each. There is thus a short-circuiting effect that causes the water to be transmitted rapidly into the profile along larger pores, cracks and other channels, leaving the fine matrix relatively dry. (Darcian models will be most applicable to horizons that have a micropore system. All water will enter and leave the horizon vertically. Any lateral flow will thus invalidate such Darcy models).

Preferential flow refers to the uneven and often rapid movement of water and solutes through porous media (typically soil) and fractured media, characterised by regions of enhanced flux, so that a small fraction of media participates in most of the flow, allowing much faster transport of a range of contaminants, including pesticides, nutrients, trace metals, and manurial pathogens (Steenhuis *et al.*, 2002). This creates significant consequences for groundwater quality (Figure 4-5). High pesticide concentrations which are associated with preferential flow phenomena, were initially described by Lawes *et al.* (1982). During field drainage experiments, the authors distinguished between preferential and matrix flows (diffisuve, piston like), and pointed out that the relative importance of the two kinds of drainage depends on soil type and rainfall intensity. Matrix flow is the relative slow and even movement of water and solutes through the soil while sampling all pore spaces, obeying the convective-dispersion theory, which assumes that water follows an average, flow path through soil (Figure 4-6). These two types of flow affected solute transport differently.

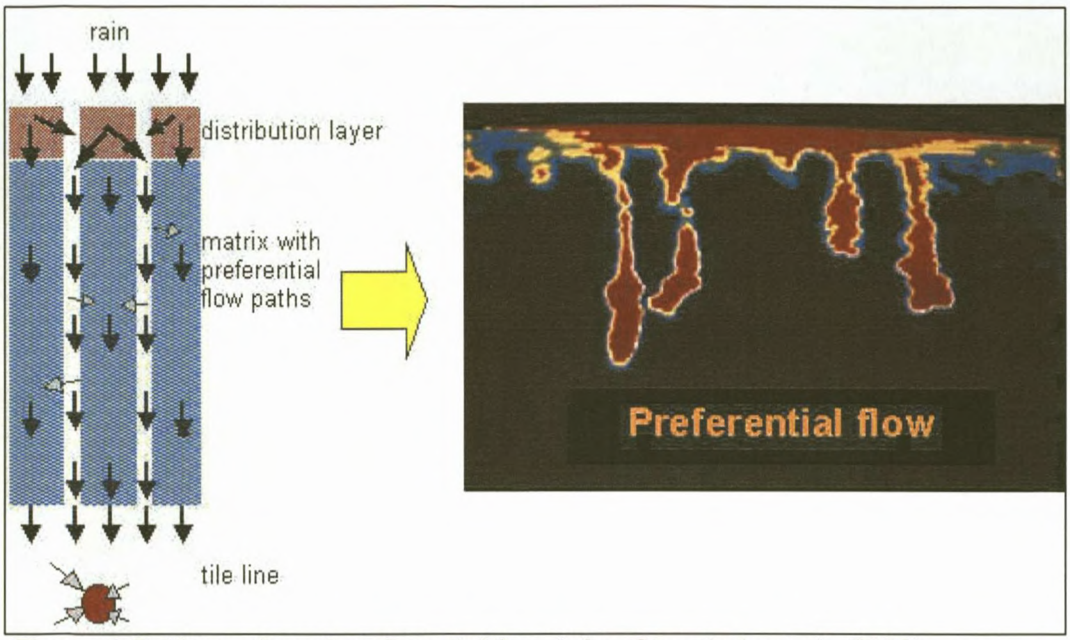


Figure 4-5: Illustration of preferential flow (after Steenhuis et al., 2002)

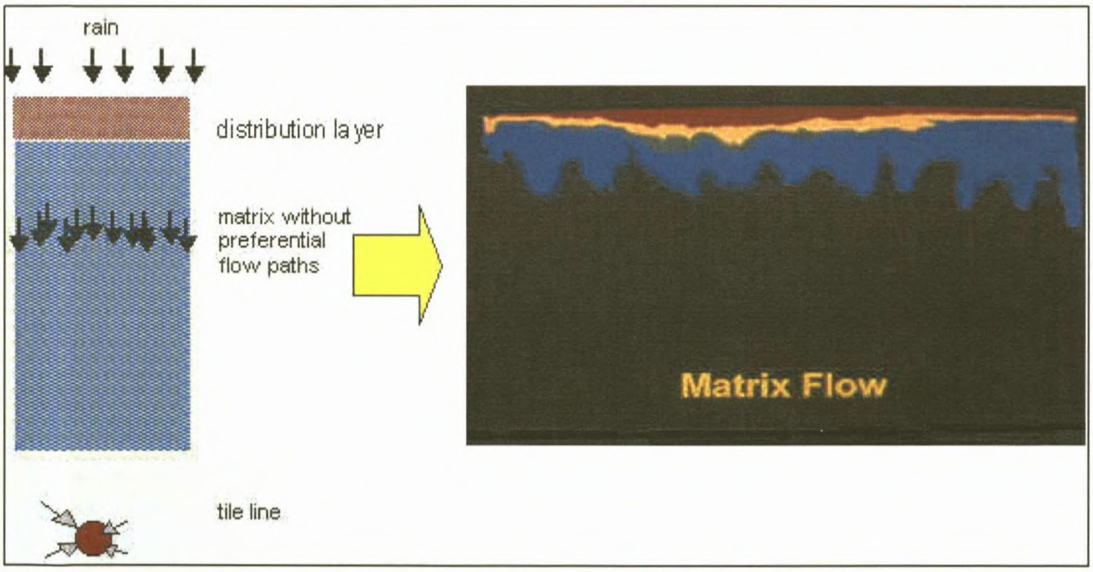


Figure 4-6: Illustration of matrix flow (after Steenhuis et al., 2002).

Due to its rapid movement, preferential flow allows much faster contaminant transport, creates significant consequences for groundwater quality and has direct impacts on drinking water and human health, animal waste management, nutrient and pesticide management, and watershed management. In the mining sector, the phenomenon of preferential flow has been used in designing the best configuration for tailings left behind by mining operations. By including clean material at strategic places where preferential flow is directed, the toxicity of leachates can be greatly reduced. Because of the rapid movement of the water, the dilution factor is also much larger, and concentrations measured in the water will be greatly reduced.

Subsurface preferential flow, in which small areas of the subsurface carry large portions of the flow, has been observed in a variety of soils (Hill and Parlange, 1972; Beven and Germann, 1982; Glass *et al.*, 1987, 1989; Baker and Hillel, 1990; Ritsema and Dekker, 1994 and Johnson *et al*, 1983). As preferential flow provides a mechanism to bypass most of the porous media, the effects include enhanced solute transport, less filtering and adsorbing of contaminants in the soil, and fast travel to groundwater or flow lines. Preferential flow can result from macropores and other inhomogeneities (Beven and Germann, 1982), but it has also been observed in uniform soils with uniform rainfall and low application rates. Sharma and Hughes (1985) studied the groundwater recharge in Western Australia and concluded that more than 50% of recharge occurs through preferred pathways bypassing the soil profile. If this is the case for sandy coastal aquifers, it can also be valid for the porous soils at the research sites.

Kirchner *et al.* (1991) studied recharge in the Dewetsdorp aquifer in the central parts of South Africa, using 20 neutron moisture probes at 13 sites with different types of soil to a depth of 1.7m. The Zero Flux Plain (ZFP)-method, based on locating the point of zero hydraulic gradient, and thus the zero reference flux in the soil profile, summing up the changes in water content below that point, was used. It was found that even during the 1988 floods in the central parts of South Africa a zero flux plain still existed. This implies that there was no water movement through that plain. The only explanation for this behavior of the unsaturated zone is that recharge has occurred along preferred pathways by bypassing the soil matrix. Iinfiltration took place through the soil matrix of the upper (30 cm) of soil. Measurable downward fluxes occur, until a relatively heavy clay layer is reached, from where the water movement is predominantly horizontal. At specific locations the clayey layer may have wide cracks, leaving a pathway for water to travel along. Dieleman and De Ridder (1963) found similar results when studying the recharge near Lake Chad in Central Africa. In a similar study at another test site at De Aar in the Karoo by Kirchner *et al.* (1991) tests yielded a saturated K-value (K_s) of $1*10^{-4}$ m/d for the first seven days after the start of the experiment, and for the next 14 days no measurable amount of water flow occurred due to swelling of the clay. However, after the flood, some movement through the matrix did occur. (The determination of the unsaturated K-value is an integral part of the calculations of the Darcy fluxes in the unsaturated zone). The unsaturated K value is related to the saturated K-value measured ($4.3*10^{-3}$ m/d) and was calculated at $7*10^{-6}$ m/d. With the total recharge, measured at 5% in the aquifer during the 30 days after the flood, this low value ($7*10^{-6}$ m/d) could only be representative of the soil matrix, and strengthens the belief that recharge had also taken place along preferred pathways. At this site it was also found that downward infiltration occurred until a clayey layer was reached, from where the movement of the soil water is predominantly lateral. Wood *et al.* (1997) found that at the Southern High Planes of Texas and New Mexico macro pore flux is between 60% and 80% of total recharge flux.

Preferential flow (also referred to as macropore flow by Wood *et al.* (1997) and J. Wagenet of Cornell University, USA) in soil may result from biological activity (e.g. root channels, worm holes, meerkat or rodent holes, etc.), geological tectonic forces (e.g. subsurface erosion, cracks and fractures), geological pressure release forces (bedding plane fractures) or agrotechnical (manmade) practices (e.g. ploughing, bores and wells). Along these paths solutes and contaminants are transmitted to groundwater at much higher velocities than those predicted by Darcy's equation. Surface cracks and channels that bypass the root zone are also responsible for rapid water and chemical transport through the unsaturated zone.

Figure 4-7: Earth worm, a pathway generator (after Steenhuis et al., 2002).

4.1.3.2 Types of flow.

Soil texture is important in the type of flow (Steenhuis *et al.*, 2002):

1. Highly conductive **macropore** pathways form and persist in structured soils. These macropores are the result of a variety of soil-forming factors such as flow through non-capillary cracks or channels within a profile. In clay and loam soils, for example, areas of relatively low permeability are riddled with channels consisting of cracks partially filled with sand and small stones, as well as passages formed by roots and earthworms. When it rains, water infiltrating the ground follows these channels in preference to the surrounding matrix,

whose small pores are penetrated comparatively slowly. Flow is often fairly uniform through the uppermost soil horizon (typically the plow layer for current or former agricultural soils), which functions as a "distribution zone", distributing the flow to macropores in the subsoil. Different channels sometimes cross each other, resulting in the mixing of water and solutes. Flow in macropores and channels can occur with little or no interaction with the surrounding soil matrix. On the other hand, matrix flow is the comparatively slower movement of water and solutes percolating though soil pores. The relative importance of the two forms of percolation is dependent on soil type and rainfall intensity. For example, well-structured soils consisting of clay and loam mixes typically experience low permeability rates. In such soils, less than 1% of the pore volume consists of cracks and subsurface channels. However, during rain events, water infiltrating from the soil surface often flows through these channels in reference to the surrounding soil matrix, whose small pores are penetrated comparatively slowly. Even though these channels consist of a relatively small percentage of the total pore volume, they may be responsible for the bulk of moisture and solute transport after an infiltration event. Preferential flow may be initiated well below soil-water saturation (Steenhuis *et al.*, 2002). Fracture flow below the water table is thus also a case of preferential flow (van Tonder, 2006). Maini and Hocking (1977) give the equivalence between the hydraulic conductivity in a fractured medium and that of a porous medium. For example, the flow through a 100m-thick cross-section of a porous medium with a hydraulic conductivity of 10^{-7} m/s could also be the result of a single fracture with an opening no wider than 0.2mm in a fractured rock medium with an impervious rock matrix. This shows the immense importance of the flow of one single fracture (or preferential pathway) even when it is not very wide.

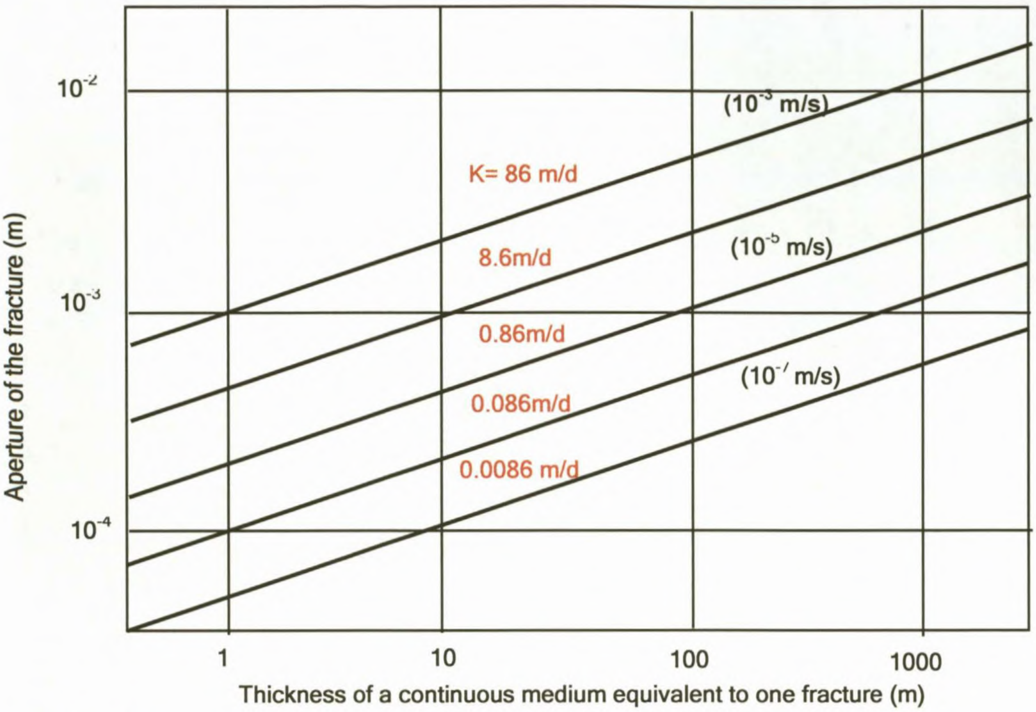


Figure 4-8: Comparison between the hydraulic conductivity of the porous medium and the fractured medium versus the aperture (From Maini and Hocking, 1977).

2. Instability in the wetting front leads water to find its way down through coarse soils in a number of channels called **Fingers**. This fingering phenomenon also occurs in homogeneous soils. Hill and Parlange (1972) were the first to document preferential flow in homogeneous sand at low infiltration rates. They have shown that water finds its way down through sandy soils in a number of channels called **Fingers**. A poorly conducting layer of topsoil at the surface produces a wetting-front instability. Gravity drives the instability, while surface tension has a contrary, stabilizing effect. What occurs is analogous to water dripping from a sponge; the pull of gravity is opposed by surface tension, which makes the drops increase in size before they fall. In the case of soils, this balance of forces determines the diameter of the fingers. In sand this is quite homogeneous, the fingers are nearly vertical and do not merge with one another. If the sand is less homogeneous; however, the fingers deviate from a strictly vertical path, and can merge. Finger type preferential flow also creates a non-uniform moisture profile in the soil. The soil within the initial preferential flow paths will remain wetter than the soil outside of the fingers. The persistence or horizontal spreading of this non-uniform water content will affect subsequent infiltration events. *Glass et al.* (1989) found that in laboratory sandy soils, non-uniform water contents remained after two weeks of continuous infiltration. **Subsequent infiltrations followed the old finger paths, resulting in persistent preferential flow**. Conversely, if the soil is uniformly wet, Liu *et al.* (1994) found that the finger widths are much greater, while Diment and Watson (1985) and Lu *et al.* (1994) found that

preferential flow might even be completely inhibited. At irrigation sites the type of soil will determine if the soils will wet uniformly.

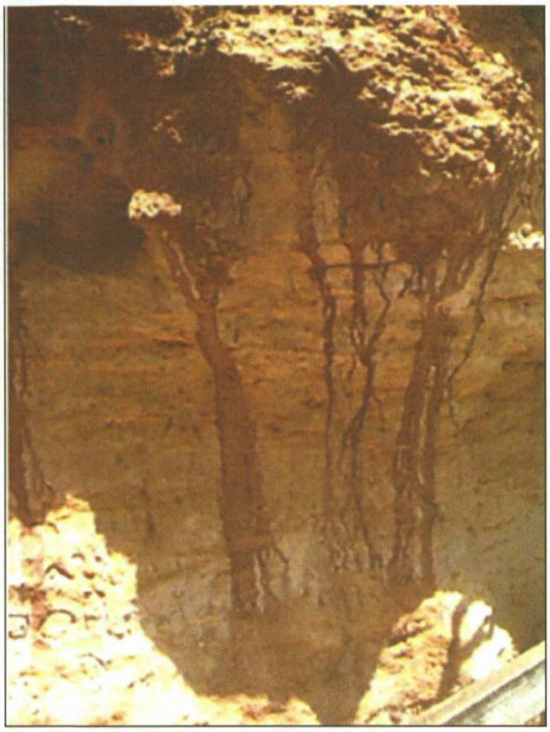


Figure 4-9: Formation of soil water fingers (Source: Steenhuis et al., 2002).

3. **Funnel flow** occurs when sloping geological layers cause pore water to flow laterally, accumulating at a low region (Steenhuis et al., 2002). If the underlying region is coarser, finger flow may also occur. The way in which soil is layered makes a big difference in how water and solutes find paths down to ground water. The way in which these flow paths merge depends on inhomogeneities in the soil, and sloping structural interfaces have a considerable effect on the degree of merging and rate of flow. Soil deposited by ocean currents, rivers, lakes, or glaciers consist of strata formed at different times and under different conditions, causing them to differ in composition and permeability. Various experiments have shown that at **low flow rates**, coarse layers act as **funnels**, collecting water from a broad area and channeling it through a small number of drainage fingers. At higher flow rates, these coarse layers begin to leak, and the funnel effect becomes less significant (Figure 4-10).

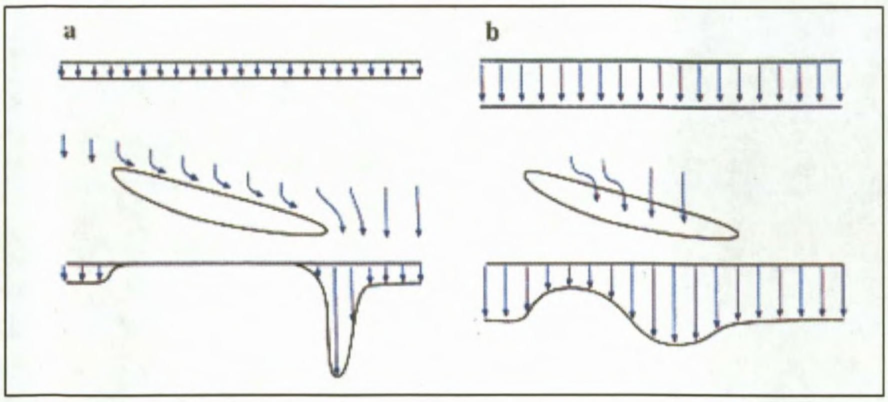


Figure 4-10: The funnel effect in sandy soil. With a relatively low flow rate [a], a fast-moving spout forms beneath the lower end of an inclined layer of coarse material. Such inequalities in penetration are minimized when the flow is greater [b]. (After Steenhuis et al., 2002).

One might expect that soil water in contact with the coarse layer might travel straight through the layer. However, under unsaturated flow conditions, greater pressure is required to push moisture into large pores from the small pores (Steenhuis *et al.*, 2002). Therefore, moisture tends to flow over the layer rather than through it. At low flow rates, the horizontal component exceeds the vertical component until the edge of the layer is reached where moisture then funnels through. Since moisture is forced to take this narrow route, the concentration of moisture and solutes may once again bypass much of the soil matrix and be directed to the groundwater. **The diversion of flow by layering is significant, because even in areas where groundwater monitoring is conducted routinely, pollution may be missed entirely if the well is placed in an incorrect location** (see discussion in Section 6.6.5).

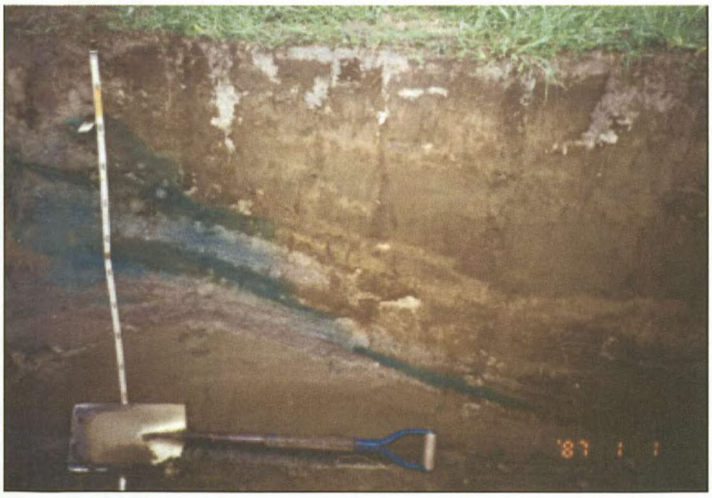


Figure 4-11: Funnel flow at field site. Blue dye flowing vertically (unsaturated flow) moves laterally when it encounters a sloping coarse-texture lens. (Source: Soil and Water Lab Website, Cornell University).

4.1.4 *The hydrochemical effects of irrigation with saline water on the soil.*

Any water used for irrigation carries ions in solution. Depositing this water on fields in the form of irrigation can affect the concentration of salts in croplands. If these salts become excessively concentrated, it can lead to salinisation (Steffen and Savina, 1996). Salinisation can reduce yields in its earliest stages and eventually lead to the destruction of fertility in the soil. This is referred to by Steffen and Savina as "*The Secondary Salinisation Process*": Salinisation has a direct effect on both plant growth and the structure of the soil. If the soil is saline a plant will have to expend energy to bring water into its cells because it is forced to work against osmotic potential. The cation exchange capacity (CEC) affects the stability of colloid-sized particles in the soil. The cation's positive charge will be attracted to the negative charge found on clay particles, which make up most of the colloid fraction. Divalent cations (Ca, Mg) will allow the colloidal particle to group together closely enough so that Van Der Wahls forces will cause the clays to flocculate, or form stable aggregates. Sodic soils, whose CEC is dominated by mono-valent sodium cations, will tend to be dispersed and not form stable aggregates. Sodium is mono-valent and can not pull the colloid particles close enough together for the short range Van Der Wahls forces to act. Sodic soils will tend to have a dark, organic appearance due to the dispersion of clay and organic particles while saline soils will tend to have a white crusty surface due to the precipitation of salts (Lax *et al.*, 1994). Both these effects will lead to decreased permeability and hydraulic conductivity.

4.1.5 *Prior-conceptual model for irrigation at virgin soil sites.*

A new mindset and paradigm for studies that may involve groundwater has been suggested by LeGrand and Rosen (2000) , the objectives are (1) obtaining optimal value from existing information, (2) reaching a high plateau of knowledge as a basis for further study and (3) providing an early perspective to be explained to involved stakeholders.

Specialised hydrogeologists rarely use experience, generalisations and qualitative linguistic modeling to obtain full synergistic value that will maximise understanding. The application of systematic reasoning is refered to as prior conceptual modeling explanation (PCME) and represents an initial high grade, synergistic analyses of hydrogeological foreknowledge. PCME leads to a package of open-ended thoughts and statements that allow for further study, provisional decisions or definite decisions. If properly prepared and presented at an early stage, a large part of the total hydrogeological information needed for site studies at an average site is already available, partly in unrecognised or latent form. With this advanced background of foreknowledge, adequately developed and displayed, only a fraction of time and money normally used in site studies may be needed in most cases.

Monitoring by the Institute of Groundwater Studies over the years has indicated that very little salinity applied on surface during irrigation is detected the water table. (See Appendix D for "Monitoring data"). This indicates that most of the salts are retained in the soil profile. The general belief is that the salts move according the water currents and accumulate in soils where evapotranspiration (combined evaporation from soils and transpiration by plants) exceeds combined precipitation and irrigation (Cordy and Bouwer, 1999). Due to the composition of the coal mine waters, gypsum precipitation should occur. Annandale *et al.* (2002) concluded that there is thermodynamic proof, in the form of calculated Ca and SO_4 activities, that gypsum is present in the soils irrigated with gypsiferous mine water. Concentrating the gypsiferous soil solution through crop evapotranspiration precipitates gypsum in the soil section and therefore removes it from the water system and reducing potential pollution (Annandale *et al*, 2002). More clayey layers will retard the vertical flow of the water, resulting in salt build-up due to precipitation and adsorption.

Hutson (1983) states that water applied to the soil surface initially moves rapidly through macropores and other pathways, but more slowly through finer matrix pores.

Subsurface preferential flow of water, in which small areas of the subsurface carry large portions of the flow, has been observed in a variety of soils (Hill and Parlange, 1972). Due to the nature of the soils at the irrigation sites, preferential flow will occur due to the abundance of earth worm and rodent holes, as well as cracks in the more clayey soils. According to Sharma and Hughes (1985) a decrease in chloride values with depth in the unsaturated zone implicates bimodal flow. Under preferential flow or bypass flow conditions part of the precipitation water (with relatively low chloride concentrations) will flow directly along these preferred pathways to below the root zone. This bypass flow component, unaffected by evapotranspiration, dilutes the soil water that has been concentrated by transpiration, resulting in relatively low concentrations in the percolation zone with respect to the concentrations encountered in the root zone. The decrease in chloride values in the boreholes thus implies preferential flow at the test sites.

Work at numerous sites in the Mpumalanga Coalfields has indicated a saturated weathered zone of 10m - 15 m deep. Water moves laterally along this zone of higher transmissivity, and salts that does reach the water table will become diluted in this zone of higher flow. Only a small part of the salts will move along vertical fractures to the deeper aquifers. *Monitoring may thus portray a false picture of what really reaches the water table if boreholes are constructed incorrectly, or sampled at incorrect depths.*

Figure 4-12 presents a concept of what occurs at an irrigation site. Irrigation and rain are applied, and a large portion of this water evapotranspirates. The rest moves down the soil profile, with a build-up of salts in the soil, and the conservative ions e.g. chloride moving through. The concentration of the chloride with depth indicates if bimodal or only diffusive flow would occur. Once reaching the water table, lateral flow will dilute the water in the saprolite zone, with some moving further down towards the deeper aquifer. Some will daylight or seep into streams.

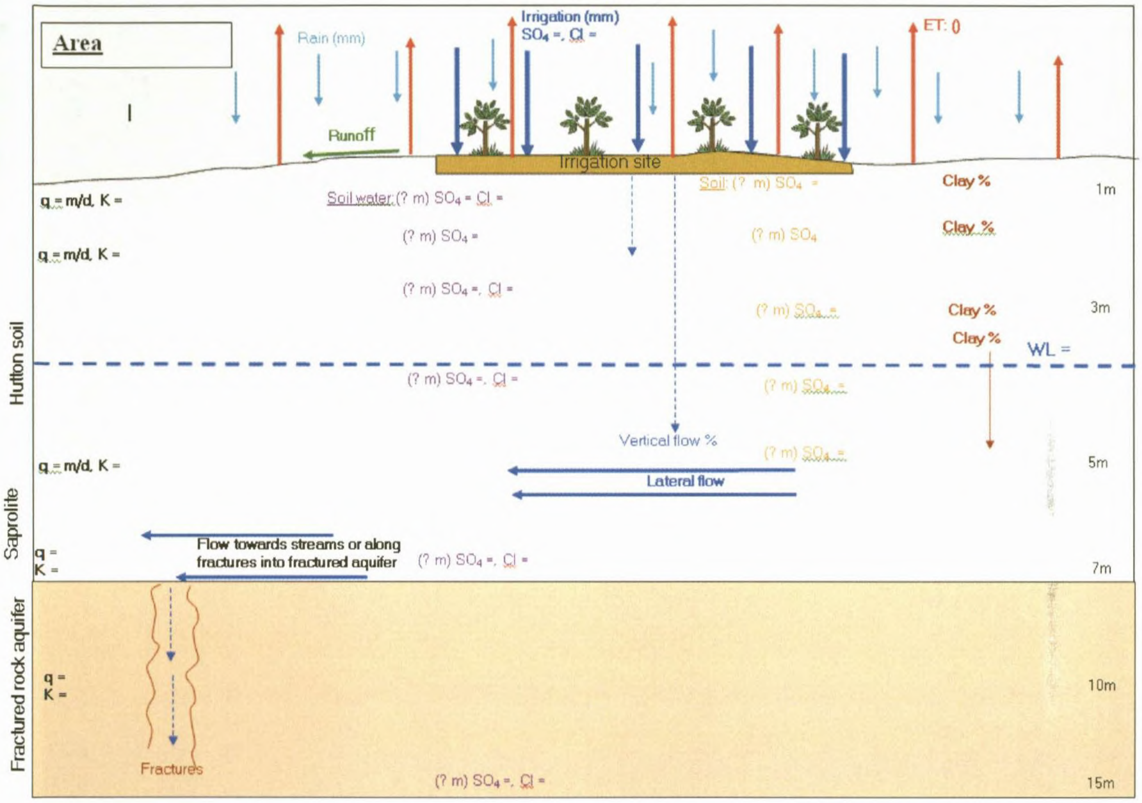


Figure 4-12: Pre-conceptual model of the irrigation sites.

4.2 Spoils irrigation

Spoils irrigation refers to irrigation on opencast rehabilitated land, which is underlain by spoils.

4.2.1 *Introduction*

In opencast pits, the material that remains is extremely heterogeneous, ranging from boulders down to very fine particles. This provides a highly reactive area when compared to underground mining, and if large quantities of pyrite remain in the spoils, high sulphate generation rates can be obtained. The recharge rate is far higher than that for underground mining; thus dilution is an important mechanism in such a system. Localised areas of acidity (hotspots) will occur, which serve as initiators of large-scale pyrite oxidation. The decant elevation in these pits is of prime importance; where the elevation is at a point where most of the spoils are submerged, the water quality is expected to improve over time. Where largely unsaturated conditions subsist, the likelihood of acidification and poor quality water with high sulphate increases.

Coal strip-mining was introduced in the Mpumalanga Coalfields in 1971, and became widespread during the mid-1970s. During the 1980s the awareness of changes in the hydrological properties of soil became widespread. (The mining method involves the complete removal of the overburden above the coal in adjacent strips). Following the removal of the coal, the material from an adjacent strip is dumped into the void and graded to form a new surface topography. Usable soil materials stripped ahead of mining are then replaced on the new surface. Because of the large volumes involved, heavy machines are required, which exert a compactive force on the soil over which they travel. Various soil amelioration and revegetation operations then follow to complete the rehabilitation process). In an effort to improve rehabilitation and quantify impacts, large mining companies conducted a number of studies (Tanner, 1993; Viljoen, 1993; Van der Merwe, 1993).

In order to understand these processes better, a research initiative by the WRC was conducted at six sites at Kriel, Middelburg South and Optimum (Schoeman *et al.,* 2002). The study was linked to work previously done during 1994 - 1996 at Arnot, Kleinkopje and New Vaal. The findings include:

- The cover soils consisted of structureless clay loam to sandy clay loam, derived from orthic, red, yellow-brown and plinthic soil horizons, and ranged in depth from 0.55 to 1.05 m. The pH of the soil cover was low in places (average pH_{KCL} 5.7, 5.5, 5.0, 4.8, 4.5 and 4.4 at the six sites respectively), and that of the spoil material was low at Middelburg South (<4.5) but above 6 and 7.1 at the Optimum and Kriel sites respectively. Pockets of strong acidity do occur in spoils material, but acidity due to pyrite oxidation was not identified as a major limitation to land use (Usher *et al.,* 2003).
- Mineralogically, the fine fractions of the cover soils are strongly dominated by kaolinite (55-80%). Approximately 10% clay-sized quartz occurs. Water-dispersible to total clay ratios vary between 0.01 and 0.34, indicating relatively high to intermediate aggregate stability. The cover soils are susceptible to compaction and hardsetting behaviour.
- Water available for evapotranspiration varied between 45% and more than 100% of the annual rainfall. Maximum rates of evapotranspiration were in the order of 5 to 8 mm per day. The net gain or loss of soil water during the season was small.

- Water loss through deep percolation varied from zero to 40%. This was strongly affected by rainfall distribution, and also differed between sites. Some spoils are almost permanently dry below a depth of 1-1.3 m. Internal water drainage occurs by means of deep percolation from the soil profile to a depth greater than the bottom of the root zone. Bennie *et al.* (1998) describe it as the unidirectional vertical flux q (mm/d) through an arbitrary plane, the bottom of the root zone (WD, m). This is mainly determined by the hydraulic conductivity ($K(\theta)$, mm/d), which is a logarithmic function of the average water content θ, so that $q = K(\theta)$. Regarding the estimation of K and deep percolation, the image emerging from studies by the various researchers is one of slowly permeable spoil materials with K_s-values of less than 0.007 m/d. Seasonally, lateral drainage may occur along major slopes, leading to water accumulating in hollows. Although percolation through the spoil matrix is slow, it may be greatly influenced by settling cracks.
- The calculated run-off varies between 1.9 and 10.8% of the annual rainfall. The reconstructed soil profiles can generally be regarded as poorly drained. This causes certain topographical features, e.g. local hollows, to become water collection sites through lateral surface as well as subsurface run-off, particularly during wet periods.

Viljoen (1992), in a study of soil formation in spoil material between 1 and 18 years old at Optimum, observed that dense layers appear to become less obvious over time and that coarse fragments in the upper soil appear to weather rather rapidly. The clay content of the upper spoil and signs of wetness increase over time, particularly in low-lying landscape positions. De Villiers (1992), in a study of nearly 100 profiles, noted that dark, fissile shales particularly appear to soften and disintegrate quite rapidly. This is consistent with their often high pyrite content.

4.2.2 *Hydraulic Properties at Opencast Collieries*

4.2.2.1 Spoils hydraulic properties

Hawkins (2004) investigated the predictability of surface mine spoil hydraulic properties in the Appalachian Plateau. During surface mining, strata overlying the coal (overburden) are removed by blasting and excavation. Once the coal is extracted, the fragmented spoil is dumped and pushed into the pit during backfilling. Initially, material placed on the elevated spoil ridges and piles tend to be poorly sorted. Larger spoil particles will however roll to the base of the spoil ridges, creating well-sorted, highly transmissive zones. Extreme heterogeneity is introduced into the backfill material by the broad range of particle sizes and differences in particle sorting (Hawkins, 1998).

Heterogeneities introduced during mining and reclamation cause spoil to exhibit a dual-flow groundwater system. Mine backfill contains a substantial percentage, by volume, of large (macro) voids. The void volume may equal the spoil swell (a volume increase from mining, which may be as high as 20 to 25%. Porosity values of 16 to 23% have been recorded by field measurements in mine spoil in the coalfields (Rahn, 1976; Hawkins, 1998). The macro-voids are within a matrix of unconsolidated material composed of clay-sized (<2 microns) to boulder-sized (>2m) particles. The macro-voids' behaviour is similar to that of a karst aquifer, capable of storing and transporting large volumes of water. They may exhibit multiple water tables within the same unit (Caruccio *et al.,* 1984), whereas spoil material itself behaves as a highly transmissive unconsolidated porous medium. Mine spoils exhibit an average hydraulic conductivity of two orders of magnitude greater (geometric mean) than the adjacent unmined strata (Hawkins, 1998).

The water level and conductivity forecasting are based on the factors of mine backfill age, spoils lithology and thickness, dip of the pit floor and distance to the closest unmined strata (highwall). Spoil age is important as a parameter, because spoil properties evolve with time.

In aquifer testing, mine spoil behaves as an unconfined aquifer under most circumstances. A summary of aquifer testing illustrates a wide range of K-values, and ranges over seven orders of magnitude from 3.5×10^{-4} to 1.73×10^{3} m/d. The smaller K-values associated with mines <31 months old are attributed to the poor interconnection of voids and pore spaces of the relatively freshly acclaimed spoil in which the water table may take up to 24 months to rebound. On the other hand, small K-values at mines >100 months old appear to be caused by spoil compaction, rock weathering, piping and settlement that decrease the void and pore space as these sites age. However, no reasonable correlation for K could be approximated by regression analysis for age or any other factors.

Greater saturated thicknesses were associated with higher sandstone content (>35%). This relationship is related to the higher rates of recharge associated with blocky sandstones. Analyses indicate that the prediction of saturated thickness is directly dependent on the sandstone/shale ratio, age of the spoil, total spoil thickness, and the distance to the highwall. This relationship is strongest for sites <60 months old, but is still somewhat viable for sites > 60 months in age. The decreased predictability at the older sites appears to result from differing degrees of spoil compaction, piping, settling, and rock weathering commonly observed between mine sites.

Even though it seems as if the findings of the different researchers differ, there is truth in all the statements. From personal experience the author has seen spoils that drain fast, as well as spoils that drains very slowly. Much depends on the type of spoils, the age and the clay content in the weathered rock, as well as the capping material and the degree of compaction by construction vehicles.

Sracek *et al.* (2004) investigated the geochemical characterisation of Acid Mine Drainage from a waste rock pile at Mine Doyon in Québec, Canada. Pore water in the unsaturated zone was sampled from suction lysimeters and with piezometers in underlying saturated rocks. The investigation revealed strong temporal (dry period vs. recharge period), and spatial (slope vs. central region of pile) variability in the formation of Acid Mine Drainage. The main secondary minerals observed were gypsum and jarosite.

The AMD production in mine tailings has been studied extensively, for example by Dubrovsky *et al.* (1985) and Blowes *et al.* (1991). In contrast, much less is known about AMD generation from waste rock. Several waste rock studies have evaluated temperature and gas concentration profiles (Lefebvre *et al.*, 2001 and Kuo and Ritchie, 1999). These studies revealed the significant role of air convection in the unsaturated zone of very reactive waste rock piles. However, the geochemical environment within waste rock piles is less well known. Until recently, the focus in waste rock geochemical studies has been on the quality of drainage water flowing from the waste rock base (Morin *et al.*, 1994). This type of monitoring represents an integral part of the acid drainage produced in various parts of the dump over space and time. However, this information does not provide a clear picture of geochemical processes within the pile (Ritchie, 1994). There have been attempts to obtain data on water chemistry within the unsaturated zone of waste rock piles (Shafer *et al.*, 1994). They were not very successful, however, because of the low water content and correspondingly high suction values characteristic of semi-arid climate conditions in the northwest USA. The acquisition of geochemical data from the unsaturated zone of a waste rock pile remains a topic of on-going research (for example, Smith *et al.*, 1995 and Stockwell *et al.*, 2001).

The approach that Sracek *et al.* (2004) use for the assessment of water quality within waste rock deposits was based on sampling leachate from both unsaturated and saturated zones within the pile combined with transport and geochemical modelling, and solid phase analysis.

4.2.2.2 Hydrogeology of coal mine tailings

Tom and Blowes (1999) studied the hydrogeology of tailings impoundment. They stated that, because flowing pore water in tailings can transport dissolved constituents from the enclosed impoundment into the surrounding environment, an understanding of the flow system is critical to accurately assess the environmental impact of tailings disposal. In addition, long-term water-treatment costs are affected by the amount and quality of the effluent from the tailings. Important aspects of the groundwater flow system within the tailings and surrounding natural geological materials are the direction and rate of groundwater movement and the distribution of recharge and discharge areas. Delineating recharge areas is important, because geochemical processes such as sulfide oxidation may degrade the quality of the recharging pore water, ultimately affecting the quality of the pore water throughout the impoundment. When the locations of recharge areas are known, steps may be taken during mine decommissioning to protect these areas from the effects of sulfide oxidation.

To characterise the pore water flow system within the tailings, the hydraulic conductivity (K), hydraulic head and the water table elevation at piezometer nests located within the tailings impoundment were measured.

Results of the study indicated that hydraulic conductivity measurements with the Hvorslev method (Hvorslev, 1951) range between 8×10^{-5} to 8×10^{-2} m/d. The values obtained using the constant-head permeameter were consistent with this range, with fractured samples displaying K values of up to one order of magnitude greater than the matrix (10^{-4} vs. 10^{-5} m/d). The narrow distribution of K within the tailings was a reflection of the uniform grain-size distribution. There was a trend toward decreasing K with increasing depth, which may be due to consolidation of the tailings. The lowest K values ($<1 \times 10^{-8}$ m/s) were obtained from the deepest piezometers, thought to be installed within the underlying silt and clay (Al *et al.*, 1994b).

4.2.2.3 Stratification and mineralogy of spoils versus hydrochemistry

Some mining types have a set of conditions that promote poor quality water, while others ameliorate the effects of pyrite oxidation. In all mining types, however, the local mineralogical conditions provide the most important driver of water quality. Newbrough and Gammons (2002) emphasise the importance of understanding the relationship between mine drainage chemistry and the mineralogy of the surrounding rocks, and how these relationships can vary on a district scale.

Usher (2003) indicates the validity of this observation by means of trenches dug in the spoils. In underground mining, this is no less important. A case study at an underground compartment shows that the roof sediments have a higher probability of acidification than the coal seam itself, implying that the high extraction areas pose the greatest risk. The balance between the increased recharge, with the addition of alkalinity and faster inundation, against the higher surface area and lower net neutralising potential will determine the final water quality.

Table 4-1 summarises some of the key issues from a hydrogeochemical perspective:

Table 4-1: Key processes in opencast mining that affect water quality (Usher, 2003).

	Rehabilitated Opencast
Recharge	15%-25%
	Dilution can occur
Relative Surface Area	High
	Faster reactions; high salt loads
Porosity	25%
	Flooding can occur to prevent excessive salt loads
Coal Removal	90%
	If coal seams are the most likely to acidify, it reduces the risk
Decant	Likely
	Outflow can occur with small amount of material flooded

4.2.2.4 Conceptual model for irrigation on spoils

The way in which the spoils heaps react to irrigation is an important consideration for correctly including the influences within a reactive model. Major aspects are schematically indicated in Figure 4-13

1. All the spoils above the flooded or final decant elevation will remain reactive for extended periods after closure. Pyrite oxidation will continue and, provided that enough calcareous carbonate material occurs, concentrations will not exceed in the order of 5000- 6000 mg/l. If acidity occurs, this value can be greatly increased. Recharge onto rehabilitated spoils will be in the order of 15-20%.

2. In the flooded spoils, oxidation reactions will decrease in most cases. James (1996) shows this to be the case in laboratory tests on South African spoils, while research by Vermeulen (2003) shows this to hold for spoils at Transvaal Navigational Colliery (TNC) and Schoongeschigt Colliery. Van Tonder *et al.* (2003) and others have shown that the inflow and outflow volumes in the pit are in the same order. The transmissivity of the spoils is extremely high, resulting in a flat water table controlled by the decant elevation.

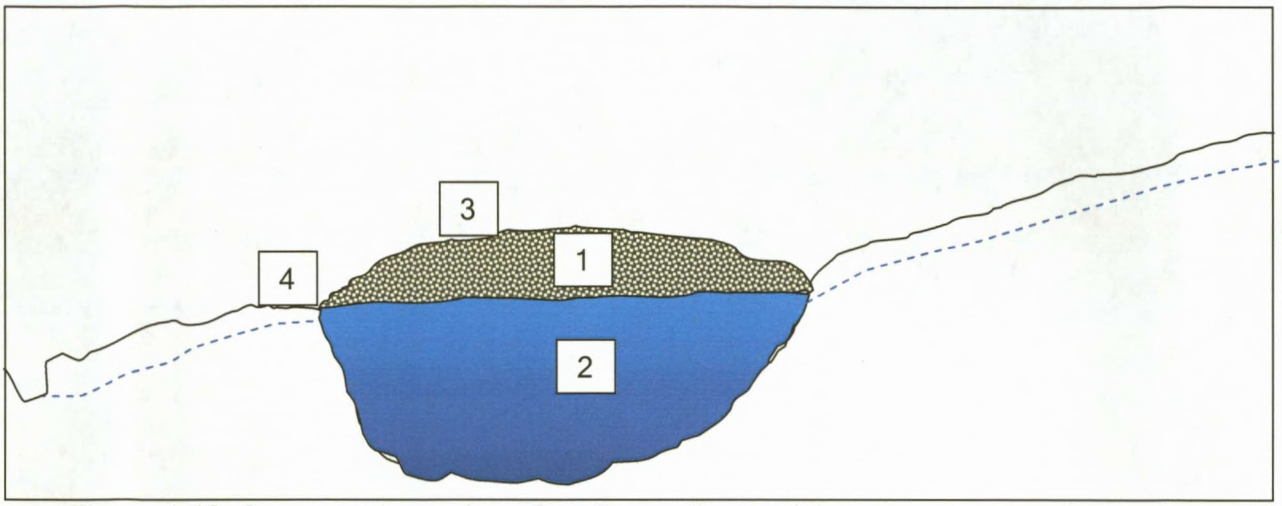


Figure 4-13: Conceptual overview of spoils reactive model

3. If irrigation is added to the normal recharge, the irrigated areas will have an additional salt load and provide an additional source of moisture to sustain AMD processes in the unflooded zone. This additional water may also provide a medium of transport for the precipitated salts in the unflooded zone.

4. In general, all rehabilitated opencast pits will decant at the lowest level at which the spoils intersect the topography. This decant will constantly add salt load to the system in the long term, as long as water infiltrates the spoils. It is considered unlikely that, on the scale of more than 75 000 ha, engineered covers will be largely employed. This constant salt load addition must therefore be included in the assessment of any comparative management.

5 METHODOLOGY

5.1 Introduction

Irrigation with mine water has been ongoing at the different pivots (as described in Chapter 3) for periods of three to nine years. Monitoring the groundwater quality at these sites has not detected significant deterioration of groundwater quality. The focused and detailed monitoring of the groundwater throughout the duration of the project is one of the pillars of this project, and may even be extended beyond the duration of this work.

To achieve the aims of this study, the methodologies that are outlined in this chapter were applied. Detail of each approach is given in the different sections of this chapter.

5.2 Groundwater monitoring

Boreholes were drilled at all the irrigation sites, and placed at such positions that the water levels and water quality, inside and outside the irrigation areas (for background values), could be measured.

The boreholes were drilled by means of air percussion method. The boreholes were drilled to a diameter of 165 mm. All the boreholes were cased as a precautionary measure against collapse.

The monitoring investigation included:

- Investigation of the local geology
- Water level measurements and interpretation.
- Multi-parameter chemical profiling of the water quality in the boreholes.
- Sampling and chemical analyses of water in the boreholes

5.2.1 *Geochemical profiling*

The boreholes were profiled with an YSI multi-parameter Sonde probe (Figure 5-1) connected to a laptop computer. Multi-parameter logs ensure that water qualities are measured, as they are in-situ, without disturbing the water column in the boreholes through sampling. The advantages of such probing are as follows:

- In-situ measuring of temperature, DO, ORP, pH and conductivity.
- The position of fractures can be identified.

- Stratification of the water column can be recognized.
- The data can be used for hydrochemical modelling.

Figure 5-1: Multi-parameter probe with different sensors.

An example of probing results is shown in Figure 5-2. These data can be related to geohydrological programs such as WISH for interpretation, as illustrated in Figure 5-3. The stratigraphic nature of the water column is clearly shown in Figure 5-2.

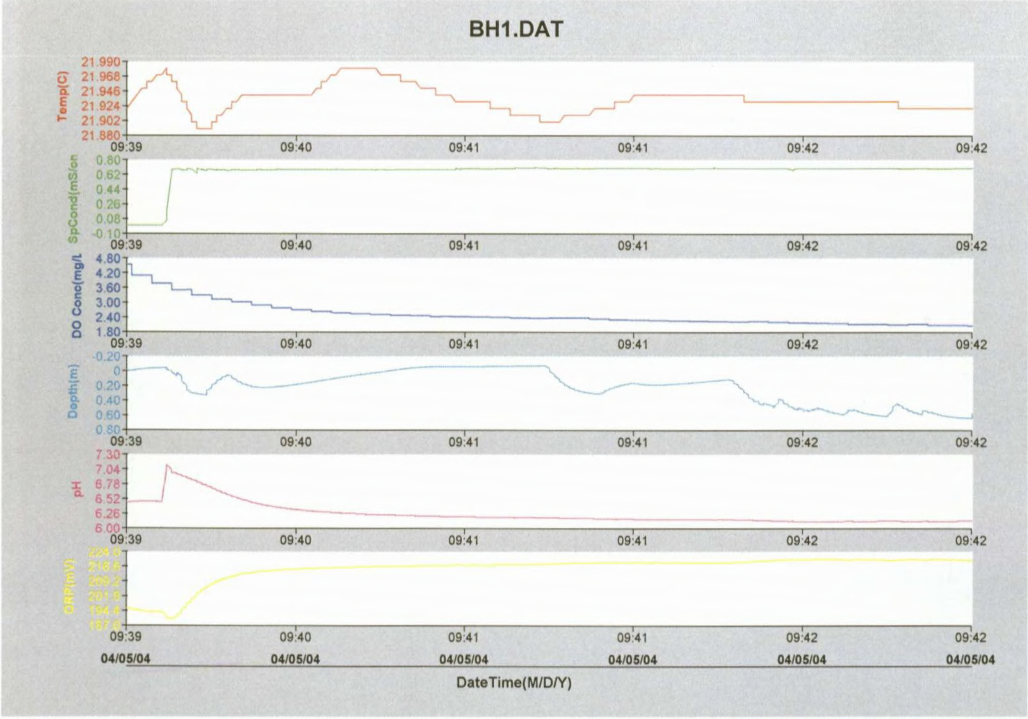


Figure 5-2: Graph of profiling down a borehole.

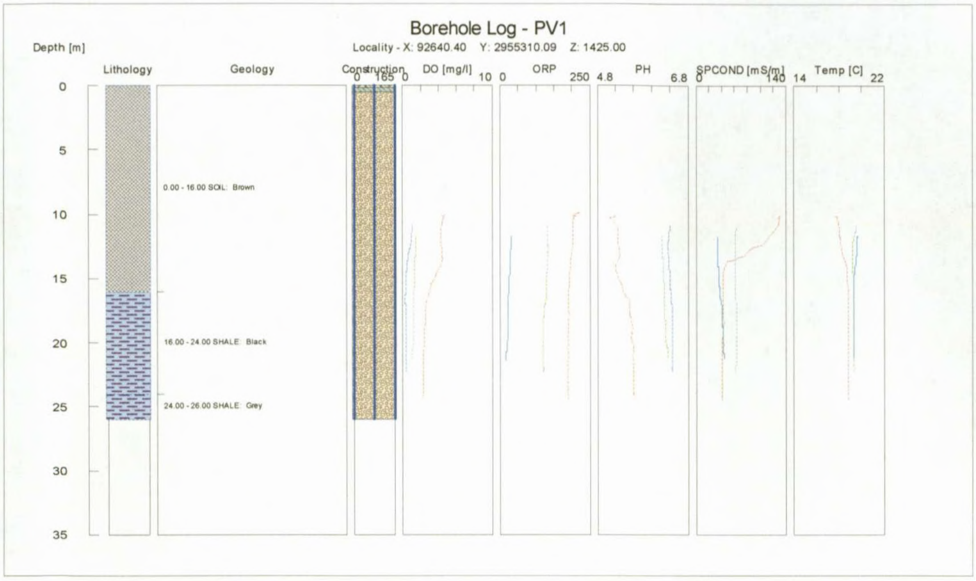


Figure 5-3: Multi-parameter profiling in WISH.

In piesometers such as those installed at New Vaal a TLC (temperature, water level, electrical conductivity) meter was used to measure the electrical conductivity and temperature in depth.

5.2.2 *Chemical analysis*

Following the water quality probing in the boreholes, sampling was done with a sophisticated pressurized stainless steel depth sampler (Figure 5-4). Depending on the result from the profiling, sampling depths were determined.

Figure 5-4: Specific Depth Sampler (from www.solinst.com)

It is essential that sampling should always be at exactly the same depth in order to get a uniform picture of the true water quality. Sampling at different depths can result in incorrect concentrations. In order to prevent heavy metals in the water samples to precipitate, part of it was filtered and acidified to a pH of below 3 immediately after sampling. After every sample all the equipment was washed with deionized water to ensure that cross-contamination is ruled out.

All analyses were done at the Institute for Groundwater Studies at the University of the Free State. The following methods were used:

Anions: A filtered water sample was injected into a stream of carbonate-bicarbonate eluent and passed through a series of ion exchangers. The anions of interest were separated on the basis of their relative affinities for a low capacity, strongly basic anion exchanger (guard and separator columns). The system used is the Dionex DX-120 ion chromatograph and the columns used are Ionpac AG 14 and AS14 columns.

Cations: Dissolved metals were determined in filtered and acidified samples. An ICP source consists of a flowing stream of argon gas. A sample aerosol is generated in an appropriate nebulizer and spray chamber and is carried into the plasma subjecting the constituent atoms to temperatures of 8 - 10 000 K. The high temperature of the plasma efficiently excites atomic emission. The light emission is registered and the concentrations of the metals determined.

5.3 Soil Sampling

Obtaining soil and rock samples is a vital component of any drainage prediction methodology and relies on adequate representative sampling. Sampling was conducted at the various irrigation areas by means of (Figure 5-5):

- Core drilling
- Auger drilling and
- Test pits / trenches
- Samples were taken inside as well as outside the irrigation areas to obtain background values. These samples were analysed at distinct lithological horizons to determine clay content as well as the ion / mineral content.
- An excavator was used to dig the inspection pits in virgin soil and spoils to depths of approximately 4m. From these, the stratigraphic nature of the soil, salient features and the hydraulic features could be studied. *In-situ* samples were taken, which stored in airtight bags.

Figure 5-5: Soil sampling methods.

5.4 Soil Analysis

5.4.1 *Soil Properties*

Sampled soil was analysed at the Glen Agricultural College near Bloemfontein to determine the soil texture and clay content. For this determination, a 7 Fraction Texture Analysis was used as follows:

Weighed 10 g of soil, add 25 cm^3 of calgon, and dispersed the sample for 10 minutes. Washed dispersed sample in a 1 litre cylinder and stirred for 1 minute. Pipetted 25 cm^3 of the suspension (pipette at the 1 min reading mark) into weighed beakers. After 4 min: pipetted 25 cm^3 of the suspension (pipette at the 4 min reading mark) into weighed beakers. After six hours: pipetted 25 cm^3 of the suspension (pipette at the 6-hour reading mark) into weighed beakers. Placed beakers in an oven at 105^0C and dried until constant mass. It was cooled in a desiccator before weighing the beakers. From this the silt and clay fractions and sieve sand for sand fractions could be calculated which was important in the soil moisture calculations.

5.4.2 *Soil chemical analysis*

All chemical analyses were done at the Institute for Groundwater Studies. All samples were milled to pass a 250-µm sieve and dried in the oven at 45 °C (ISO 11048).

Normally all leaching methods in soil sciences were developed to determine total plant-available sulphate (Tabatabai, 1982 and DeJager, 2005). De Jager developed a method to determine the dissolved and exchangeable/adsorbed sulphate in the soil due to irrigation activities, which was used to analyse the soil:

A suspension of 5g soil and 50 ml of water was shaken for four hours and left to suspend for 16 hours. It was then filtered with Whatman No1 filter paper after which the extract was analysed with ion chromatography and ICP to determine the precipitated part of the sulphate and other ions. The soil residue from the filter was then dried, and a suspension of 5g soil and 50 ml potassium-ortophosphate was treated in the same way to determine the adsorped sulphate and other ions.

5.4.3 *XRD and XRF*

All samples were sent to the Geology Department at the University of the Free State for X-ray diffraction analysis to determine the presence of gypsum and clay minerals. The mineral composition of a sample will ultimately determine the contribution of different species in the system as a whole (Usher *et al.*, 2003). The analyses were carried out with a Siemens D5000 Diffractometer with a CuKα radiation at 30kV and 40mA. Diffraction scans of the X-ray intensity pattern against a 2θ angle were viewed and interpreted using DIFFRAC-AT V.3.0. software together with the JCPDS Mineral Powder Diffraction File Data Book (1980a) and JCPDS Mineral Powder Diffraction File Search Manual (1980b). X-ray diffraction from crystalline solids occurs as a result of the interaction of X-rays with the electron charge distribution in the crystal lattice. The diffraction peaks are individually considered to be the result of the diffraction of the incident X-ray beam of wavelength λ from crystal lattice planes, having Miller indices hkl and spacing d_{hkl}. Plotting the measured intensity against the 2θ angle (or corresponding crystal d-spacing) produces a diffractogram from which the minerals in the sample can be characterised (Wainerdi and Uken, 1971).

X-ray Fluorescence (**XRF**) is the key technique for characterizing the element composition of rocks and soil. XRF is generally used for analysis of bulk solids, and can be used to routinely analyse for almost any element heavier than neon including non-metals. XRF analyses have the additional benefit that it does not depend on putting a sample into solution, thus eliminating problems with insoluble residues.

5.5 Soil water sampling (Porous cup lysimeters)

The unsaturated zone is the portion of the subsurface above the groundwater table. It contains air as well as water in the pores. Its thickness can range from 0 meters, as when a lake or marsh is at the surface, to hundreds of meters, as is common in arid regions (GCRIO Website http://www.gcrio.org/geo/grndwt.html). At irrigation sites the elevated perched water table will normally vary between 2m and 10m.

Soil Water Samplers, also referred to as suction lysimeters or porous cups, are used to collect water samples from soil profile. The samplers are installed at the desired depth and left in the soil, allowing periodic sampling to occur with minimal disturbance of the soil. The samplers consist of a porous ceramic cup and a sample collection tube. A vacuum pump is used to create a vacuum in the sampler, which draws water from the soil matrix, which passes through the ceramic cup and into the sampler. The water sample can then be extracted from the collection tube and taken to the lab for chemical analysis.

In 1961, Skaling and Wagner, of the University of Missouri, fashioned the first suction lysimeter (Soil Report Newsletter of Soilmoisture Equipment Corp, 2002). The suction lysimeter was a cylindrical device consisting of a porous ceramic cup (to withdraw soil pore water); a body tube to act as a reservoir; and a simple stopper assembly with a single hole for creating a vacuum and retrieving the sample. These early suction lysimeters allowed pore water to be extracted from unsaturated soils near the surface. Subsequent changes to the suction lysimeter added a "pressure" port to the stopper assembly and the "pressure/vacuum" lysimeter was born. The new pressure/vacuum lysimeters extend the use of lysimeters to greater depths or even remote locations. Recently lysimeters have been extensively used to evaluate solute transport models (Corwin *et al.*, 1992; Klein *et al.*, 1997 and Butler *et al.*, 1992), to monitor the fate and mobility of soil contaminants (Burne *et al.*, 1994; Kelly *et al.*, 1998 and Corwin *et al.*, 1994) and for evapotranspiration studies (Prueger *et al.*, 1997).

Unsaturated soils and the vadose zone are composed of a mixture of soil particles, water held on the surface of soil particles and in small capillary spaces between the particles and interconnecting air passages that are open to the atmosphere at the soil surface.

Extraction of a pore liquid sample requires a hydrophylic porous material with numerous pore channels such as ceramic to transport soil water fluids without alteration or leaking, in order to establish and maintain intimate hydraulic contact between interstitial pore liquid and the sampler chamber. Because of its surface tension characteristics, water in contact with a ceramic cup will completely fill its pores whenever the air pressure differential across the ceramic does not exceed a critical value related to pore size called the “air entry value” or “bubbling pressure”. Volumetric porosities of the interface material should be greater than

10% and pores small enough to sustain air pressures "or bubbling pressures" greater than 10 psi Ceramic soil water samplers have a maximum pore size of 2.5 microns and can maintain a vacuum in excess of 0.95 bar.

Generally there are four possible materials considered for the interface: porous plastic films, porous plastic shapes, sintered metals and ceramics. The first three materials have significant drawbacks in terms of functionality. Delicate plastic films tear easily and cannot be well supported. Porous plastic shapes have large non-uniform pores and require special surface treatments to become hydrophylic. Sintered metals have high exchange capacities, will frequently oxidise, and again have non-uniform pore sizes. Ceramics are historically applied and is known for their long-term use, with alumina and porcelains preferred for their inert and tough characteristics.

Today's suction lysimeters and pressure/vacuum lysimeters rely on a surface of uniform wetted pores that act as contact points that draw fluids from soils, through interface pore channels into the reservoir of the sampler (lysimeter). If the pores of the sampler's interface material are either not small enough in size or not uniform, the water links between the soil and the sampler break. Air instead of water then enters the sampler under vacuum. In dry conditions, water in the pores of the ceramic will move out of the cup, into the surrounding soil, and the vacuum in the sampler will be relieved. Since the unsaturated hydraulic conductivity of soil decreases exponentially with increasing dryness, liquid phase movement virtually ceases in dry soils. When a wetting front pattern approaches, the soil moisture tension will decrease. As the soil moisture tension falls below about 2 bars, a vacuum can be maintained in the soil water sampler. At a soil moisture tension of about .65 bars, a pore liquid sample will be drawn into the sampler.

The photograph in Figure 5-6 illustrates what the porous cup lysimeters built for this research look like. PVC tubing and fittings were bonded using a mix of epoxy bonds. Two pipes were connected to the tubing, with one placed into the ceramic cup. The latter is used to extract the water with. The water was easily extracted by pressurising the sampler through the one pipe and thus forcing the water out through the deeper pipe in the ceramic cup.

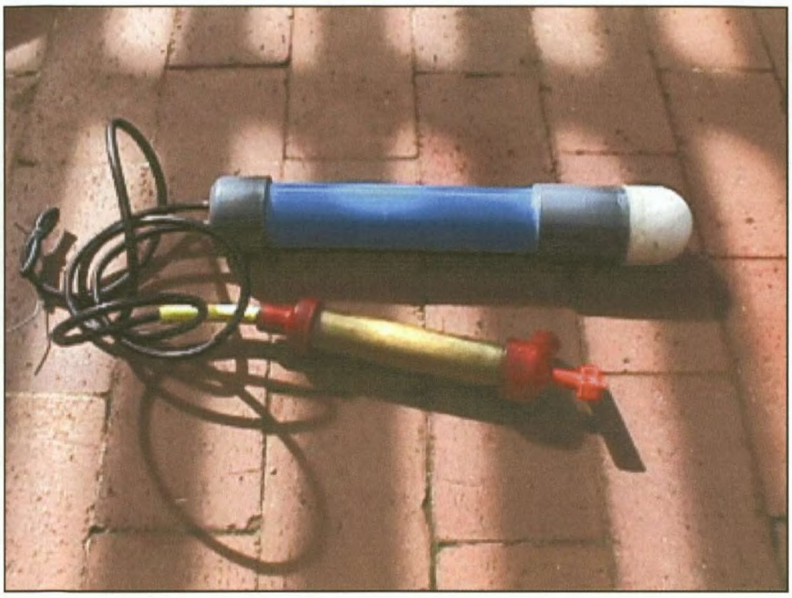


Figure 5-6: Porous cup lysimeters and vacuum pump.

The soil water samplers were installed in diamond drilling holes. The ceramic cups were bedded in very fine-grained silica flour so that the porous ceramic was in intimate hydraulic contact with the soil. These samplers were installed every meter down to 4 meters, bedded in the silica. The hole was filled halfway with the original soil, up to the next sampler. A cement seal layer was then applied, and soil was entered on top of this again until the next sampler was reached. The top of the hole was also sealed with a layer of cement. The cement layers ensured that water would not move vertically down the borehole, but rather downwards in the undisturbed soil.

Whenever a sample was needed, the sampler was placed under suction for three days, after which the water was sampled using very low pressure.

5.6 Tensiometry

Soil water tension, soil water suction, or soil water potential are all terms describing the energy status of soil water. Soil water potential is a measure of the amount of energy with which water is held in the soil. A soil water characteristic or water release curve shows the relation between soil water content and soil water tension.

Tensiometers have been used for many years to measure soil water tension in the field. Tensiometers are water-filled tubes with hollow ceramic tips attached at one end and a vacuum gauge (or mercury manometer) and airtight seal at the other end. The device is installed in the soil with the ceramic tip in close contact with the soil at the desired depth. The water in the tensiometer eventually arrives at pressure equilibrium with the surrounding soil through the ceramic tip. Water is extracted into the soil through the ceramic tip, creating tension in the closed tube. As the soil is re-wetted, the tension gradient reduces, causing water to flow into the ceramic tip. As the soil goes through wetting and drying cycles, tension readings can be taken.

Most commercially available tensiometers use a vacuum gauge to read the tension created and have a scale from 0 to 100 centibars (one bar or 100 centibars of pressure or tension is equal to 14.7 psi). The practical operating range is from 0 to 75 centibars. **If the water column is intact, a zero reading indicates saturated soil conditions.** Readings of around 10 centibars (cb) correspond to the field capacity for coarse-textured soils, while readings of around 30 cb can approximate field capacity for some finer-textured soils. The upper limit of 75 cb corresponds to as much as 90% depletion of total available water for the coarse-textured soils, but is only about 30% of the depletion for silt loam, clay loams, and other fine-textured soils. This limits the practical use of tensiometers for coarse-textured soils or to high frequency irrigation where soil water content is maintained at a high level.

Tensiometer readings may be used as indicators of soil water and also of the need for irrigation. When instruments installed at shallower depths of the root zone reach a certain reading, they can be used to determine the time to start irrigation, based on soil texture and crop type. Similarly, instruments at deeper depths of the root zone may be used to indicate when adequate water has been applied. It can also be used to determine the soil water volumes (and movement) deeper down towards the water level. Careful installation and maintenance of tensiometers are required for reliable results. The ceramic tip must be in intimate and complete contact with the soil. During this study holes were drilled with a core-drilling rig to install the tensiometers in. A slurry of silica flour and original soil was introduced into the hole at the desired depth into which the tensiometer tip was inserted. The hole was filled with some of the original soil, sealed with cement halfway between two tensiometers and the process was repeated with the next tensiometer in the same fashion as with the porous cup lysimeters. A few days are required for the tensiometer to arrive at equilibrium with the surrounding soil.

For this research, Lorentz and Pretorius from the School of Bioresources Engineering and Environmental Hydrology at the University of Kwazulu-Natal designed custom-made tensiometers to measure tension as deep as 6 m, and depending on the depth of the water table, tensiometers were installed at every meter down the drilled hole (Figure 5-7). The operation of these tensiometers is described in Manual for the operation of Tensiometer Nests using the HOBO Logger System (Thornton-Dibb and Lorentz, 2002).

A four-channel logger was developed to record signals from pressure transducers attached to tensiometers and submerged in groundwater wells. The automatic tensiometers house the water phase in a hydraulic hose, which is protected using PVC conduit. The components are all modular, which allows for convenient assembly in the field to lengths determined *in-situ*. Tests indicated no apparent temperature effects on the electronics that would cause observable signal fluctuations, and that the diurnal fluctuations in automatic tensiometer signal appears to be the result of expansion and contraction of air entrapped in the tensiometer. Hence a rigorous maintenance program, ensuring that air pockets are removed from the apparatus at regular intervals, must accompany the use of automated tensiometers (Figure 5-7).

Figure 5-7: Installation of tensiometers (left) and replenishment (right).

5.7 Leaching columns

Leaching column tests were undertaken to determine the kinetic behaviour of waste rock, soil, ore or tailings stored on the surface and exposed to atmospheric weathering (sub-aerial storage), or stored under water (sub-aqueous storage). In either case the aim is to monitor water (leachate) quality with time by cyclic (daily, weekly or monthly) sampling. Unlike humidity cell procedure (see Sectiion 5.8), there is little, if any, standardisation of column testwork procedure, allowing considerable flexibility. This flexibility permits column operations to be highly site- or material- specific with regard to material particle size and size range (which for waste rock, soil, or drill core is usually greater than that used for humidity cell tests, but still less than that of site conditions), sample mass, water infiltration or flow rate, and degree of oxygenation.

Different leaching column tests were performed to investigate various aspects of the movement of water, and the accumulation and dilution of salts in the soil and spoils of various irrigation areas, including the following:

- Leaching of acidic and non-acidic spoils with deionised water, irrigation water and irrigation return water. Three duplicate sets of 2-m columns with a diameter of 160 mm were packed with raw spoils obtained directly from the mines. After thorough mixing, equivalent amounts of spoils were loaded sequentially into each column by hand. The columns were loaded until each contained 50 kg of material. Initially the cells were leached with 5 litres of water to completely inundate the column and leach out the accumulated oxidation products.
- *In situ* columns were installed at the spoils irrigation site at Optimum. These columns were 215 mm in diameter. Three columns with lengths 2m, 4m and 4.5m were installed and filled with spoils in the exact sequence of collection from the pit in which these columns were placed. These columns include a dead end at the bottom, which was filled with fine-grained washed gravel where the water could assemble. A small piezometer pipe was installed in each column to measure water levels and extract water.
- Leaching of unpolluted background soils with irrigation water (25 pore volume cycles) with gypsiferous waters in order to determine precipitation and adsorption capabilities of the soils. The columns were 65mm in diameter and 2.5 m in length.
- Leaching of irrigated soil columns (sampled down to the water table) with rainwater. This was done to determine the time required to flush polluted soils, at which rates and tempos. The columns were 65 mm in diameter and 3.5 m in length, analogous to the real distance to the water table. These columns were not scaled down.
- Short, wide drums were used for gypsum leaching. Different gypsum concentration scenarios were run for the different types of soils at Kleinkopje Pivot Major (Bainsvlei and Clovelly soils -lower clay content, 5-10%) and Pivot 4 (Hutton soil - higher clay content, average 18%), Syferfontein Pivot (Arcadia soil -high clay content, in the order of 60%) and New Vaal Pivot (sandy soil). For the Kleinkopje Pivots three scenarios were simulated i.e. 10 ton gypsum / ha, 20 ton gypsum / ha and 40 ton gypsum / ha, but for Syferfontein and New Vaal only one scenario each i.e. 20 ton gypsum / ha. During each leaching event 75 mm of rainwater was applied to each drum, and the water analysed. The soil was then dried out under natural conditions. This process was repeated eight times. After each drying cycle, the soil was loosened as if cultivated by the farmer. This was done to simulate realistic agricultural conditions.

The photographs in Figure 5-8 show the different column designs used in the experiments as well as annular rings that were installed to prevent sidewall flow.

Figure 5-8: Photograph of the different leaching columns used (left) and annular rings (right).

A common criticism of many soil lysimeter designs has been the existence of artificial flow paths along the soil-wall interface (Saffigna et al., 1977 and Corwin, 2000). This artificial flow is referred to as sidewall flow. Sidewall flow in a soil lysimeter indicates the artificial channelling of water due to the separation of the soil from the lysimeter wall creating airspace. These airspaces serve as artificial flow paths that permit the rapid flow of water and the transport of solutes, which is a condition that is not representative of the field. Because of this anomalous flow behaviour along the column walls, the past use of lysimeters to evaluate solute transport models and the mobility of contaminants through soil has been questionable. A simple lysimeter design modification utilising annular rings to divert sidewall flow near the soil surface into the soil column to minimize the occurrence of sidewall flow along the remainder of the column's length, was evaluated by Corwin. A chloride-tracer experiment was used to evaluate the effectiveness of annular rings in minimising sidewall flow in a mesoscale soil lysimeter (0.6 m in diameter and 1.83 m in height). The tracer-experiment data showed that even though sidewall flow may not have been completely eliminated it was reduced to an undetectable level based on chloride distributions and time domain reflectometry measurements. However, a delicate balance exists between minimizing sidewall flow and significantly altering the natural water-flow dynamics when using annular rings. The simple design modification provides a means of using a disturbed column of soil to evaluate models of solute transport, and to study preferential flow and contaminant mobility without concern for spurious data due to artificial flow along the soil-wall interface of the lysimeter.

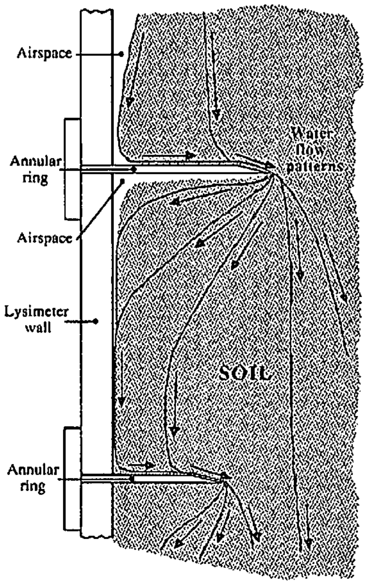


Figure 5-9: Idealised depiction of how annular rings minimise the artificial flow of water along the soil-wall interface of the lysimeter by redirecting sidewall flow inward (after Corwin, 2000).

Aside from the use of annular rings, another aspect that is crucial to minimising sidewall flow is the way in which the soil is packed into the lysimeter or column, particularly at the soil-wall interface. Precautions were taken to create a column of soil that correlates as closely as possible with naturally occurring preferential flow paths. Care was taken to add very small increments of soil into the column that were compacted uniformly with applications of water rather than using the physical pressure of pounding. This was done in an effort to pack the column uniformly. After each increment of soil was added, a series of wetting-and-drying cycles were used to compact the soil. These cycles, with the purpose to promote particle settling and compaction of soil particles, has been a common approach for packing lysimeters (Shih and Rosen, 1985 and Bowman, 1988), and used in this research.

5.8 Humidity cells

Kinetic tests are intended to mimic the geochemical processes at mining sites, usually at an accelerated rate. These tests require more time and are considerably more expensive than static tests (US EPA, 1994).

Acid-base accounting procedures are used as a screening process to categorise materials into potentially acid generating, potentially non-acid generating and uncertain groups. For material where the potential for acid generation is uncertain, kinetic test work is performed in an attempt to define acid generation characteristics. The term kinetic is used to describe a group of test work procedures wherein the acid generation (and metal solubilisation and transport) characteristics of a sample are measured with respect to time (Mills, 1998).

Internationally, humidity cells have become the most popular devices for conducting kinetic tests. Locally the usage has, unfortunately, been very limited. Cell designs can vary in the material of construction, geometry and size. A typical cell is constructed of plexiglas with the dimensions 10 cm diameter by 20 cm in length, and has a nominal capacity for 1 kg of rock. The rock sample is typically crushed to grain sizes of less than 6 mm in diameter and placed on a perforated plate to permit the flow of air through the bed of rock. The cell can be provided with a bubbler tube containing water, attached to a tight-fitting lid, through which the exiting air is passed. The bubbler provides a visual check that air is flowing through the cell, and allows the operator to achieve a semi-quantitative balancing of airflow through a bank of humidity cells. Dry or humidified air is supplied to the underside of the perforated plate. The temperature of the water in the humidifier should preferably be maintained slightly above ambient to ensure a good supply of humidified air. Leachate, usually distilled water, is periodically added through the lid of the cell. The mode of addition can vary. In some test programs, the water, typically 250 mL to 500 mL is added slowly over several hours (percolation leaching). In this method, the valve at the bottom of the cell is open to allow free draining. In other programs, sufficient water can be added to completely submerge the sample for a period of time, before the bottom valve is opened to allow draining (Usher, 2003). Humidity cells that are constructed as illustrated in Figure 5-10 are currently used at the Institute for Groundwater Studies (IGS).

Humidity cell tests are performed to evaluate the long-term acid-producing potential of mine waste rock, tailings or spent ore. The test simulates the accelerated weathering of the sample. This is done by passing moist air followed by dry air through the sample chamber; moist air for three days, followed by dry air for three days, and distilled water on the seventh day. The leachate is analysed for pH, conductivity, sulphate, acidity and dissolved alkalinity. This one-week cycle is typically run for 20 weeks (Usher, 2003). Samples are usually selected to represent the various lithologies at the mine, along with a range of ABA and/or NP/AP values. In this way, humidity cell results can be used to identify or confirm the AMD risk associated with a range of ABA values. It is normal for data to be quite erratic over the first few cycles, before consistent results are obtained. This is due to the removal of readily soluble components from prior oxidation and weathering. It is not unusual for humidity cell tests to continue for several months, or even more than one or two years (Lawrence and Day, 1997).

Figure 5-10: An IGS humidity cell, left and an array of cells set up at the IGS, right (after Usher, 2003).

Different weekly methodologies for this research were used. Two identical sets of non-acid generating rock were used for the first experiment that ran over 20 weeks (obtained from Optimum Colliery). This was followed with two sets of acid-generating rock for the second experiment (obtained from Middelburg Mines).

- Cells 1 and 4 were leached each week by the addition of mine water.
- Cells 2 and 5 were leached each week by the leachate from that column, made up to 500 ml by mine water.
- Cells 3 and 6 were leached each week by the addition of deionised water.
- Two cells, not connected to the humidity cell system, were filled with irrigation water and also closed at the top. The rock in the cells was totally submerged, and the water quality was only measured every seven weeks to keep as little air as possible from entering the system. This was done to simulate "flooded" background pit conditions.

5.9 Point Dilution Tests

The point dilution test is a simple method to find the groundwater velocity. Since high velocities are related to highly conductive units, the test is used to locate fractures and other conductive features at less time and cost than the geophysical methods. The test requires careful data measurement and interpretation, but will not indicate groundwater flow directions.

The use of artificial tracers involves the injection of tracers in the subsurface and their detection down gradient in monitoring wells (Freeze and Cherry, 1979; Riemann, 2002 and Van Tonder et al., 2002b). Taking the effect of dispersion into account, the groundwater flow rate and direction can thereby be evaluated. However, this experiment needs more funding and is time intensive. An easy and inexpensive alternative is the use of point dilution tests to estimate groundwater velocity (Lamontagne *et al*, 2002 and Drost et al., 1968). A single well point dilution test method aims to relate the observed rate of tracer dilution in a borehole, or a segment isolated in a borehole, to the Darcy velocity in the aquifer. The groundwater flow gradually depletes a tracer introduced to the well to produce a concentration-time relationship from which the Darcy velocity and horizontal hydraulic conductivity can be evaluated.

The aim of the point dilution experiment can be summarised in the following three points:

- Delineation of hydrogeologic profiles within a borehole
- Estimation of Darcy velocity
- Estimation of horizontal hydraulic conductivity.

The experiments were performed in boreholes at each irrigation site. The procedures were the same in all the boreholes (Gebrekristros, 2006). The background EC-value was firstly measured. After estimating the volume of water in the borehole section, NaCl was used as a tracer. Changes in concentration were measured in terms of electrical conductivity (EC). From experimental results, the concentration of NaCl, in mg/L, was found to be four times the value of the EC (mS/m). This means that every change in concentration of NaCl (in mg/L) resulted in a linear increase in the EC (in mS/m). The amount of tracer solution introduced should be high enough to be distinguished from the background EC value in the borehole. If the concentration is too high however, it may create a density gradient and the vertical movement of the solution may occur. A 100% increase of EC i.e. doubling the initial concentration is usually sufficient, although the increase may vary from 50 to 200% depending on the groundwater flow velocity. If the velocity is expected to be high, then the influence of solution movement by density gradient would be insignificant and a higher concentration of tracer solution could be applied.

The pump inlet is positioned at the bottom of the borehole while the injection pipe outlet is at the top, just below the water level. A flow cell on the surface connects the abstraction and injection pipes. The flow cell has an opening through which the tracer is injected and the EC probe could be inserted for measuring inside the flow cell. Water is abstracted and flows through the flow cell and injection pipe, and finally back into the borehole. The tracer solution must be inserted uniformly in a single well volume. The insertion of the tracer is very important. Improper insertion results in an error in the estimated velocity value.

The water level in the aquifer must remain static and steady-state flow must be maintained throughout the test. If the experiment is continued while the water level is lower than the static position, the dilution rate will be higher until the borehole recovers to its static position and Darcy velocity will be overestimated.

After the release of the tracer, the circulation is continued for at least one well volume so that the solution will mix completely. During the borehole-mixing process, activities that may result in the increase of the rate at which the tracer moves out of the well, termed as dispersion by Lamontagne *et al.* (2002), should be avoided. Tracer dispersion results in the dilution of the tracer at higher rates at an early stage. This would occur because some of the tracer initially displaced upstream by dispersion would later re-enter the well by advection. Turbulent flow due to a high pumping rate could result in dispersion; therefore, the optimal circulation velocity may be a compromise between greater mixing and less dispersion.

After the concentration/EC had stabilised, indicating complete mixing, the pump is switched off and the reading of EC values proceed at specific depths within the borehole. The measurement continued until the solution is diluted to about 20% of its initial value.

Before the evaluation of the velocity, the measured EC value was normalised as follows:

$$C(t) = \frac{Ci - C_b}{C_0 - C_b}$$

Where

C(t) = normalised EC

Cb = background EC value

Ci = measured EC value

C_0 = Initial EC at time t_0

The Darcy velocity for the different sections in the borehole can be evaluated from the measured concentration values using the Drost and Neumaier (1974) equation as follows:

$$q = -\frac{V}{\alpha A t} \ln c(t)$$

Where:

q = Darcy velocity

V = volume of fluid contained in the test section

A = cross sectional area normal to the direction of flow

α = borehole distortion factor (assumed to be equal to 2)

t = time when EC value was Ci

From these values, the flow zones at depth could be identified, and the flux as well as the conductivity for the flow zones could be calculated.

5.10 Slug tests

In a slug test, a small volume of water is suddenly removed from the borehole after which the rise of the water level in the borehole is measured. Alternatively, a small slug of water is poured into the borehole and the subsequent fall of the water level is measured (Kruseman and De Ridder, 1994). This is very useful to determine the transmissivity of the upper soil layers at the irrigation site where no water level occurs. If these values are compared to those of the layers below where conductivity values were obtained by the point dilution method, the conductivity values for the whole profile can be established.

In South Africa slug tests are conducted for the following two reasons:

- To estimate the hydraulic conductivity (K) of the aquifer in the vicinity of the borehole (Van Tonder and Vermeulen, 2005) and
- To obtain a first estimate of the yield of a borehole (Vivier *et al.*, 1995).

As we are only interested in the hydraulic conductivity (K) of the aquifer in the vicinity of the borehole, only the applicable theory will be dicussed. Usually the Cooper method (Cooper *et al.*, 1967) or the Bouwer and Rice method (1976) is used to estimate the K-value (or T-value in the case of the Cooper method).

In the FC program, developed by Van Tonder *et al.*, 2002, the Bouwer and Rice method (1976) was applied to calculate these conductivity values. The method applies to unconfined conditions and is based on the Thiem equation. The Bouwer and Rice equation reads:

$$K = \frac{r_c^2 \ln(R_e / r_w)}{2d} \frac{1}{t} \ln \frac{h_0}{h_t}$$

Where:

r_c = radius of the unscreened part of the borehole where the head is rising

r_w = horizontal distance from the borehole centre to the undisturbed aquifer

R_e = Radial distance over which the difference in head h0 is dissipated in the flow system of the aquifer

d = length of the borehole screen or open section of the borehole

h_0 = head in the borehole at time=0

h_t = head in the borehole at time t

The estimated K-value of Bouwer and Rice is dependent on the thickness open to flow d which in this case refers to the different layers in the soil.

At all the irrigation sites a number of boreholes were augured to a depth just above the water level. The boreholes were saturated with water to minimise the unsaturated flow conditions discussed in Chapter 4 (water was poured down the augured holes for a number of times over a period of two days). They were then filled with water, and the recession time was measured, after which the hydraulic conductivity values were calculated for the different zones.

5.11 Pumping Tests

Pumping tests are the most important experiments for aquifer investigation in the groundwater industry (Van Tonder *et al.*, 2002). They are the only method that provides simultaneous information on the hydraulic behaviour of the well (borehole), the reservoir and the reservoir boundaries, which are essential for efficient aquifer and wellfield management.

The general objectives of a pumping test are:

- A better understanding of the aquifer system,
- Quantification of its hydraulic characteristics and properties

The interpretation of pumping test data is based on mathematical models that relate the drawdown response to the discharge of the pumped well. The results obtained from this short duration test are then used to estimate the borehole performance over a period of many months (or even years). The mathematical model could be solved by the application of analytical or numerical techniques (Van Tonder *et al.*, 2002). If the aim is setting up a 3D numerical model, a number of piezometers must be installed (to measure pressure heads and vertical K-values for each layer).

Every borehole in a fractured-rock aquifer reacts differently, and therefore it is of no use to give one general recipe on how to conduct and analyse pumping test data. If the objective of the pumping test is to estimate aquifer parameters that are to be used in e.g. a numerical management model, the constant rate test is most important and is set as minimum requirement for parameter estimation. One of the most important factors of a constant rate test in this case is selecting the abstraction rate during the test. The yield must be chosen in such a way that no main water-yielding structures will be dewatered during the test.

The FC (flow characteristic method) software was used (Van Tonder *et al.*, 2002) and includes the following procedures to deal with the different types of flows and aquifers in South Africa:

- Porous aquifer solutions (Theis, Cooper-Jacob I and II and Hantush methods and also a solution for water-table aquifers).
- Step drawdown and multirate analyses.
- Fractal pumping test analysis (Barker's Generalised Radial Flow Model).
- Slug test analysis (Bouwer and Rice method).
- Different diagnostic plots for flow regime identification (e.g. derivatives, second derivatives, log-log (Theis)-plot, lin-log (Cooper-Jacob)-plot, square root of time plot, fourth root of time plot, spherical and recovery plot).

A number of pumping tests were performed at each pivot site to determine the transmissivity values. These values could then be compared with the values of the other flow zones higher up in the profile, in order to determine the flow paths of the water over the total depth of the aquifer measured. Very low pumping rates were used in all the boreholes (< 0.1L/s). The data were analysed with the FC program, and transmissivity values calculated.

In Table 5-1 a summary of all the experiments and the sites where they were conducted, are portrayed.

Table 5-1: Summary of all the experiments.

Site	**Description**
Kleinkopje 1 (Major) and 4 Syferfontein New Vaal	Borehole monitoring
Kleinkopje 1 (Major) and 4 Syferfontein New Vaal	Pits and soil sampling
Kleinkopje 1 (Major) and 4 Syferfontein	XRD
Kleinkopje 1 (Major) and 4 Syferfontein Optimum	XRF
Kleinkopje 1 (Major) and 4 Syferfontein Optimum	Porous cups
Kleinkopje 1 (Major) and 4 Syferfontein Optimum	Tensiometers
Kleinkopje 1 (Major) and 4 Syferfontein Optimum	Point Dilution Tests
Kleinkopje 1 (Major) and 4 Syferfontein Optimum	Falling head tests
Kleinkopje 1 (Major) and 4 Syferfontein Optimum	Pumping tests
Laboratory	Leaching columns -spoils
Laboratory	Leaching columns - adsorption
Laboratory	Leaching columns - salt leaching
Laboratory	Leaching drums
Optimum - lab	Humidity cells

6 DETAILED CHARACTERISATION OF VIRGIN SOIL IRRIGATION SITES

6.1 Introduction

- In this chapter, the groundwater quality is discussed at various sites, together with related results and conclusions.
- This will be followed by a discussion of the soil properties, the soil moisture and gypsum precipitation and adsoption in the profile.
- An assessment of the hydraulic behaviour and chemistry will be investigated, including soil moisture, a salt balance, salts leaching through the profile, as well as flow determination. The influence of clay on these properties will also be discussed.

6.2 Groundwater monitoring

Detailed groundwater monitoring has been ongoing at the irrigation sites since the inception of the irrigation project by the University of Pretoria in 1999. **(The complete data set of all the monitoring data at the different sites is portrayed in Appendix D).** As described in Chapter 3, boreholes were drilled inside and outside the pivot areas for monitoring of the groundwater.

Figure 6-1: Monitoring borehole at Kleinkopje Pivot 4.

6.2.1 *Kleinkopje Colliery*

6.2.1.1 Groundwater quality analysis Pivot 1

The analysis of the sampling done during November 2005 is illustrated in Table 6-1.

- According to these analyses, the water quality of all the boreholes sampled inside the pivot area is acceptable water, except for elevated nitrate in PV1BH2.

Table 6-1: Water quality of the groundwater at the Kleinkopje Pivot1 (November 2005).

Site Name	pH	EC	Ca	Mg	Na	K	PAlk	MAlk
PV1BH2	5.69	73.5	51.5	36.2	30.4	9.2	0	13.6
PV1BH3	6.45	3.6	0.6	0.2	7.8	2.0	0	15.4
PV1BH6	6.43	5.36	1.5	0.8	7.4	2.1	0	18
PV1BH7	6.42	6.25	3.6	1.5	7.9	6.5	0	17.5
Site Name	**F**	**Cl**	**NO2(N)**	**Br**	**NO3(N)**	**PO4**	**SO4**	**Br**
PV1BH2	<0.01	41.1	0	0.1	25.46	<0.01	197.0	<0.04
PV1BH3	<0.01	1	0		0.64	<0.01	1.2	<0.04
PV1BH6	<0.01	1.5	0	0.02	1.52	<0.01	0.9	<0.04
PV1BH7	<0.01	4.8	0	0.06	3.07	<0.01	1.8	<0.04

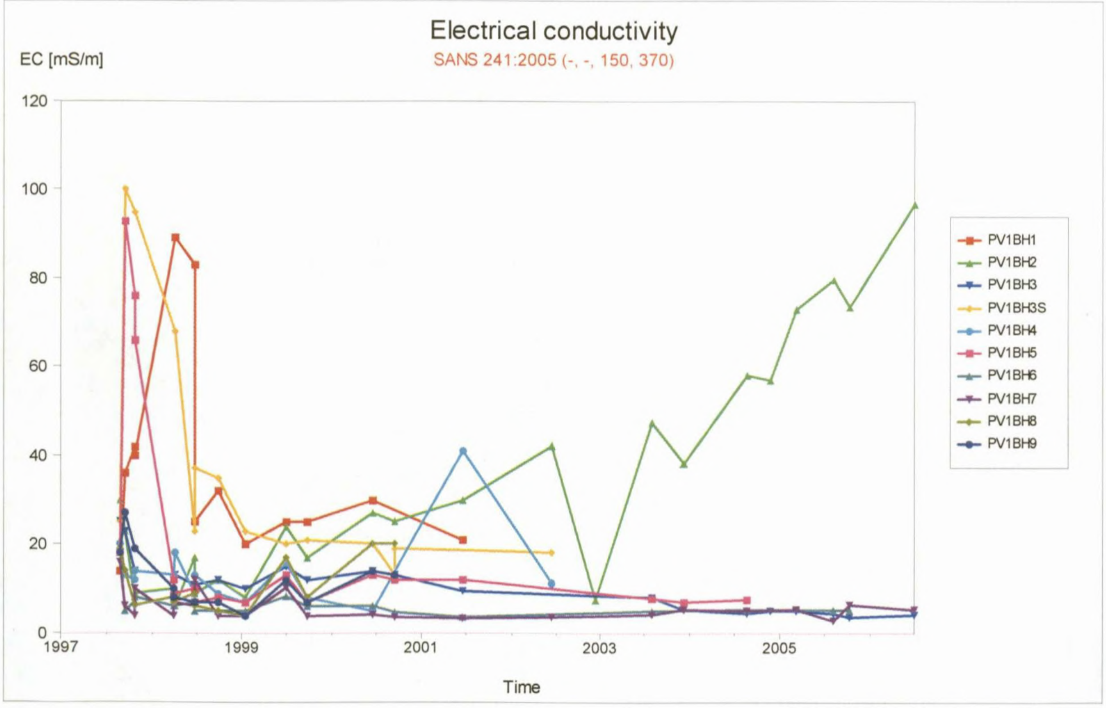


Figure 6-2: Time graph of the electrical conductivity at Kleinkopje Pivot1.

- The overall water quality trend of all the boreholes is sideways (Figure 6-2), indicating that over the period of irrigation, water quality has not deteriorated within the underlying aquifer. The only exception is PV1BH2, where a rise in salinity is evident.

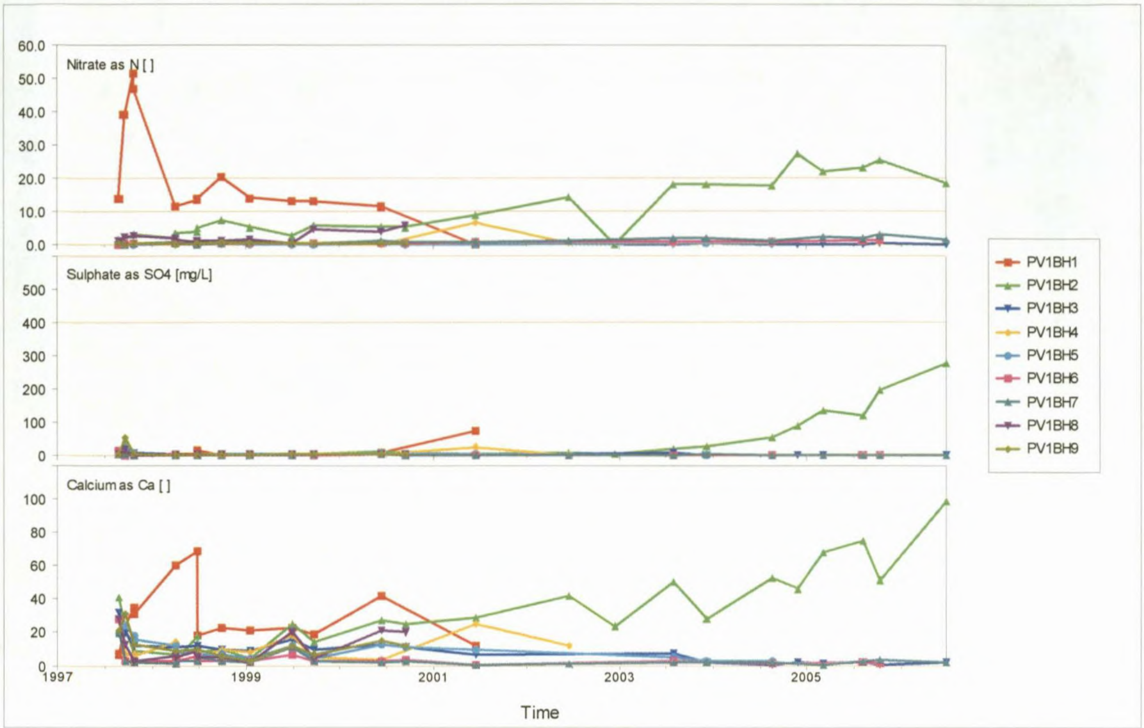


Figure 6-3: Time graph of the calcium, sulphate and nitrate at Kleinkopje Pivot1.

- The majority of the groundwater constituents showed no increase over time, as illustrated in the time graph of calcium, sulphate and nitrate in Figure 6-3. This suggests that these macro constituents do not reach the groundwater. The exception is PV1BH-2, which deteriorated drastically in water quality since 2003. As this borehole is down gradient from the expected flow direction, the vast increase in dissolved solids is cause for concern. The water is probably being transported from elsewhere in the pivot area by the bedding-plane fracture situated at approximately 10m towards PV1BH-2. This situation must be closely monitored to minimise regional impacts.
- The steep increase in nitrate in PV1BH2 since 2001 correlates with the increase in dissolved solids. The values are currently an order higher than in the other boreholes. As this borehole is down gradient from the expected flow direction this vast increase in nitrate is cause for concern.

Conclusion: The salinity in the monitoring boreholes is surprisingly low for an irrigation site, given that the TDS off the irrigation water is nearly 4000mg/L. This indicates that the salts are attenuated in the soil, but because PV1BH2 shows an increase in salinity over time, the other boreholes are probably constructed wrongly (see Section 6.6.5.3 for a discussion on this issue).

6.2.1.2 Groundwater Quality analysis Pivot 4

The analysis of the sampling done during November 2004 is illustrated in Table 6-2. According to the analysis, the water quality of all the boreholes sampled is ideal except for PV4BH2, which has elevated nitrate content. Unfortunately this was the last time all the boreholes could be sampled. Since then two of the boreholes were destroyed.

Table 6-2: Water quality of the groundwater at Pivot 4 (November 2004).

SiteName	**pH**	**EC**	**Ca**	**Mg**	**Na**	**K**	**PAlk**	**MAlk**
PV4BH1	5.16	13.7	5.8	5.0	4.3	7.14	0	2
PV4BH2	6.89	73.5	49.9	43.6	36.8	5.41	0	95
PV4BH3	5.2	6.6	1.8	1.4	4.8	2.04	0	1
PV4BH4	5.25	5.1	1.6	1.0	5.2	0.83	0	1
PV4BH6	5.11	9.16	3.5	2.4	7.7	2.10	0	3
SiteName	**Cl**	**SO4**	**NO3-N**	**F**	**NO2-N**	**NH4**	**PO4**	**Br**
PV4BH1	4.2	0.4	13.75	<0.01	<0.01	<0.1	<0.1	<0.04
PV4BH2	50.3	240.0	0.04	0.03	<0.01	<0.1	<0.1	0.12
PV4BH3	4.9	4.0	2.46	<0.01	<0.01	<0.1	<0.1	<0.04
PV4BH4	5.3	4.1	2.66	<0.01	<0.01	<0.1	<0.1	<0.04
PV4BH6	4.1	0.4	9.28	<0.01	<0.01	<0.1	<0.1	<0.04

- The overall water quality trend of all the boreholes indicated relative stability, indicating that water quality did not deteriorated within the underlying aquifer over the initial period of irrigation (Figure 6-4). The increase in the EC in PV4BH2 during 2004 is the result of a broken-down pivot that caused water logging. The borehole is downgradient and water infiltrates via the broken casing into the borehole. The EC should return to the original values over time (there was already a slight improvement during the next sampling run). Unfortunately this borehole has been destroyed, and cannot currently be monitored.
- Since 2006 the electrical conductivity of boreholes inside the irrigation area indicated a relatively sharp increase.

Conclusion: The exceptionally high rainfall during the rainfall season may be the cause of leaching of salts from the soil profile. Only continued monitoring at this site will indicate if this trend will continue.

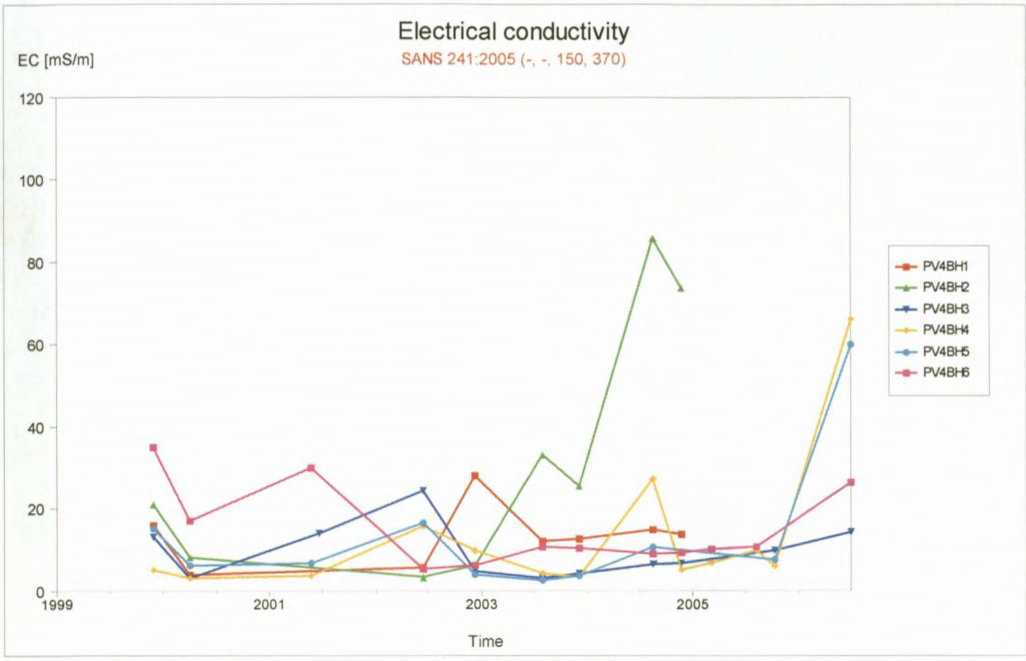


Figure 6-4: Time graph of the EC at Pivot 4 boreholes.

6.2.2 *New Vaal Colliery*

6.2.2.1 Groundwater Quality Analysis (see Appendix D for Monitoring data).

According to the analysis of the sampling done, the water quality of all the boreholes sampled, except PV2, indicates very little pollution. PV2 contains completely different water. The reason for this is that the water originates from the dam overflowing. Unfortunately this borehole became blocked and could not be sampled since 2005. Regarding the 2005 sampling (Figure 6-3), it is clear that the water in the shallow piesometers, installed above the clay layer, is highly polluted. Evapotranspiration resulted in an increase in sailinity, and can clearly be seen in the salinity of the water in the piesometers, which is much higher than that of the irrigation dam.

Table 6-3: Quality of the groundwater at the New Vaal Pivot in mg/L (March 2005).

SiteName	pH	EC	Ca	Mg	Na	K	PAlk
PV3	6.99	105	77	31	96	5	0
PV4	7.34	20	15	7	11	2	0
PV5	6.64	32	26	11	18	3	0
Short piezo	7.64	223	142	50	290	23	0
Solid piezo	7.64	255	115	60	422	6	0
SiteName	**MAlk**	**Cl**	**SO4**	**NO3-N**	**NO2-N**	**Br**	**NH4**
PV3	83	125	271	0.06	<1	0.54	0.06
PV4	44	8	34	1.11	0.03	<1	0.23
PV5	17	41	75	0.13	<1	0.08	0.26
Short piezo	163	79	745	27.60	0.06	<1	0.19
Solid piezo	226	98	896	6.17	0.71	0.43	0.17

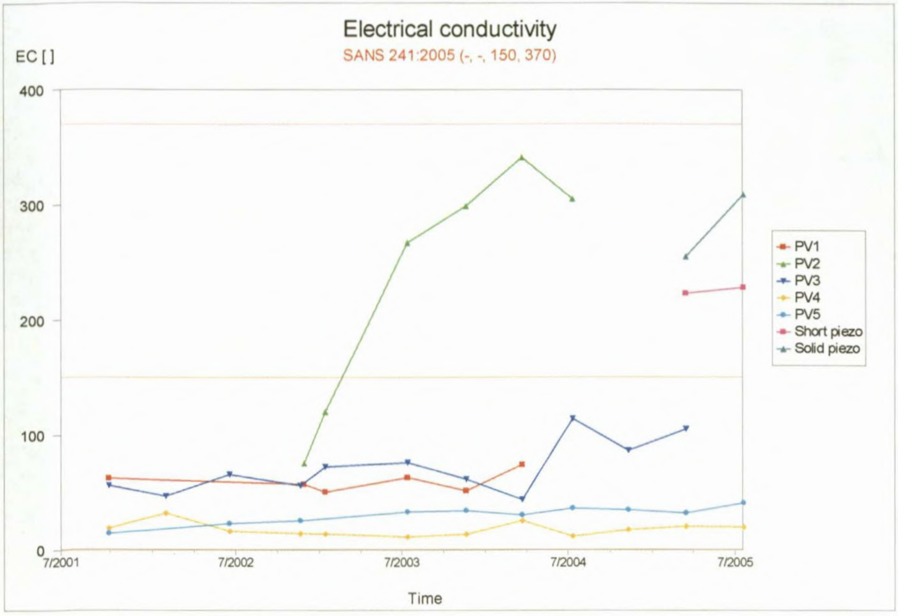


Figure 6-5: Time graph of the Electrical Conductivity at New Vaal Pivot.

This indicates that, over time, the water quality did not deteriorated significantly within the underlying aquifer because of irrigation. The reason may be dilution due to the high lateral flow of water through the sandy layers above the clay layer and high natural recharge of the sands. The clay layer previously discussed also limits downward migration and therefore only gradual contamination of the aquifer occurs from slow leakage through this layer.

It is insightful to focus on Borehole PV5 in the pivot area as far as trends are concerned (Figure 6-6).

Figure 6-6: PV5 electrical conductivity trend since monitoring began.

Although the water quality in this borehole is acceptable, the results from the analysis show that there is a steady and consistent rise in the electrical conductivity in the borehole. This indicates that the irrigation water is slowly leaching through the clay layers and starting to influence the groundwater quality directly below the pivot. The trend in this borehole is cause for some concern and future phases will need to investigate this further if irrigation is to continue. At the current increase rate, irrigation will start to cause marked deterioration in values beyond the trigger values for this site within a few years.

6.2.3 *Syferfontein Colliery*

6.2.3.1 Groundwater Quality analysis

The analysis of the sampling done during June 2006 (the last time sampling was possible) is illustrated in Table 6-4. According to this analysis, the water quality of all the boreholes sampled excluding OBH6S is acceptable, except for Nitrate. OBH6S is a shallow borehole and shows the effect of the irrigation.

Table 6-4: Water quality of the groundwater at the Syferfontein Pivot.

SiteName	pH	EC	Ca	Mg	Na	K	MAlk	Cl	SO4	NO3-N	Br
		mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
OBH1	7.55	99	86	49	55	1.7	414	102	4	1.8	0.3
OBH2	7.81	95	76	46	66	2.0	415	41	37	11.4	0.6
OBH3	7.96	88	83	64	35	1.9	327	17	175	3.8	0.1
OBH6D	7.60	99	89	48	69	0.8	315	13	177	20.6	0.3
OBH6S	7.80	189	198	123	605	1.7	481	28	1715	7.4	0.2
OBH7	7.46	87	105	62	158	5.9	383	24	432	4.6	1.6
OBH8	7.61	90	70	38	77	1.5	344	24	65	10.8	0.7

The electrical conductivity of all the boreholes is illustrated in Figure 6-7. The deeper new borehole (OBH6D) inside the irrigation area shows no variation or increase in electrical conductivity from the other boreholes outside.

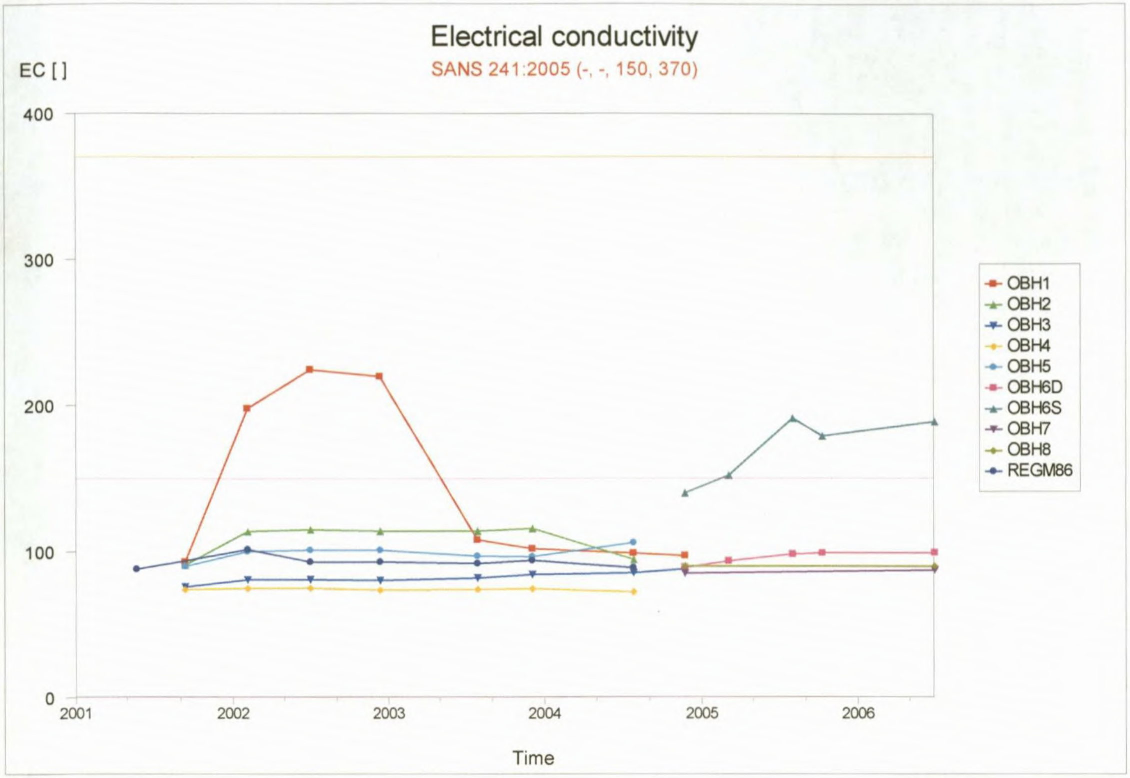


Figure 6-7: Time graph of the Electrical Conductivity at Syferfontein Pivot.

OBH1 has shown a vast improvement since the construction of run-off trenches in 2003 and was similar in water quality to the other boreholes when monitoring ceased.The overall water quality trend of all the boreholes is sideways, indicating that over the period of irrigation water quality has not deteriorated within the deeper aquifer. However, the shallow aquifer has deteriorated.

6.2.4 *Overall conclusions from the groundwater monitoring at the pivots*

- The water levels at all the pivots have varied very little over time. The water levels at New Vaal are deeper than most other irrigation schemes. This can be attributed to the high conductivity in the soils above the clay layers, resulting in faster drainage towards the river. The water levels at the other irrigation sites are very shallow due to the increased local recharge.
- The overall water quality trend in the deeper aquifer indicates no significant water quality deterioration over the monitoring period. The exception is Borehole PV5 at New Vaal within the pivot area itself which shows signs of consistent water quality degradation, with increases in most of the constituents.
- The irrigation water has, as yet, shown a minimal impact on the groundwater. Some exceptions occur, but none of the boreholes outside the pivot areas show any meaningful change in water quality from leaching from the irrigated area. This implies

a very slow movement of the constituents in the irrigation water, and that these are attenuated by different mechanisms between the surface and the aquifers, often in the clay layers. The amount leaching through the soil is small enough to be easily diluted by the regional groundwater flow. It thus appears that the soil type and morphology plays a very important role in the vertical movement of the irrigation water constituents.

- It is unknown how long this accumulation of salts in the upper layers can continue before leaching into the underlying aquifers, but in the short to medium term, the evidence from groundwater monitoring shows that irrigation with mine water does not hold significant threats for the regional groundwater quality.

The irrigation water has, as yet, shown only a minimal impact on the groundwater. **It is important to consider reasons that the irrigation water is not represented in the groundwater.** The hydraulic and attenuation factors preventing the salts in the mine water used for irrigation from being mobilised down the soil profile and into the aquifer are important considerations in this process. ***The soil composition and associated sorption and hydraulic properties may be informative.*** The amount leaching through from the pivots is small enough to be easily diluted by the regional groundwater flow. The larger concentrations of nitrate are due the agricultural activity at the pivot. Of concern is the fact that the relatively mobile constituents (e.g. nitrate) are able to move through the soil profile into the groundwater and results in quality degradation.

6.3 Soil analysis

To determine the soil composition and texture, which is important in understanding the downward flux of the irrigation water, trenches were dug and core drilling was done in order to sample the profiles at the different sites with depth. The soil was also analysed to determine the salt balance in the profiles with depth.

6.3.1 *Kleinkopje*

To determine the soil composition and texture, two trenches were dug for inspection and soil property analysed. The soil at Pivot 4 is fairly homogeneous (Hutton soil), whilst that at Pivot 1 varies with depth (Bainsvlei and Clovelly soils). The distinctive geological layers were selected, sampled and soil properties were determined in terms of relative clay, sand, silt etc. content. The results are shown in Table 6-5 and indicate clayey layers in the soils.

Table 6-5: Soil properties at Kleinkopje Pivots (%).

Pivot Name	Depth (m)	Sand	Coarse silt	Fine silt	Clay
1	0-0.4	79.19	5.18	9.34	4.67
1	0.4-0.8	78.39	9.74	4.62	4.62
1	0.8-1.0	73.74	10.30	13.93	0.00
1	1.0-2.5	61.11	16.46	9.29	18.58
1	2.5-2.8	66.33	15.37	9.24	9.24
4	0-0.6	72.50	9.20	4.60	13.79
4	0.6-1.0	64.32	11.75	4.62	18.48
4	1.0-2.0	56.06	10.80	13.93	18.58
4	2.0-3.0	50.50	15.29	4.60	27.59
4	3-3.2	53.27	19.49	4.62	23.10
4	3.2-3.5	59.60	9.79	4.64	23.22

Three core boreholes were drilled at each of the pivots, two inside the pivot areas and one outside for background values. The core samples were analysed for the major cations and anions at the IGS laboratory. Figure 6-8 and Figure 6-9 shows the leaching of water-soluble constituents for two cores inside the pivot areas.

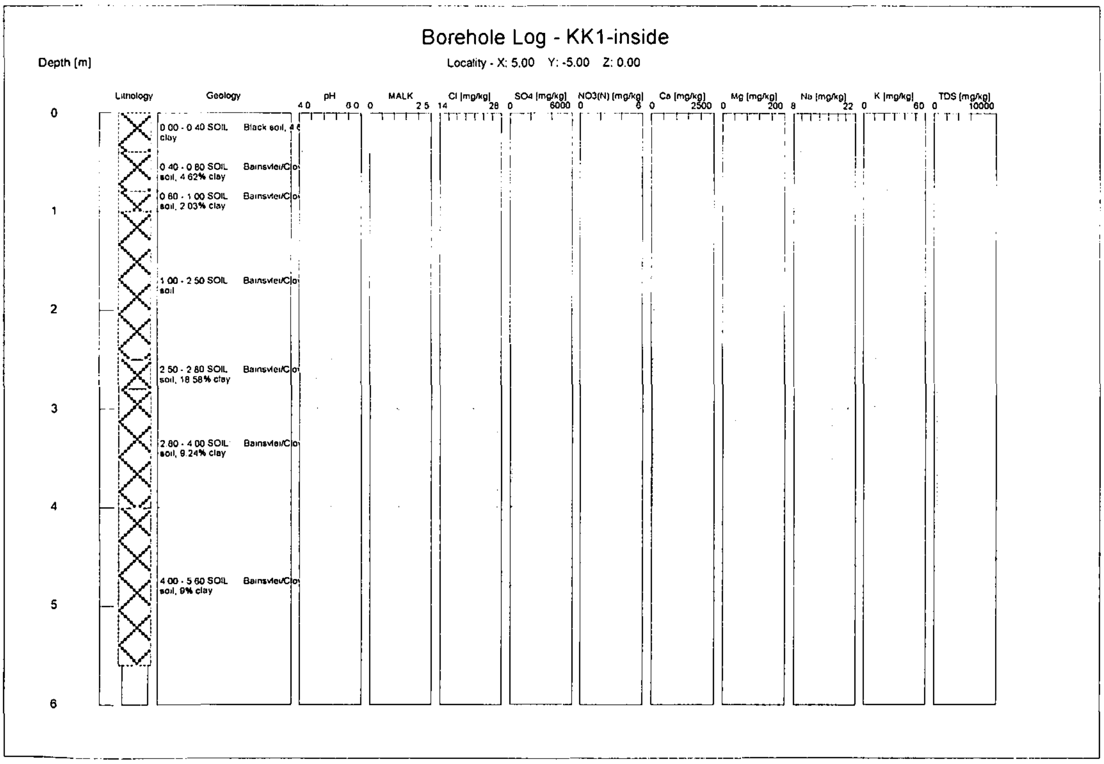


Figure 6-8: Soil leaching analyses with depth within Pivot 1.

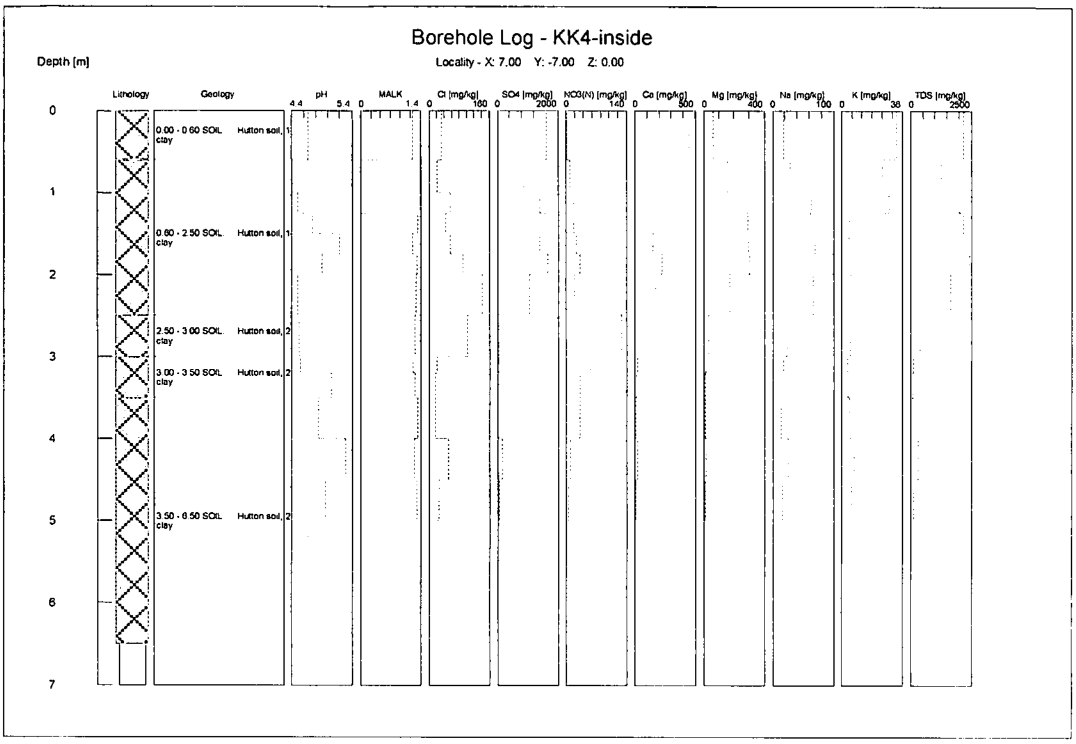


Figure 6-9: Soil leaching analyses with depth within Pivot 4.

From these figures it is clear that there is currently a build-up of salts in the soils above and within the clayey layers, and that a limited proportion of the associated salts move through into the groundwater.

6.3.2 *New Vaal Colliery*

Different activities were undertaken to determine the reason for the relatively deep water levels:

1. Two trenches were dug inside the pivot area, and inspected. Water seepage is very shallow, and occurred approximately 2.4m below surface.

The distinctive geological layers were selected, sampled and soil properties were determined in terms of relative clay, sand silt etc content at Glen Agricultural College. Table 6-6 confirms the clay layer below 2.4 m, which is also a reason for the water logging at this pivot.

Table 6-6: Soil properties at New Vaal (%).

Depth (m)	Sand	Coarse silt	Fine silt	Clay
0-0.6	94.50	4.60	1.01	3.59
0.6-0.75	94.95	4.64	0.70	3.95
0.75-0.85	96.02	4.57	1.05	3.52
0.85-1.0	91.46	6.13	0.65	3.97
1.0-2.1	93.47	4.62	1.39	3.23
2.1-2.2	96.48	4.62	0.92	3.70
2.2-2.4	89.34	7.21	1.40	3.27
2.4-4.0	42.27	15.25	18.96	23.70
8.0-9.0	57.14	15.10	14.07	14.07

2. Three auger boreholes were drilled at the pivot, one inside the pivot area and one outside for background values. Another one was drilled between the irrigation dam and the pivot to determine the leaching properties from the irrigation dam towards the pivot, and to determine the influence of the dam on the water logging problems. The auger samples were analysed for the major cations and anions at the IGS laboratory. The figures below show the leaching of water-soluble constituents for the auger hole inside the pivot, with a high concentration of constituents in the clay layer.

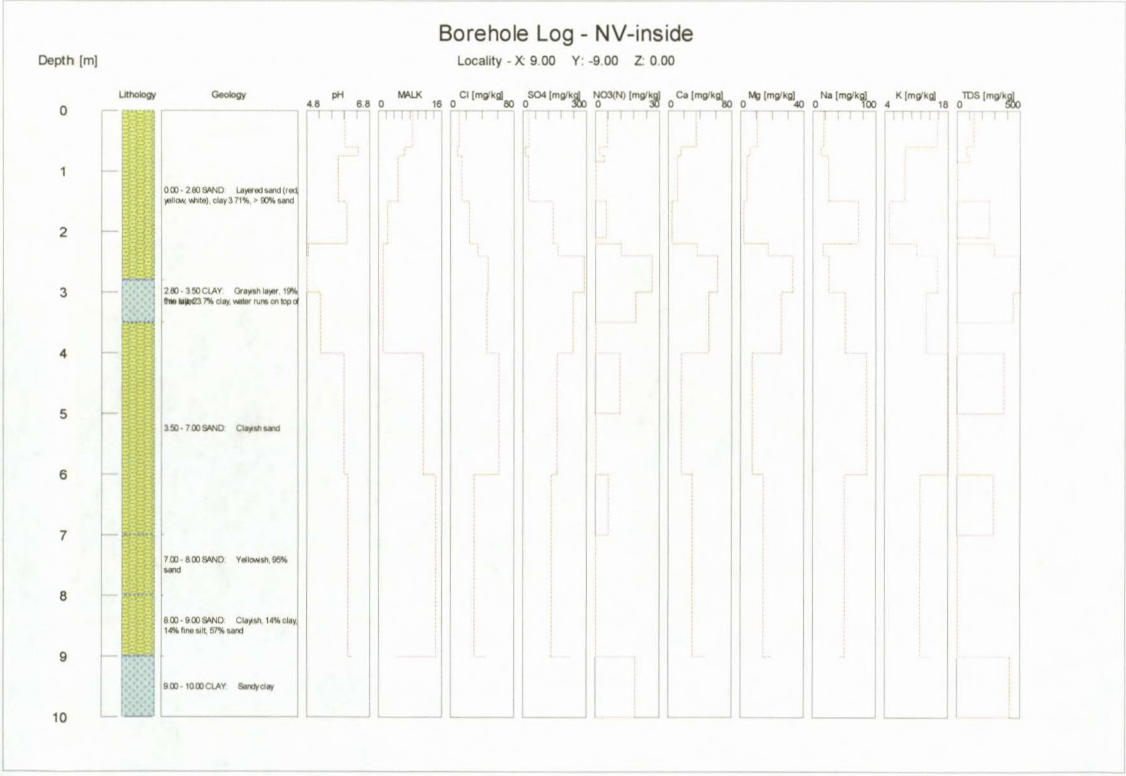


Figure 6-10: Soil leaching analyses with depth inside the pivot area.

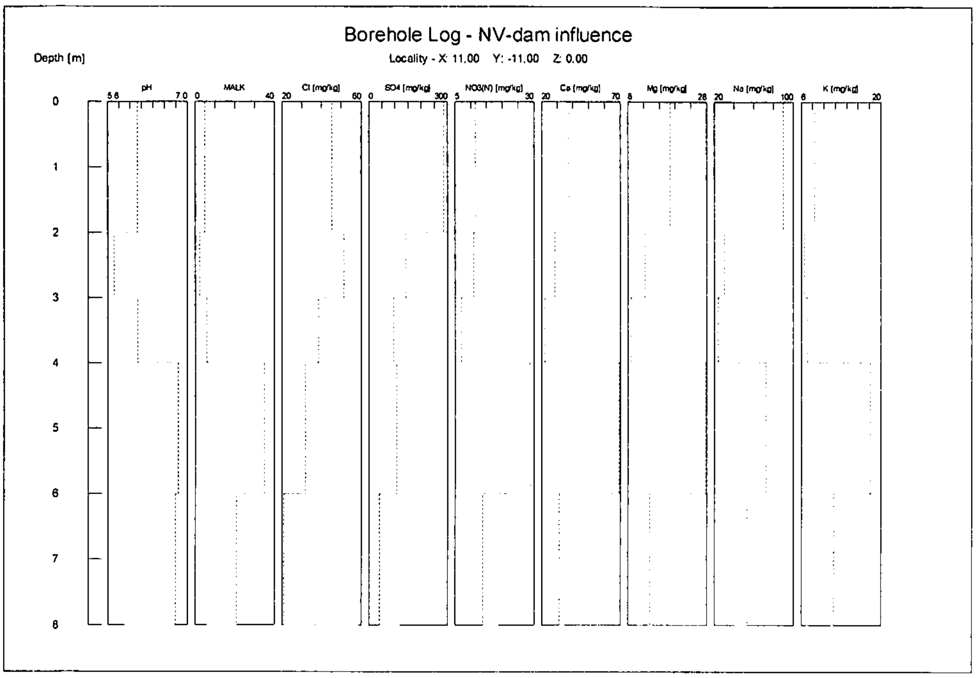


Figure 6-11: Soil leaching analyses with depth showing the dam's influence.

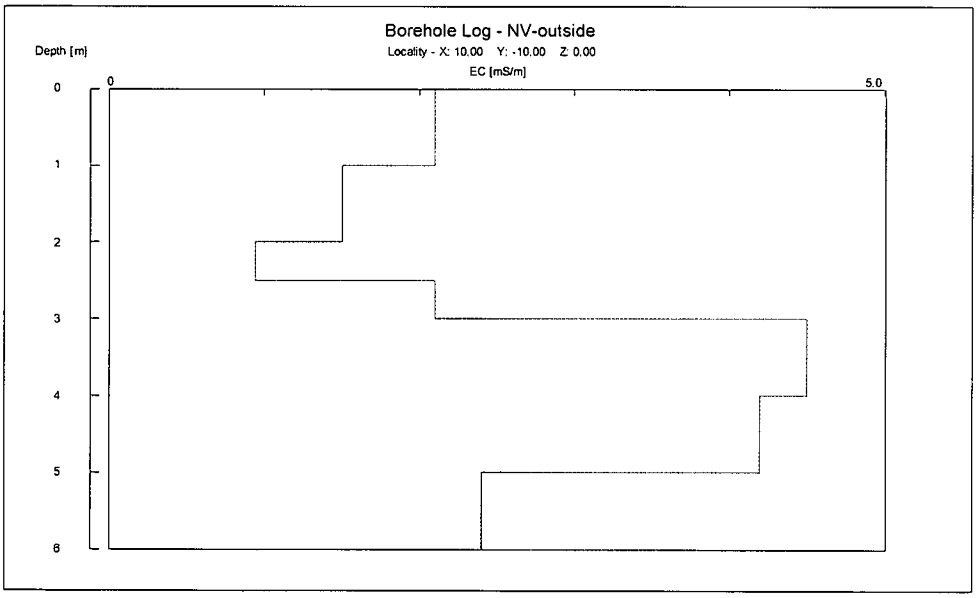


Figure 6-12: Soil leaching analyses with depth outside the pivot area.

These graphs (Figure 6-10 to Figure 6-12) show that there is a significant clay layer below 2.4 m in the pivot area (as also depicted in Table 6-6) and slightly deeper towards the dam. This layer impedes downward migration of water and associated salts, which is associated with the observed ponding in the pivot area.

3. Two piezometers were installed close to PV5 to study the influence of the clay layer on the irrigation waters.

Table 6-7: Chemical analysis of water in the piezometers.

pH	EC	Ca	Mg	Na	K	PAlk	MAlk
	mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
8.33	232	118.55	33.54	407.63	20.59	4.00	140
F	Cl	NO2(N)	Br	NO3(N)	PO4	SO4	B
mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
0.8	126	0.09	0.44	7.96	0	968	1.321

A chemical profile of the EC down the hole in PV5 (near the centre of the pivot), and the piezometer hole adjacent to PV5, also shows vast differences in water quality (Table 6-8). The very high EC values in the piezometer hole compared to the boreholes also indicate that water does not migrate easily downwards through the clay layer at 2.4 m.

Table 6-8: Down-the-hole profiling of EC (mS/m).

Depth	PV5	Piezo
1.47		148.7
2		242.2
12.78	17.3	
13.5	17.9	
14	37.3	
15	39.7	
20	37.9	
25	37.9	
28.5	35.9	

Conclusion: There is a significant clay layer below 2.4 m in the pivot area and slightly deeper towards the dam. This layer impedes downward migration of water and associated salts, which give rise to the deeper water levels that are uncommonly deep for an irrigation site. The installed shallow piezometers support these findings since the water quality measured in these indicated elevated concentrations consistent with evaporated mine water that could not migrate downwards (Table 6-7). The Durov diagram in Figure 6-13 illustrates these differences in water quality between the monitoring boreholes (except PV2) and the piesometers very clearly.

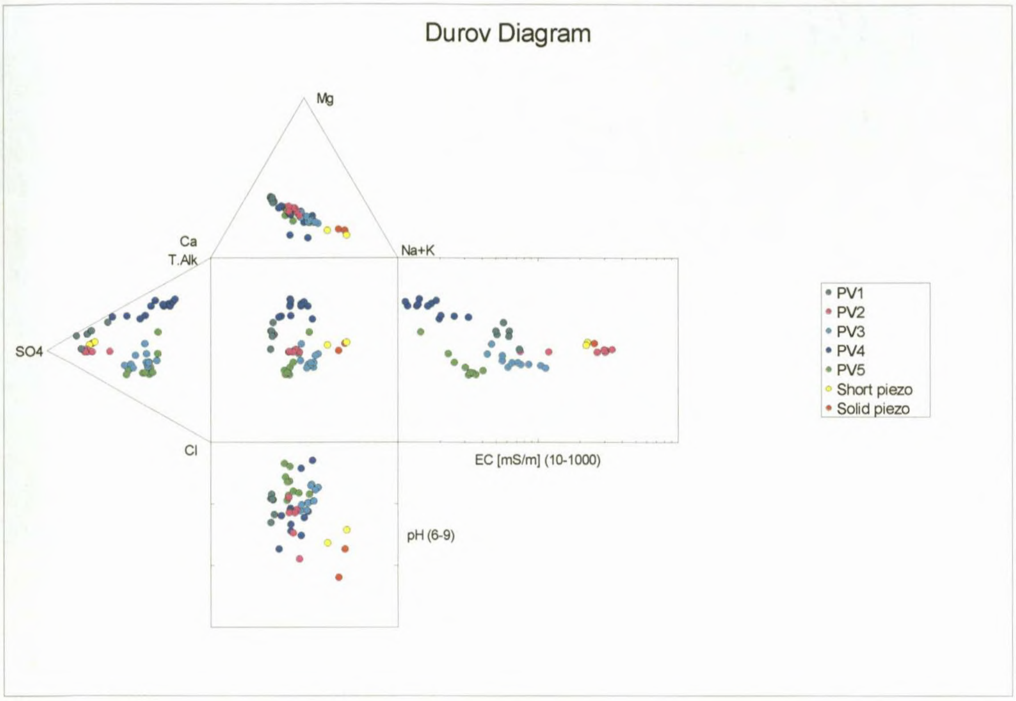


Figure 6-13: Durov diagram of the monitoring holes and piesometers at New Vaal.

6.3.3 *Syferfontein Colliery*

In order to determine why the aquifer below and adjacent to the pivot area is not polluted, soil tests were performed.

- Core drilling was carried out at various sites inside and outside the irrigation area. From the core the distinctive geological layers were selected and soil properties were determined in terms of relative clay, sand silt content at Glen Agricultural College. The results are shown in Table 6-9.

Table 6-9: Soil characteristics at Syferfontein Pivot.

Depth (m)	Sand	Coarse silt	Fine silt	Clay
0-0.8	28.04	8.99	0.10	63.49
0.8-1.44	na	na	na	na
1.44-2.44	44.19	16.27	0.40	40.70
2.44-3.5	62.11	8.42	0.40	31.58
3.5-4.65	67.71	10.02	0.30	26.04
4.65-5.46	82.50	10.00	0.40	10.00

The soils are of the Arcadia form with a high clay content. They vary in thickness from 300 mm to 900 mm. Two layers are visible. The upper layer of 200 mm has a strong, fine, angular blocky structure. The horizon 200+ mm has a strong, coarse, angular blocky structure. It lies on weathered dolerite saprolite. The colour of the soil is black. It is very high in clay. Slickensides occur deeper than 400 mm. A few distinct mottles occur at the bottom of the soil layer and above the saprolite. Some soft lime concretions and planar accumulations of calcite occur deep in the saprolite (>1500 mm).

The morphology is typical of well-developed Arcadias. It is high in swelling smectite clay (See Section6.4.3.1). Smectite clay is physically very active. It swells when wet and shrinks when dry. After rain it is swollen and only a few isolated macropores may exist. Water movement is restricted to micro pore flow. Water infiltration in Arcadia soils can be lower than 10 mm/h (le Roux, 2004 during site inspection). In these Arcadias the infiltration rate and saturated hydraulic conductivity in the soil layer may be 1 mm/h. This is 175 mm in a week. All additional rain will accumulate in pools and run off.

The underlying saprolite is coarser and micro pore flow is restricted. This results in the accumulation of water in the bottom of the soil layer and the formation of mottles. A typical Highveld thunderstorm may react slightly differently. After the dry winter, the soil is dry and cracks form. The cracks extend as deep as the saprolite. During the first downpour the water penetrates the cracks and drains through the saprolite quite quickly. It moistens the underlying weathering rocks and initiates a new incidence of chemical weathering. This process results in calcite formation. The limited amount of calcite is an indication that weathering is slow or leaching is high. The low saturated hydraulic conductivity of the soil restricts drainage and therefore the later alternative is unlikely.

- Leaching tests were also performed with deionised water through the cores drilled inside and outside the pivot area. The leaching analyses on these samples can be graphically represented (Figure 6-14 and Figure 6-15) to show the layers where enrichment in soluble salts occurs. From these it is clear that the shallow layer under the irrigated area has values that are far higher than those in the lower layers and outside the pivot. The clays in the shallow zones appear to prevent migration and attenuate the salts strongly in the upper profile.

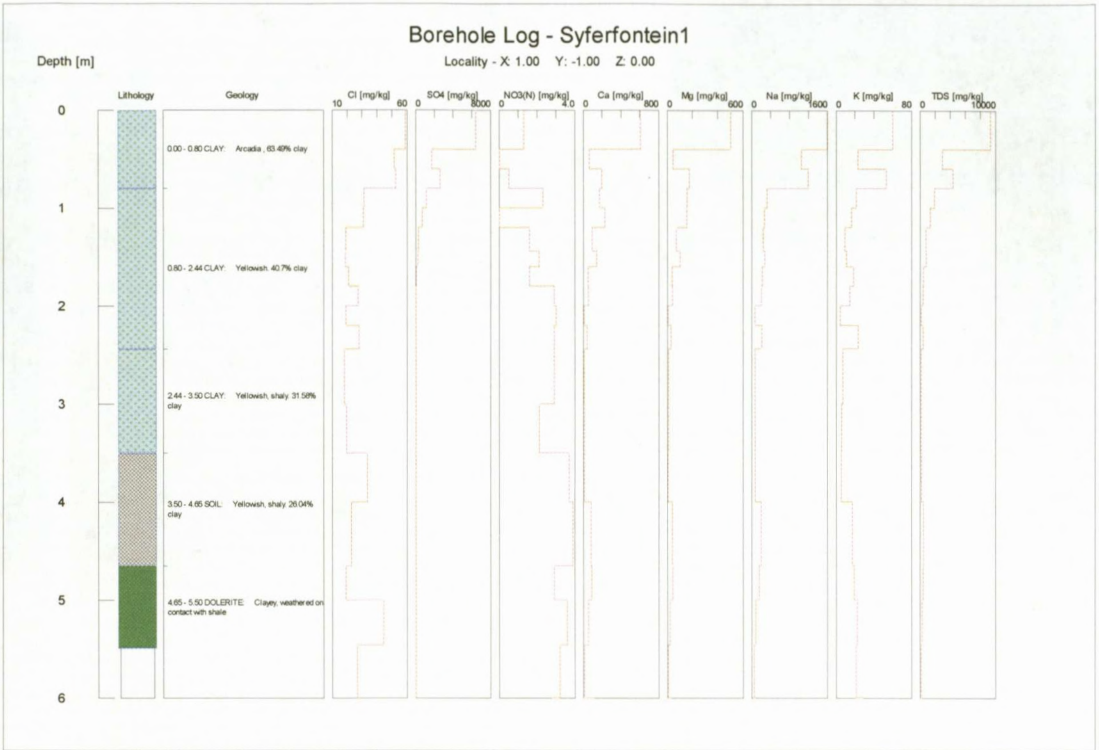


Figure 6-14: Soil leaching analyses within the pivot area.

Figure 6-15: Soil leaching analyses outside the pivot area.

6.3.4 *Conclusions*

From the soil analysis it is clear that most of the salts are captured in the upper one or two meters of the soil profile. The salts move along the profile in the soil water. The data indicates that the clay layers, which play a major role in the vertical flux of the water, therefore also have an influence on the salt distribution through the soil profiles. ***In order to determine what the salinity of the soil water through the different profiles is, soilwater sampling was performed at the different sites.***

6.4 Unsaturated soil sampling

6.4.1 *Introduction*

If gypsum accumulates in the upper meter of the irrigated soils, as predicted by Annandale *et al.* (2002), there would still be downward movement of Mg and SO_4, given that Mg will be more exchangeable than Ca in the upper part of the soil profile and that the concentration of SO_4 in the irrigation water is twice that of Ca. Furthermore, the solution that percolates from the base of a gypsiferous zone is saturated with respect to gypsum (under equilibrium conditions), and therefor soluble Ca must also be present in leachate from the zone (Campbell, 2001). Even if irrigation is managed so that leaching is negligible during the dry season, it is apparent from the data collected that significant movement of the solutes added by irrigation would take place during the rainy season. This means that in the long-term almost all of the Mg, at least half of the SO_4, and some of the Ca added by irrigation must enter the groundwater system. If sustainable gypsum precipitation does not take place, then close to all the added Mg, SO_4 and Ca will move to the local aquifer.

Porous cups were installed at the depths of 4, 3, 2 and 1m respectively (Figure 6-17 and Figure 6-17) at the different irrigation sites. This is to determine the movement of the water and the dissolved solids in the unsaturated zone, and will thus give a good indication of the ion movement, adsorption and ion exchange of the different ions in the soil. From the saturation index values in Table 6-10 it is clear that the water is saturated with respect to gypsum in the first meter of the soil at both sites, indicating the precipitation of gypsum. Deeper down the soil water is undersaturated with respect to gypsum and should not precipitate.

6.4.2 *Kleinkopje*

Four porous cups and tensiometers were installed at the depths of 4, 3, 2 and 1m respectively at Kleinkopje Pivot Major and Pivot 4. Seven sampling runs were done, of which the data (November 2004) are included in Table 6-10.

Figure 6-16: The porous cup and tensiometer installation (left) and porous cup sampler plus vacuum pump (right).

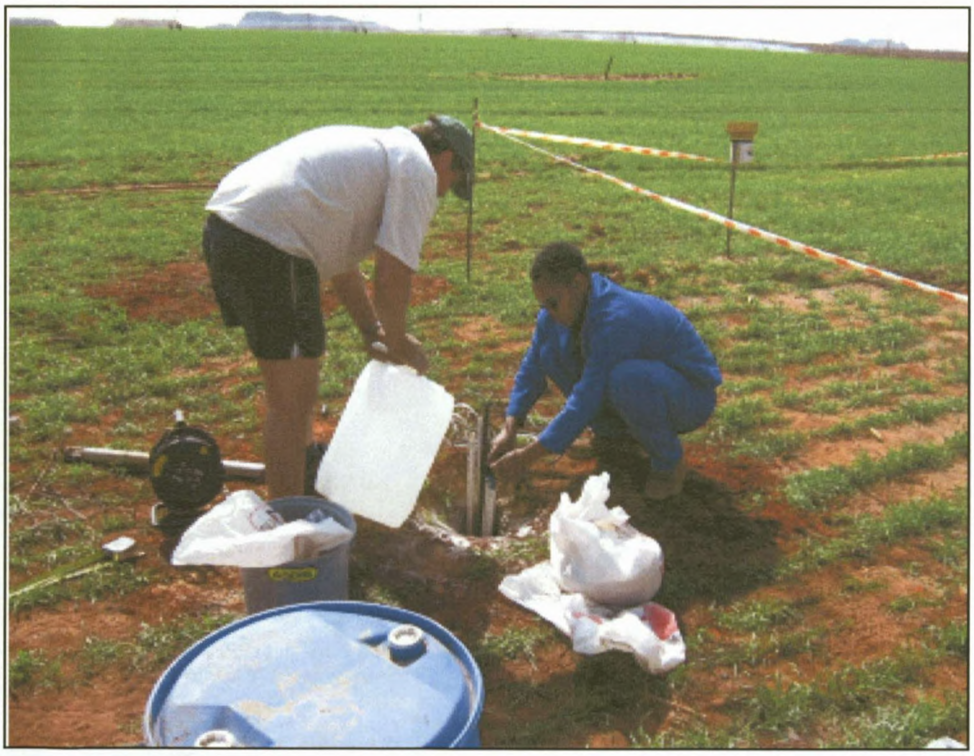


Figure 6-17: Porous cup installation at Pivot 4.

According to the soil water data in Table 6-10 the water is saturated with gypsum in the first meter at both sites, indicating gypsum precipitation.

Table 6-10: Analysis from porous cup sampling at Kleinkopje.

Pivot No	Depth (m)	pH	EC	Ca	Mg	Na	K	MAlk	F	Cl	Br	NO3(N)	SO4	SI Gypsum
			mS/m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
1	1	6.63	329	488	328	74	25	150	0.16	53	144.5	32.5	2160	-0.11
1	2	7.34	201	353	106	57	11	37	0.18	42	0.2	27.2	1217	-0.3
1	3	8.17	185	372	66	58	11	39	0.17	23	0.2	27.2	1108	-0.28
1	4	7.16	80	78	54	33	5	100	0.30	25	0.2	6.1	309	-1.22
4	1	6.97		1411	4029	1111	74		0.17	130	1.3	62.6	8732	0.42
4	2	8.25	138	91	128	38	5	245	0.08	110		4.5	466	-1.13
4	3	6.99	129	178	62	49	3	70	0.08	100	0.3	42.2	422	-0.84
4	4	7.07	166	89	58	52	9	97	0.21	33	0.3	12.7	350	-1.14

6.4.2.1 Kleinkopje Pivot 1 (Major)

The data from the porous cups monitoring provides some insight into the reasons for the apparent lack of salinity increase in the aquifer (Figure 6-18). The monitoring data show a steady decrease in sulphate concentrations with depth. This suggests that the majority of the salts are currently contained within the uppermost portions of the soil profile.

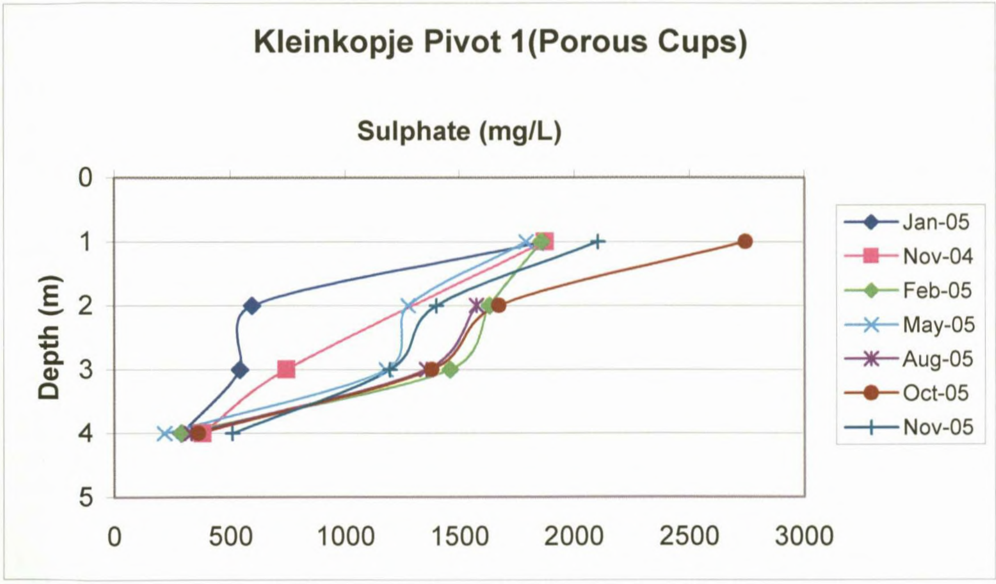


Figure 6-18: Sulphate concentrations with depth in the porous cups

If the relationship between cation qualities in the soil water for two meters depth and three meters are compared, it is clear that calcium decreases much more than the other cations, indicating gypsum precipitation. In Figure 6-19 the equivalent concentrations of the ions are shown.

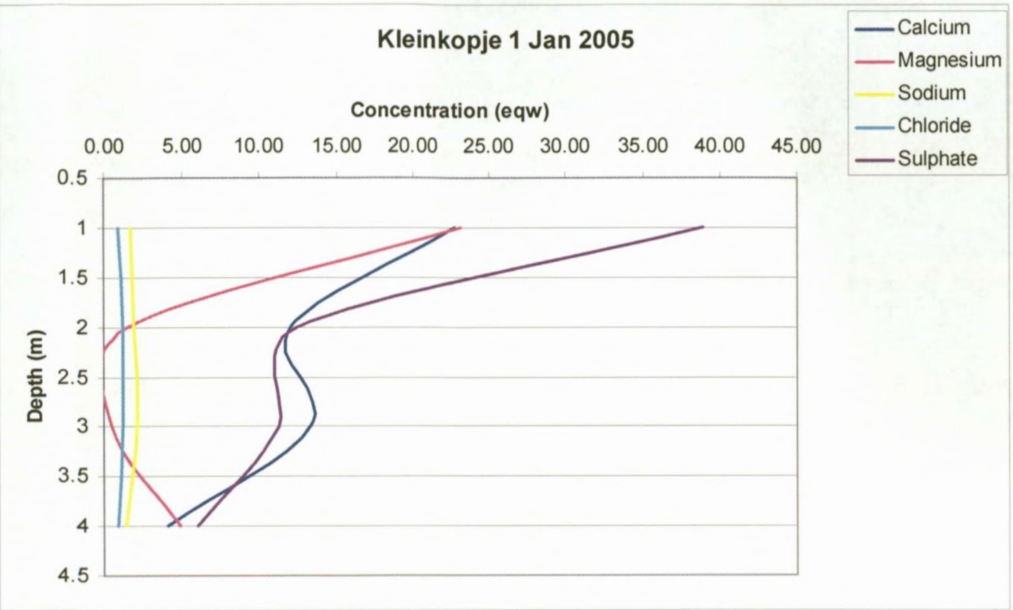


Figure 6-19: Equivalence plot of various ions at Pivot Major.

To verify this observation, leaching tests were done on representative samples obtained with depth in the soil profiles. In these tests, an excess of KCl was added to each soil sample and the liberated ions in the supernatant analysed (Figure 6-20 and Figure 6-21). The results of the soil tests suggest that the porous cup results are consistent with the trapped pore water, precipitates and adsorped ions at each of these levels.

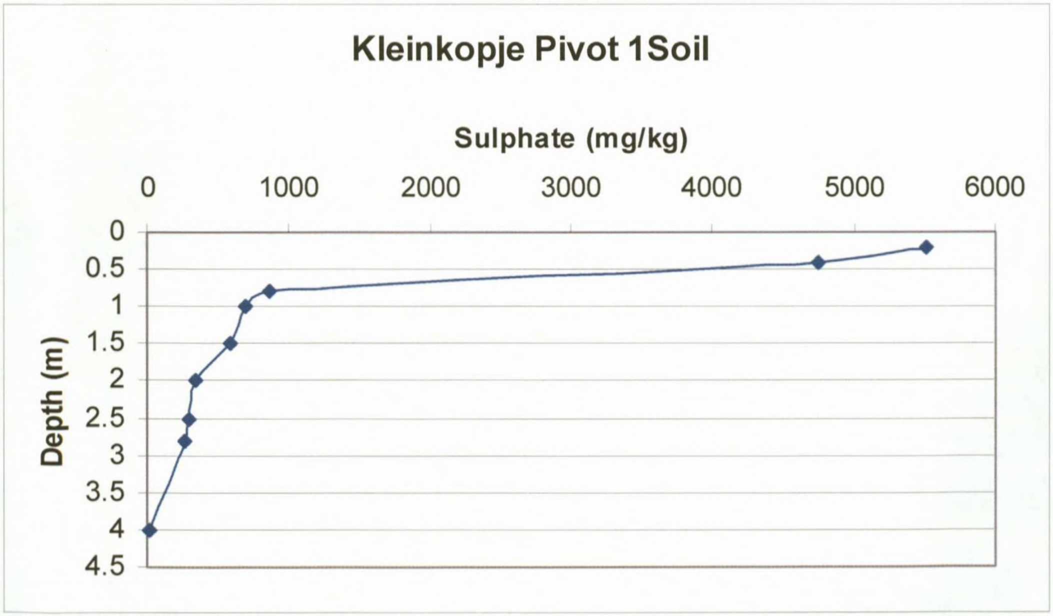


Figure 6-20: Sulphate concentrations liberated from the soil with depth.

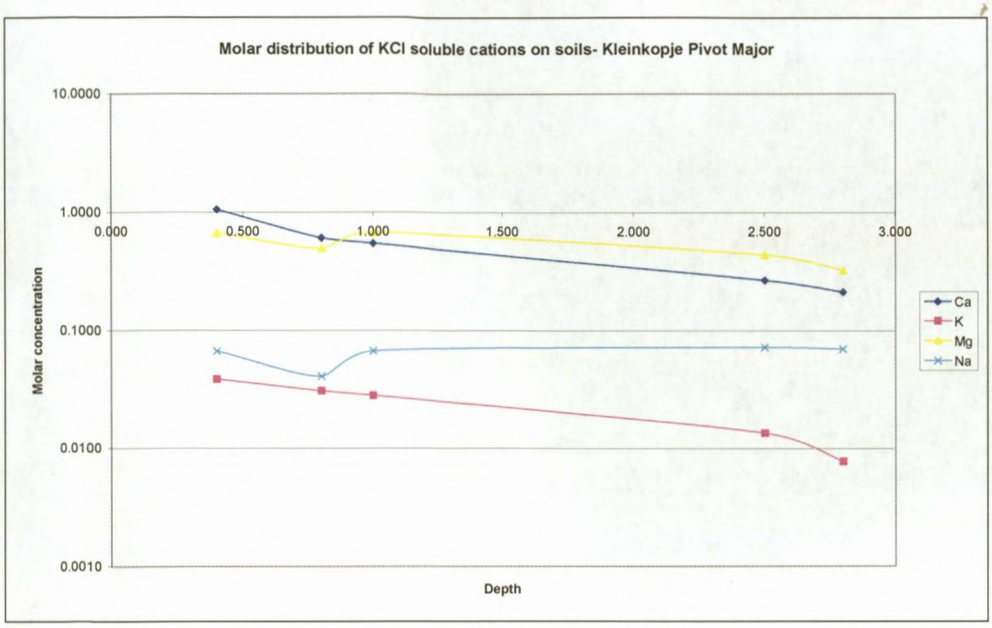


Figure 6-21: Molar distribution of cations in the soil at Pivot Major.

Figure 6-21 indicates that calcium decreases with depth, while magnesium and sodium are probably affected by the clay layer just below one meter. Potassium also decreases with depth.

One of the implications is that there are hydraulic and attenuation factors preventing the salts in the mine water used for irrigation from being mobilised down the soil profile and into the aquifer. The soil composition and associated sorption and hydraulic properties may be informative. The typical composition determined by standard soil composition tests is provided in Table 6-5.

This shows a marked increase in clay content below the depth of 1m.

6.4.2.2 Kleinkopje Pivot 4

At this pivot the porous cups were not as successful as at Pivot Major, and less water was retrieved. However, the same trend can generally be seen as at Pivot Major (Figure 6-22).

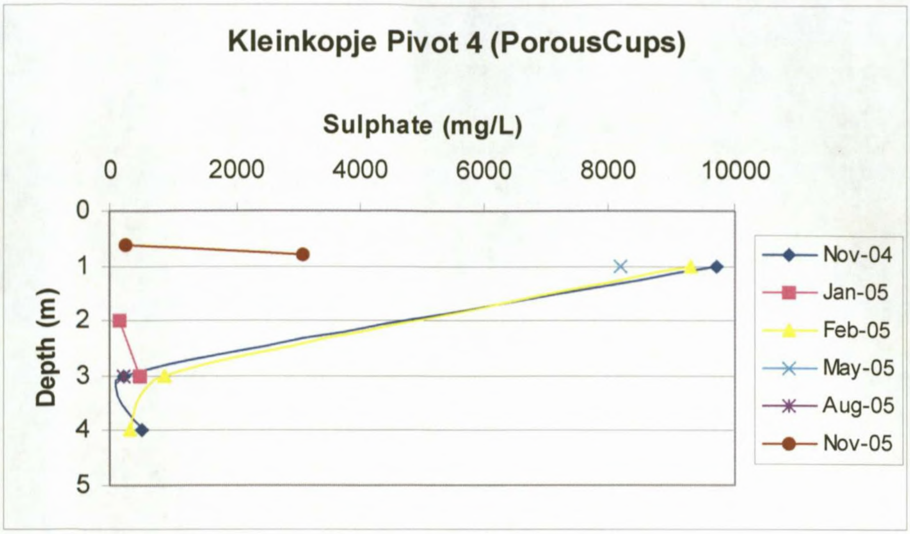


Figure 6-22: Sulphate concentrations with depth in the porous cups at Pivot 4.

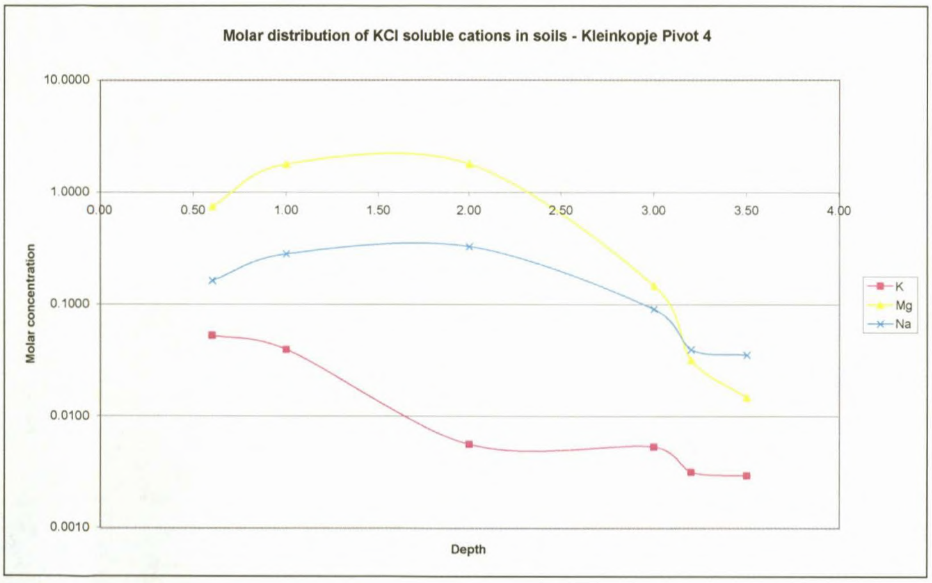


Figure 6-23: Molar distribution of cations in the soil at Pivot 4.

The soil leaching tests (Figure 6-23) indicate that the magnesium initially increases, and then decreases. This may be the result of sorption at the clay layer at 3m depth. Sodium and potassium level out at 3m, but do not decrease in value.

The results to date point to several potentially important findings for the wider application of mine water irrigation. It would appear that where the soils are richer in clay content, there is a significant attenuation of salts in the shallower zones. The groundwater monitoring results indicate that this attenuation makes mine water irrigation a viable option in the short to medium term where gypsum-rich waters are used. The fact that the data collected from the porous cups, the soil salinities and the groundwater quality indicates the same trends is encouraging. Analysis of the tensiometer data over time, continued groundwater and soil water monitoring and detailed analysis of the soil characteristics in terms of hydraulic and mass transport properties at each site, should allow the development of accurate conceptual models of the interaction between irrigation and the underlying soils and aquifers.

6.4.2.3 XRD/XRF Analysis

Sixteen samples were sent to the Geology Department of the University of the Free State for analysis (eight from each pivot), especially for gypsum and clay determination, with depth in the soils.

Table 6-11: XRF analysis of the Kleinkopje soils.

NO.	Depth	SiO2	TiO2	Al2O3	Fe2O2	MnO	MgO	CaO	Na2O	K2O	P2O5	H2O-	LOI	TOT
P1-1	0-0.2	84.56	0.49	4.86	2.71	0.04	0.13	0.53	0.12	0.33	0.06	0.9	5.05	99.78
P1-2	0.2-0.4	85.07	0.42	4.63	2.54	0.03	0.18	0.41	0.12	0.3	0.04	0.84	4.58	99.16
P1-3	0.4-0.8	86.13	0.45	4.71	2.59	0.03	0.12	0.15	0.12	0.3	0.04	0.67	3.79	99.1
P1-4	0.8-1.0	85.69	0.53	5.62	3.48	0.02	0.11	0.08	0.13	0.33	0.04	0.6	3.1	99.73
P1-5	1.0-1.5	73.27	0.59	8.82	11.09	0.1	0.16	0.07	0.12	0.49	0.06	1.03	4.53	100.3
P1-6	1.5-2.0	74.02	0.73	10.36	8.14	0.05	0.22	0.07	0.12	0.66	0.05	1.23	4.42	100.1
P1-7	2.0-2.5	76.81	0.77	10.24	5.51	0.04	0.21	0.08	0.13	0.82	0.03	1.01	3.98	99.63
P1-8	2.5-2.8	78.91	0.58	8.11	5.73	0.2	0.18	0.07	0.15	1.18	0.03	0.95	3.12	99.21
P4-1	0-0.3	86.11	0.49	5.4	2.72	0.02	0.12	0.17	0.13	0.16	0.05	0.52	3.14	99.03
P4-2	0.3-0.6	83.69	0.6	6.83	3.55	0.03	0.14	0.08	0.12	0.2	0.04	0.79	3.17	99.24
P4-3	0.6-1.0	82.15	0.67	7.68	3.84	0.03	0.18	0.08	0.12	0.23	0.05	0.85	3.43	99.31
P4-4	1.0-1.25	79.78	0.78	9.13	4.46	0.02	0.22	0.08	0.13	0.24	0.05	0.97	3.87	99.73
P4-5	1.25-1.5	80.06	0.77	9.07	4.76	0.04	0.2	0.07	0.12	0.24	0.05	0.98	3.91	100.3
P4-6	1.5-1.75	76.63	0.84	10.66	4.89	0.04	0.2	0.09	0.13	0.27	0.04	0.9	4.35	99.04
P4-8	2.0-2.5	76.37	0.84	10.89	5.4	0.04	0.09	0.06	0.11	0.3	0.05	0.77	4.49	99.41

It is evident from Table 6-11 that there are indications that gypsum precipitation should occur since Ca values are far higher in the shallow portions, while Mg values are more evenly distributed. This suggests that the distribution is chemically controlled rather than by surface interactions since these two ions should have similar sorptive capacities. This is supported by the Na values, which are evenly distributed with depth.

The XRD analysis in Table 6-12 the clay to be kaolinite, which theoretically, should adsorp sulphate (Mott, 1981).

Table 6-12: XRD analysis of Kleinkopje soils.

NO.	Quartz	Orthoclase	Hematite	Plagioclase	Kaolinite	Gypsum	Montmorillinite
P1-1	XX		<x		x		<x
P1-2	XX		<x		x		<x
P1-3	XX		<x		x		<x
P1-4	XX		<x		x		<x
P1-5	XX		x		x		<x
P1-6	XX		x		x		<x
P1-7	XX	<x	x		x		<x
P1-8	XX	<x	x		x		<x
P4-1	XX						
P4-2	XX				<x		
P4-3	XX				<x		
P4-4	XX				x		
P4-5	XX				x		
P4-6	XX				x		
P4-8	XX				x		

Dominant	XX	>40%			
Major	X	10 - 40%	Accessory	<x	1 - 2%
Minor	x	2 - 10%	Rare	<<x	<1%

6.4.3 *Syferfontein*

Four porous cups and tensiometers were installed at the depths of 4.8, 3.5, 2 and 1m respectively. This is to determine the movement of the water and the dissolved solids in the unsaturated zone. Seven sampling runs were done. The results with depth are illustrated in Figure 6-24. Figure 6-24 illustrates the soil leaching analysis of sulphate with depth for the different positions within and outside the pivot area.

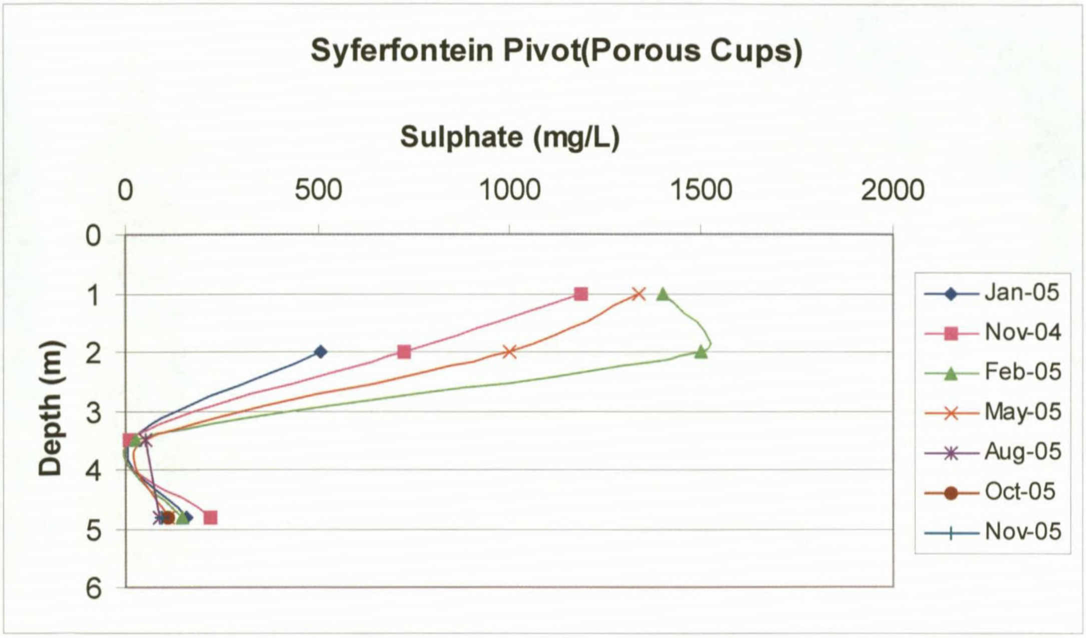


Figure 6-24: Sulphate concentrations with depth in the porous cups

If the relationship between cation qualities in the soil water for depths of 2 meters and 3.5 meters are compared, as indicated in Table 6-13 below, it is clear that there is sorption and ion exchange between magnesium and potassium because the potassium has increased in depth while magnesium decreased. The reason why sodium does not exchange is because the sodium content of the irrigation water is already very high. In Figure 6-25 the equivalent concentrations of the major ions are shown for the February 2005 sampling. The sodium sulphate water results in high sodium and sulphate content in the upper layers of soil, which decreases with depth. The conservative chloride anion moves through the different layers to the same degree, without any precipitation or adsorption.

Table 6-13: Proportional relationship between water qualities at 2 and 3.5 m depths.

Ca	Mg	Na	K
3.40	25.38	3.91	0.20

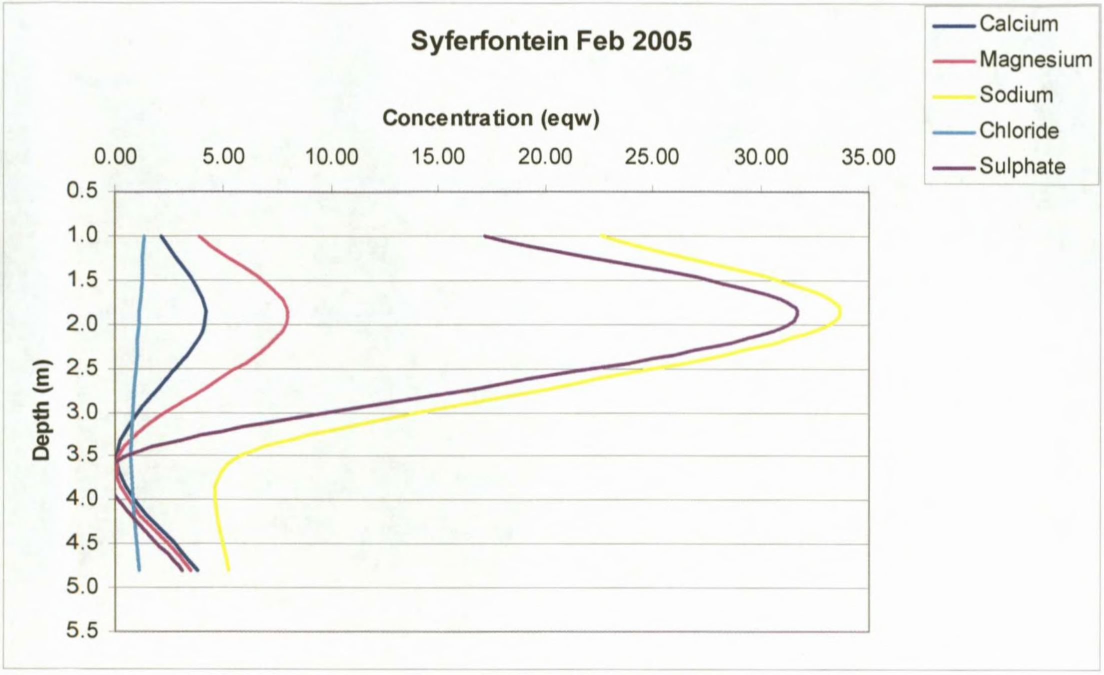


Figure 6-25: Equivalence plot of various ions at Syferfontein.

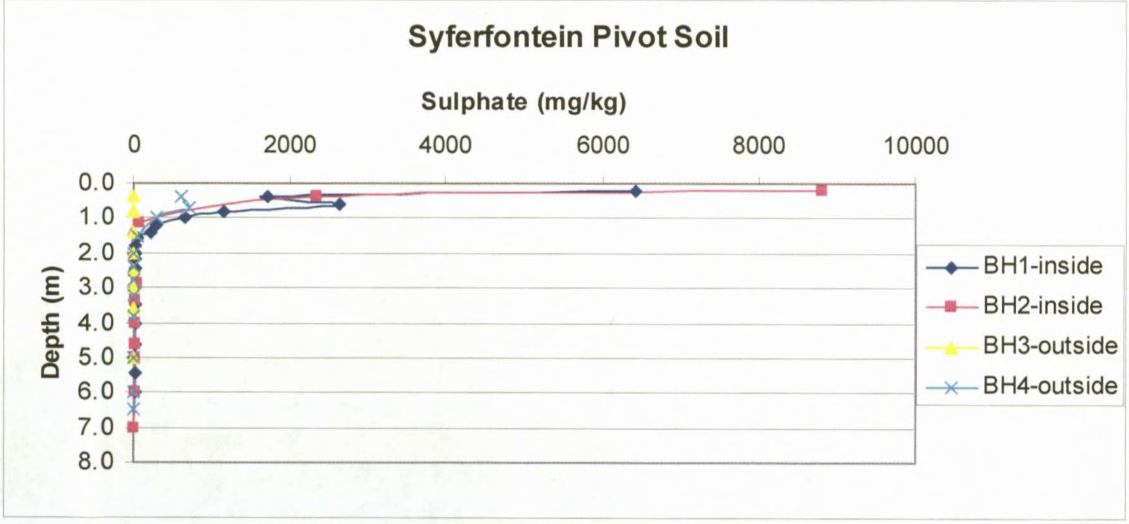


Figure 6-26: Soil leaching analysis of sulphate in depth for different positions.

To verify this observation, leaching tests were done on representative samples obtained with depth in the soil profiles. In these tests, an excess of KCl was added to each soil sample and the liberated ions in the supernatant analysed. Analysis of the soil indicates, as is the case with the Kleinkopje pivots, high sulphate concentrations in the upper one meter of soil.

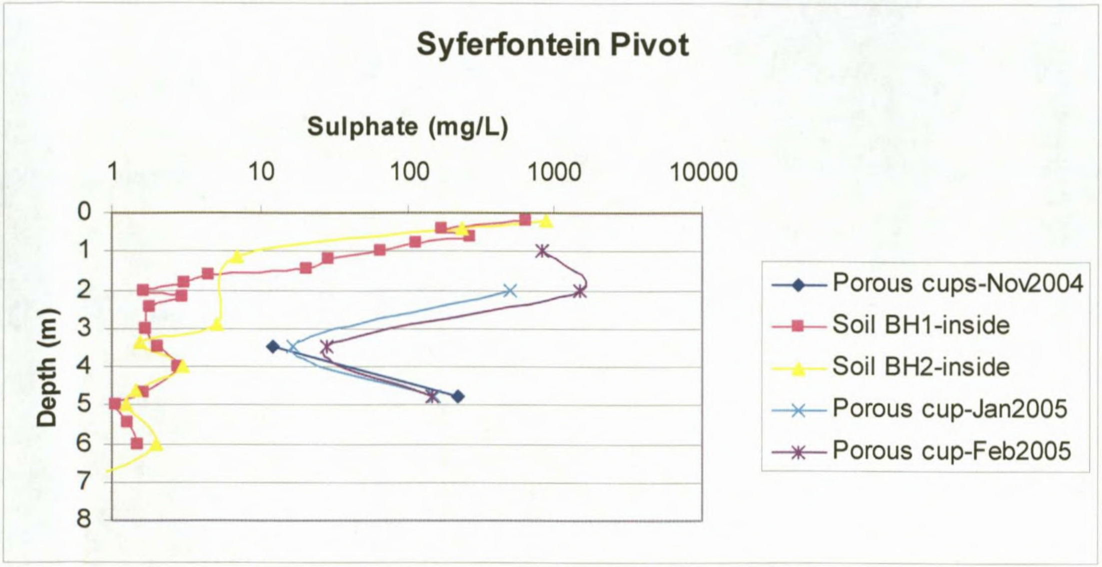


Figure 6-27: Comparison of soil water and leaching quality.

From the comparisons in Figure 6-27, it is clear that the clays play an important role in retaining the salts at the upper few layers of the profile. A comparison between the soil leaching and porous cup data supports this hypothesis.

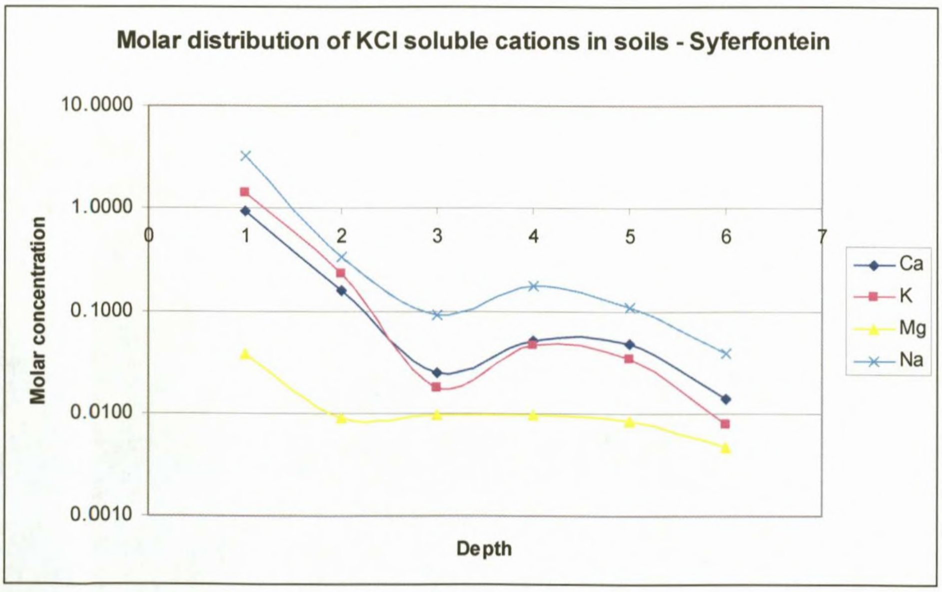


Figure 6-28: Molar distribution of cations in the soil at Syferfontein.

From the molar distribution of the cations (Figure 6-28) it can be concluded that all the cations move through the clayey Arcadia soils at the same degree, with sodium obviously at higher molar concentrations because of the composition of the irrigation water. There is much less magnesium in the water than calcium or potassium.

6.4.3.1 XRD/XRF Analysis

Eight samples were sent to the Geology Department of the University of the Free State for analysis, especially for gypsum and clay determination, with depth in the soils.

Table 6-14: XRF analyses at Syferfontein.

NO.	Depth	SiO2	TiO2	Al2O3	Fe2O2	MnO	MgO	CaO	Na2O	K2O	P2O5	H2O-	LOI	TOT	S(ppm)
SYF1.1	0-0.2	60.25	1.59	11.76	9.16	0.24	1.54	2.33	0.96	0.78	0.07	3.57	6.84	99.09	3400
SYF1.2	0.2-0.4	63.24	1.51	11.2	8.43	0.23	1.37	2.13	0.93	0.78	0.07	3.57	6.84	100.3	831
SYF1.3	0.4-0.6	63.46	1.53	11.51	8.99	0.23	1.43	2.08	0.96	0.78	0.06	2.66	6.57	100.3	1446
SYF1.4	0.6-0.8	53.66	1.51	12.49	11.55	0.3	2.92	4.35	0.85	0.77	0.13	3.9	6.73	99.16	663
SYF1.5	0.8-1.0	48.39	1.56	13.37	10.69	0.18	2.81	8.55	0.94	0.79	0.18	3.93	7.27	98.66	245
SYF1.6	1.0-1.2	52.23	1.73	13.74	11.28	0.21	2.49	5.57	1.42	0.87	0.24	4.83	4.81	99.42	>100
SYF1.7	1.2-1.44	43.52	0.9	9.37	26.31	0.45	2.31	3.06	0.84	0.96	0.16	4.28	7.77	99.93	>100
SYF1.8	1.44-1.6	58.32	0.77	15.84	7.71	0.06	1.65	0.95	0.45	2.73	0.09	5.26	5.25	99.08	

NO.	**Quartz**	**Orthoclase**	**Hemathite**	**Plagioclase**	**Kaolinite**	**Gypsum**	**Montmorillinite**
SYF1.1	X			<x			XX
SYF1.2	X			<x			XX
SYF1.3	X			<x			XX
SYF1.4	X			<x			XX
SYF1.5	X			<x			XX
SYF1.6	X			<x			XX
SYF1.7	X			<x			XX
SYF1.8	X			<x			XX

Dominant	XX	>40%
Major	X	10 - 40%
Minor	x	2 - 10%
Accessory	<x	1 - 2%
Rare	<<x	<1%

The sulphur values obtained from the XRF are of interest since they indicate a strong attenuation in the shallowest layers of the profile. This is consistent with the leaching tests and porous cup values. According to the XRD analysis the clay is montmorrilonite.

6.4.4 *New Vaal*

No porous cups were installed in New Vaal as piezometers were installed in the irrigation area.

The molar concentration comparison of the cation analysis in depth in the soil indicates that:

- Calcium and magnesium concentrations increase drastically in the clay layer at 2.4m depth. Even the potassium, which has a far lower concentration in the water, increased in the clay layer.
- The sodium shows a drastic drop in concentration at 2.4m depth, but recovers again below the clay layer. Contrary to calcium magnesium and sulphate, it also shows a decrease in concentration with depth.
- Chloride and sulphate were included in Figure 6-29 and follow the same pattern as all the major cations except sodium.

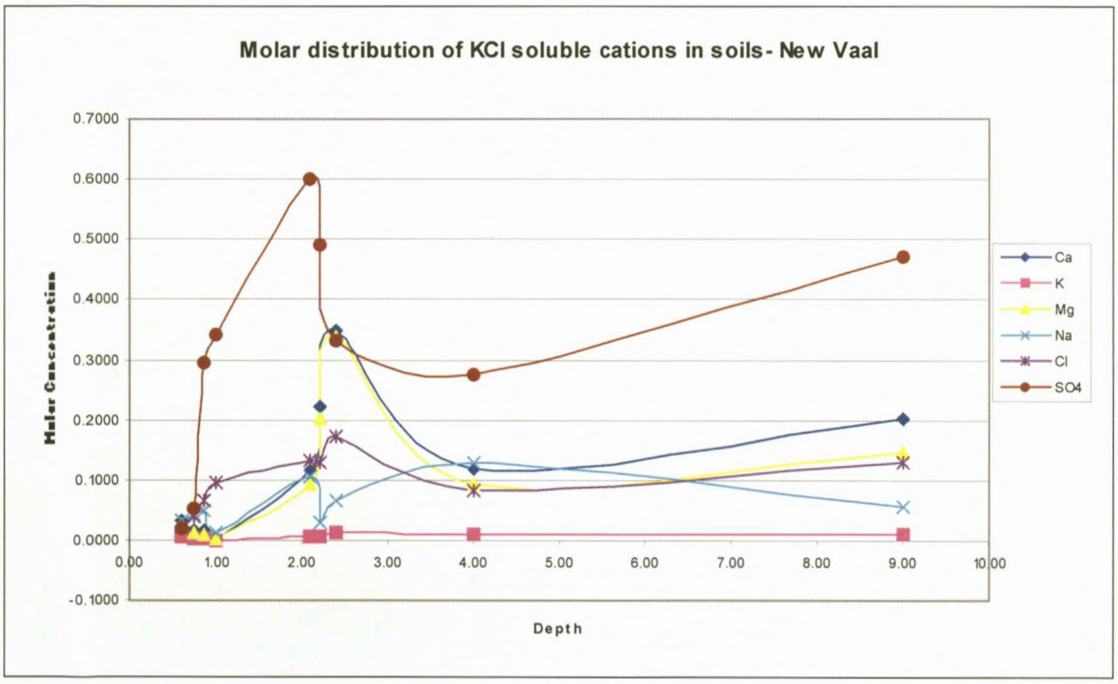


Figure 6-29: Molar distribution of major cations and anions in the soil at New Vaal.

6.4.5 *Conclusions*

There are hydraulic and attenuation factors preventing the salts in the mine water used for irrigation from being mobilised down the soil profile and into the aquifer.

- Calcium decreases significantly more than the other cations, indication gypsum precipitation.
- Sorption and ion exchange occurs between magnesium and potassium.

- The clays play an important role in retaining the salts to the upper few layers of the profile.

The next section will deal with gypsum precipitation, and determine how much of the sulphate adsorbs in the soil.

6.5 Gypsum precipitation from the $CaSO_4$-rich water

6.5.1 *Introduction*

Whether gypsum is present or not in the irrigated fields has been a point of debate since the project started. Campbell (2001) concluded that gypsum was not present at Pivot One (Major) or Pivot Four. This conclusion was based on the apparent disequilibrium of saturated pastes with respect to gypsum, which were found to have concentrations below where precipitation is expected.

The simulation of gypsum precipitation and dissolution is based on the calculations of the activities of Ca^{2+}, Mg^{2+}, SO_4^{2-} and $CaSO_4$ according to the Debye-Hückel theory. Gypsum precipitates when the ion activity product of Ca^{2+} and SO_4^{2-} exceeds the gypsum solubility product (2.63×10^{-5} at 25°C according to Drever, 1997). According to Campbell (2001) there are shortcomings in the simulations of gypsum solubility at the irrigation sites:

- The Mg SO_4 ion pair was not taken into account. In the presence of sufficient Mg in solution, this ion pair will play a comparable role to that of $CaSO_4$ in reducing the activity of SO_4^{2-} and enhancing gypsum solubility.
- Ion exchange and adsorption were not taken into account.

Campbell stated that he could not detect or confirm any gypsum with the XRD-method in the soils at the Kleinkopje pivots. He also stated that calculations of the gypsum saturation indices of saturated paste extracts from soils in the irrigated fields demonstrated their undersaturation with respect to gypsum. This suggests that only very small amounts of gypsum, if any, are present, although Van den Ende (1991) shows that saturated paste extracts from soil can be undersaturated with respect to gypsum, while the in-situ soil solution is oversaturated, and that free gypsum will thus be present in the soil. Campbell also indicates data suggesting that the adsorption of calcium and sulphate ions is the favoured mechanism to remove these ions from solution. It is possible that, with continued irrigation, the adsorption sites will reach equilibrium with a soil solution, which is sufficiently overaturated with respect to gypsum, and that precipitation may then occur. It is possible that this precipitation already occurs during the irrigation seasons, but that intense periods of rainfall would tend to dissolve a large amount of this gypsum.

However, Annandale *et al.* (2006) stated that "according to Bohn and Bohn (1996), the strict convention of saturation indices that $\log \frac{IAP}{K_{sp}} < 0$, which means that a solution is undersaturated with respect to a certain solid phase, can often not be applied in environmental chemistry. Most solubility products in the literature emanate from minerals in their standard state i.e. pure, well crystalline minerals. Minerals in the soil are not pure end member phases, but are often poor or micro-crystalline (Essington 2004). Over-or undersaturation of a soil solution could simply mean that the mineral under investigation is not in its standard state. According to Bohn & Bohn, (1996) a $\log \frac{IAP}{K_{sp}}$ ratio between -1 and 1 can be considered as confirmation that the soil solution is saturated with respect to the specific mineral. A ratio lower than -1 indicates that the solution is either undersaturated with respect to the pure mineral, or possibly that the solid phase is a minor constituent of another solid. Differences within this range can be attributed to uncertainty in the IAP measurements, as well as uncertainties of the reported K_{sp} in the literature. In the case of gypsum, four different K_{sp}'s were obtained. The standard state K_{sp} for gypsum is reported by Nordstrom *et al* (1990) to be $10^{-4.58}$, $10^{-4.64}$ according to Lindsay (1979), $10^{-4.62}$ is reported by Essington (2004) and the default K_{sp} for gypsum in the Minteq. v.4 database file is $10^{-4.61}$.

In the study by Annandale *et al.* (2006), the four solubility products obtained from the literature were introduced into PHREEQC, and the saturation of the soil solutions with respect to gypsum, was evaluated using all of the above reported solubility products. A saturation range is therefore obtained, which is based on the inherent uncertainty of the true standard state K_{sp} of gypsum. Using the K_{sp} reported by Nordstrom *et al* (1990) in saturation index calculations therefore gives the upper limit of the saturation range, while the K_{sp} reported by Lindsay (1979) gives the lower limit of the saturation range. The minerals kaolinite, goethite, hematite, gibbsite and quartz have been identified by X-ray diffraction in the soils of Pivot 1 (Major) and Pivot 4 (Campbell, 2001). To obtain ion activity- and solution speciation approximations as close as possible to those in the soil solution, the above-mentioned solid phases were introduced in PHREEQC and equilibrated with the saturated pastes. The saturation range for all depths at Pivot 1 at Kleinkopje was between -0.25 and 0.04 and between -0.09 and 0.04 for Pivot 4. At the time Campbell collected his samples at Pivot 4 (1999) the solutions were outside the proposed range of -1 to 1 proposed by Bohn and Bohn (1996), and were indeed undersaturated with respect to gypsum. Since 2000, the soil solution saturation with respect to gypsum has increased, and gypsum has accumulated in the soil profile.

Annandale *et al.* (2006) stated that saturated paste extracts are generally accepted as an approximation of the soil solution composition, ion activity and solution speciation. However, Campbell (2001) pointed out that the gravimetric water content of the samples collected is generally far from that of a saturated paste extract. The increase in the water content of the samples will definitely result in the dissolution of gypsum and an underestimation of the solid phase gypsum. Calculations with PHREEQC showed that for a specific sample the volume increase could result in the dissolution of approximately 10.1 mmol $^{-1}$, using the default K_{sp} for gypsum in the Minteq. v.4 database file ($10^{-4.61}$). The concentration of the soil solutions to field moisture levels increased the gypsum saturation from 0.00 to 0.64.

According to Annandale *et al.* (2006), gypsum quantification of the irrigated soils was initially based on the difference between total extractable Ca and SO_4 and a certain Ca and SO_4 sorption capacity. The assumption is that before gypsum precipitation will occur, a certain sorption capacity must be filled. However, this approach was abandoned because the determination of a certain sorption capacity of Ca and SO_4 in the laboratory is difficult to extrapolate to the field for various reasons:

- The sorption capacity of a soil is a function of pH, ionic strength and ion composition of the soil solution (Rietra *et al*, 1999). The experimentally obtained sorption capacity is therefore a conditional sorption capacity, and not necessarily true for all conditions. Concentration the soil solution through drying and dilution of the soil solution as a result of rain will influence this sorption capacity. The solution, with which the soil is equilibrated, should be similar to the water quality of the irrigation water, which means that soil samples should be equilibrated with neutralised acid mine drainage (NAMD).
- Surface precipitation can occur in the double layer despite the fact that the bulk solution is undersaturated with respect to the pure mineral. The NAMD is saturated with respect to gypsum, which basically means that it is impossible to determine whether the decrease in Ca and SO_4 in solution after equilibration was the result of precipitation or adsorption.

A thermodynamically more sound, and analytically easier approach was therefore chosen by Annandale *et al.* (2006). The saturation range was determined for the saturated pastes extracts. If the saturation range indicated that the solution was saturated with respect to gypsum water extractable Ca was taken as gypsum. A lesser error is involved when water extractable Ca is used to calculate gypsum because the water extractability of exchangeable Ca is lower than that of SO_4. More than 50 % of the Ca immobilised in the soil was exchangeable at both Pivot 1 and Pivot 4. Total Ca immobilised in the soil profile at Pivot 1 was 23.9 mol m^{-2} of which 11.4 mol m^{-2} was gypsum. At Pivot 4 the total Ca immobilised was 25.9 mol m^{-2} of which 10.9 mol m^{-2} was gypsum. The amount of gypsum precipitated at Pivot

Major was equivalent to **19.6 tons / ha** and that at Pivot4 to **18.9 tons / ha**. (This is in line with the findings of this research).

Annandale *et al.* (2006) concluded that there is thermodynamic proof, in the form of calculated Ca and SO_4 activities, that gypsum is present in the soils irrigated with NAMD. The saturation ranges were the same as those reported for natural gypsiferous soils in the literature. The authors stated that over the last four years gypsum accumulated in the soils to such an extent that the solutions were saturated with gypsum.

6.5.2 *Determination of the presence of gypsum in irrigated soils*

A number of soil samples were collected at shallow depths at Kleinkopje Pivot Major and Pivot 4. Some of the samples were scraped from surface where white precipitate was in abundance, usually in lower lying areas. These samples were sent to the Geology Department at the University of the Free State for X-ray diffraction analysis to determine the presence of gypsum.

No gypsum was detected in any of the samples, even those that consisted mostly of precipitate scraped from surface. Gypsum has hkl Miller indices of 1111.21, 1111, 462, 1111, 460, 2101 and 424, which did not correspond with any of the diffractograms obtained. However, further research has revealed that bassanite, the hydrous form, $CaSO_4$ $0.5H_2O$, or calcium sulfate hemihydrate, is present in most of the samples. The hkl Miller indices of 824, 741, 1002 and 628 corresponded accurately with those of the diffractogram of bassanite (Figure 6-30). Gypsum can be transformed into bassanite upon heating. It reaches a level corresponding to the semi-hydrate bassanite at 70-90°C. However, dehydration starts at 40°C. Heat build-up definitely occurs between the densely populated plants in the irrigation area, and probably dehydrates the gypsum sufficiently to transform it into bassanite in the upper soils. This may be the reason why Campbell (2001) also did not detect any gypsum in the soils. Precipitated $CaSO_4$ is thus definitely present in the soils, although it exists in its dehydrated capacity as bassanite.

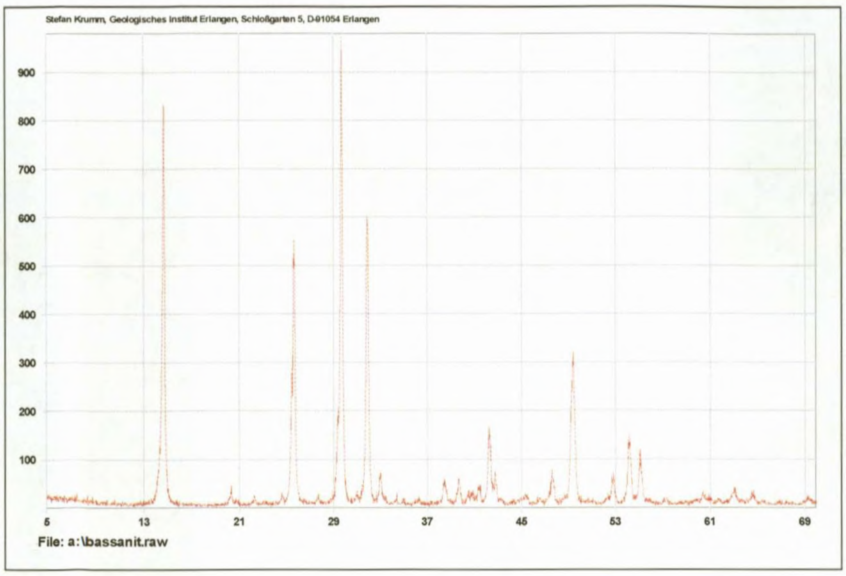


Figure 6-30: Diffractogram of Bassanite ($CaSO_4$ 0.5 H_2O).

6.5.3 *Sulphate adsorption:*

Finely divided clay minerals and organic matter have electrical charges on their surfaces and tend to adsorb ions from solution onto their charges. Most clay minerals, due to their molecular structure, have a permanently negative surface charge, which allows for the substitution of metal cations of different charge so that clay will have a net deficit of positive charge in their structure (McBride, 1994). However, kaolinite ($Al_2Si_2O_5(OH)_4$) has little or no permanent negative surface charge. The surface charge is positive at a low pH and negative at a higher pH, thus possessing CEC at a high pH and AEC at a low pH. According to Mott (1981), kaolinite has a tendency to adsorb sulphate ions on the positively charged surfaces of the hydroxides of Fe and Al, and is enhanced by low pH conditions. Sulphate may form irreversible inner-sphere complexes on these surfaces. Kaolinite reversibly adsorbs sulphate at its positively-charged edge sites. Sulphate adsorption is most favored at a pH of 2, and decreases with a rising pH (Mott, 1981), becoming negligible above a pH of 6 (Tabatabai, 1982).

Low levels of SO_4 adsorption are observed in topsoils relative to deeper horizons (Tabatabai, 1982), probably because of the abundance of negatively charged organic matter in topsoils. This is believed to be the result of electrostatic repulsion, which causes anions in solution to be concentrated in the centres of soil pores, where the flow velocity of the soil is the greatest (Leij and van Genuchten, 1999).

The literature provides evidence of a synergistic enhancement of SO_4 sorpion by Ca adsorption (Ajwa and Tabatabai, 1995 and Davis and Burgoa, 1995). A comparison of extractable Ca and SO_4 suggests that there may be co-sorption of calcium and sulphate in the irrigated soils of Pivot 1 and Pivot 4 (Campbell, 2001) where kaolinite is the major clay (see Table 6-12).

Leaching column experiments to determine the adsorption capacity of sulphate:

In order to determine the adsorption capacity of sulphate in the soils at Kleinkopje Pivot 4, experiments were conducted where field conditions were simulated in leaching columns at the laboratory of the Institute for Groundwater Studies. A four-meter soil profile (down to the water table) was taken at Kleinkopje Pivot 4 and proportionally packed into three-meter columns (Figure 6-31).

Figure 6-31: Photograph of the leaching columns.

The soil used in the leaching columns was analyzed at the Glen Agricultural College near Bloemfontein to determine its clay content, and XRD was done at the Geology Department of the University of the Free State (See Section 5.4).

Table 6-15: Clay content in the soil at Kleinkopje Pivot 4.

Depth (m)	Sand	Coarse silt	Fine silt	Clay
0-0.6	72.50	9.20	4.60	13.79
0.6-1.0	64.32	11.75	4.62	18.48
1.0-2.0	56.06	10.80	13.93	18.58
2.0-3.0	50.50	15.29	4.60	27.59
3-3.2	53.27	19.49	4.62	23.10
3.2-3.5	59.60	9.79	4.64	23.22

Leaching tests done on the soil outside the pivot areas by the IGS laboratory indicate a pH of mostly below 5, and also confirms the presence of chloride in the soil (Table 6-16). The acidic conditions in the soil will also enhance sulphate adsorption (Tabatabai, 1982).

Table 6-16: pH and chloride values of soil at Kleinkopje Pivot 4 (background values).

Depth	ph	Cl
m		mg/kg
0-0.3	4.67	33.6
0.3-0.6	4.42	22.6
0.6-1.0	4.50	55.7
1.0-1.25	4.74	91.1
1.25-1.5	5.19	141.4
1.5-1.75	4.91	102.1
1.75-2.0	4.50	20.5
2.0-2.5	4.53	16.8
2.5-3.0	4.54	16.8
3.0-3.2	5.06	16.7
3.2-3.5	4.85	16.3
3.5-4.0	5.29	50.3

The pore volume of the soil in the columns was obtained by filling the soil profle in the columns and three different scenarios were run, each with different water qualities. The composition of the water was such that the electrical conductivities corresponded with those of the irrigation water at Kleinkopje 4 (555 mS/m). The NaCl was added to the leaching waters of Columns 1 and 3 to ensure ion exchange. (Ion exchange is a reversible chemical reaction wherein an ion [an atom or molecule that has lost or gained an electron and thus acquired an electrical charge] from solution is exchanged for a similarly charged ion attached to an immobile solid particle. Na can exchange with Ca and Mg). The composition of the waters is tabled in Table 6-17. Columns 1 and 3 were leached with sodium-sulphate water with different NaCl concentrations. Column 2 was leached with pure NaCl water.

Table 6-17: Composition of the leaching water.

	Na2SO4/25L	NaCl/25L	EC (mS/m)
Colomn 1	55g	35g	555
Colomn 2		90 g	659
Colomn 3	83g	7g	545

Each column was leached with twenty-five pore volumes of the different solutions. After each pore volume was drained, the leachate was analysed for sulphate and chloride. From the time graph in Figure 6-32 the following can be concluded:

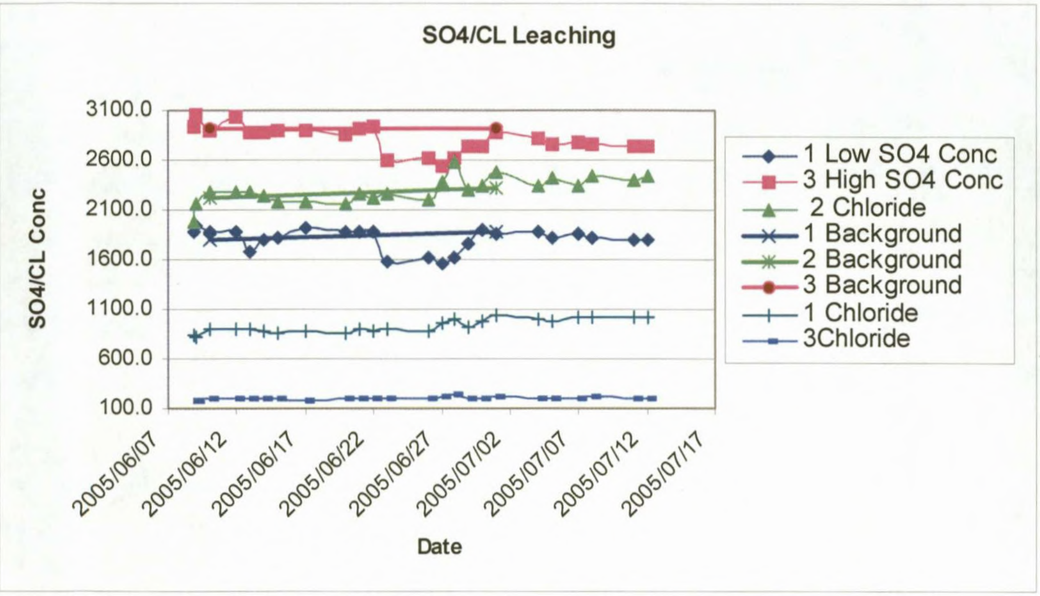


Figure 6-32: Graph of sulphate and chloride leaching columns (mg/L).

1. There is a definite increase in chloride in Column 2 (the one leached with NaCl). A possible explanation is the large pore volume of the column. As such, the initial amounts of the sodium chloride solution acts as an elutant in the column and over time the proportion of the leaching solution will increase in the leachate.
2. There is a definite decrease in sulphate in both Columns 1 and 3. This may be due to some adsorption in the column (SeeTable 6-18). However, the change in these values is not significant, as indicated by plotting the percentage of the original input sulphate against time (Figure 6-33).
3. The dip in the sulphate values for the five leaching events in the middle cannot be explained.

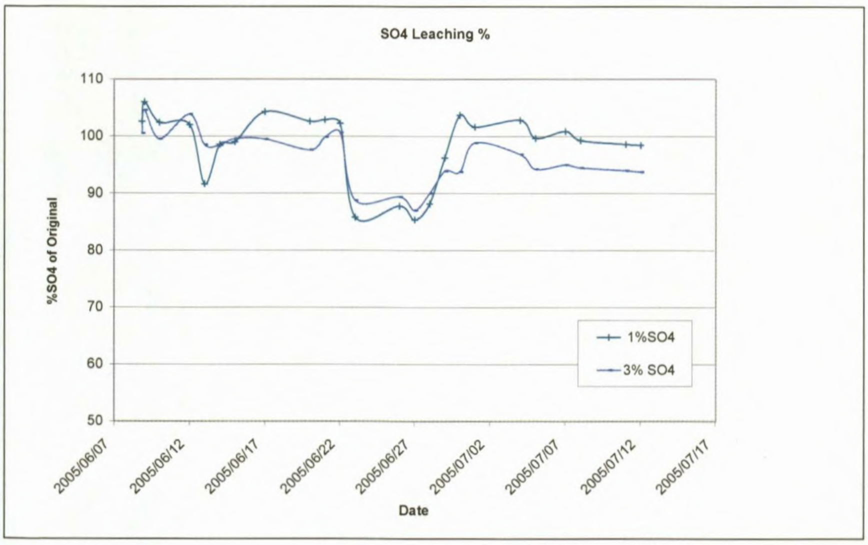


Figure 6-33: Graph of sulphate leaching columns expressed as a fraction of the input.

After the last leaching procedure, the columns dried out over a period of a month, after which they were cut lengthwise. The soil was sampled at each layer to correspond with the clay analysis. These were then analysed to determine sulphate adsorption. Normally all the leaching methods were developed to determine total plant -available sulphate (Tabatatai, 1982 and deJager, 2005). De Jager developed a method to determine the dissolved and exchangeable/adsorbed sulphate in the soil as a result of irrigation activities, which was used to analyse the soil with:

A suspension of 5g soil and 50 ml of water was shaken for 4 hours and left to settle for 16 hours. It was filtered with Whatman No1 filter paper. The extract was then analyzed by ion chromatography to determine the precipitated part of the sulphate. The soil residue from the filter was dried, and a suspension of 5g soil and 50 ml potassium-orthophosphate as then treated the same way.

The results in Table 6-18 indicate:

- An average sulphate adsorption of 24.9% of the total extracted sulphate. The rest (water extracted) is precipitation. This means that not all sulphate will be leached by excessive irrigation or rain. It must be noted, however, that desorption can occur and that the 25% sorbed sulphate will not be irreversibly fixed in the soil profile.
- What is also significant from these data is that the highest adsorption values occured in the layers where the original soil chloride values (see Table 6-16, and also Table 6-18) were high. The graphs are plotted in Figure 6-34. There is no direct correlation between the clay content of the soil and the adsorption values, but the increased values are definitely a function of the hydraulic properties of the soil. The layer with increased clay content retards the downward movement of the water at 2.5m, and this result in the increased water content above 2.5m. As a result of this, the "natural" chloride values are elevated, andthis also results in increased precipitation and adsorption of ions from the irrigation water.
- As was found by Campbell (2001), the phosphate-extractable sulphate data appeared to be independent of pH (Table 6-16). However, this can only be determined from sorption experiments in which the soils are equilibrated with sulphate solutions at various pH-values.

Table 6-18: Water and potassium-orthophosphate extraction values of sulphate.

Unpolluted soil (background values)				Leachate values	
Depth	**Cl in soil**	**Clay**	**Water**	**KPO4**	**Adsorption**
m	mg/kg	%	mg/kg	mg/kg	%
0.3	33.6	13.79	303.50	84.65	21.8
0.6	22.6	13.79	156.50	83.16	34.7
0.8	55.7	18.48	404.50	148.91	26.9
1	55.7	18.48	436.60	163.18	27.2
1.2	91.1	18.58	518.40	239.88	31.6
1.5	141.4	18.58	526.40	215.52	29.0
1.8	102.1	18.58	474.20	173.80	26.8
2	20.5	18.58	412.70	96.49	19.0
2.5	16.8	27.59	469.90	99.93	17.5
3	16.8	23.1	575.30	135.10	19.0
3.5	16.3	23.22	598.10	154.14	20.5

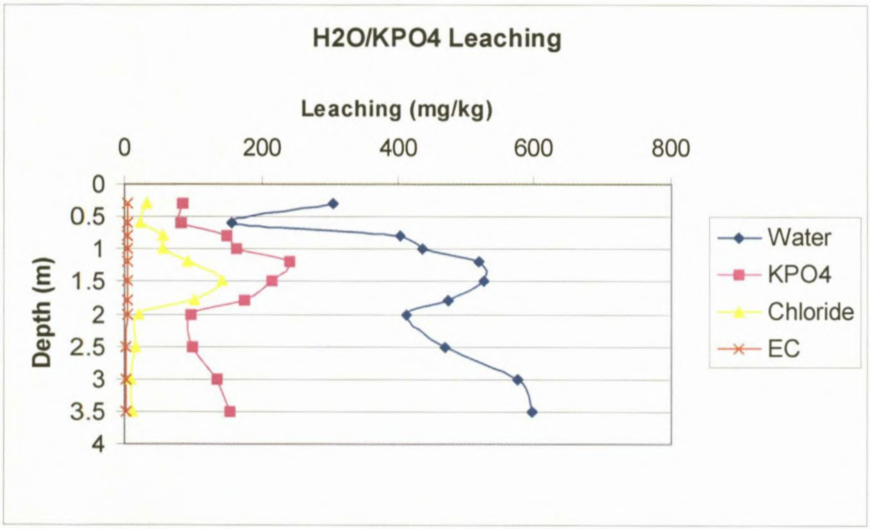


Figure 6-34: Water and phosphate leachate compared with original chloride in soil.

6.6 Assessment of the hydraulic behaviour and chemistry in the unsaturated zone at the virgin soil irrigation sites

In order to determine the hydraulic behaviour, salt balances and attenuation, and the movement of the salts at the various irrigation sites, the results of the various experiments that have been performed on site and in the laboratory will be analysed and discussed in the following sections. This includes the soil analysis, porous cup analysis, monitoring analysis, tensiometry, leaching columns, pumping tests, slug tests and point dilution tests.This will be discussed in the following sequence:

- Moisture content at the irrigation sites.

- Salt balance through the profile.
- Leaching possibilities of the salts after irrigation has ceased.
- Aquifer parameters and the determination of flow paths.
- Determination of unsaturated / vertical flow through the profile and subsequent salt attenuation.

6.6.1 *Measurement of soil moisture potential*

The moisture content of a fully saturated porous medium must be clearly equal to the porosity of the medium (Botha, 1996). In unsaturated flow, this value of θ, also known as the *saturated moisture content*, is conventionally denoted by the symbol θ_s. The moisture content and water saturation of a porous medium must thus satisfy the inequalities:

$$0 \le \theta \le \varepsilon\ (= \theta_s), \quad \text{and} \quad 0 \le S_w \le 1$$

Where: ε is porosity.

Total soil moisture potential is often thought of as the sum of matric and osmotic potentials and is useful for characterising the energy status of soil water with respect to plant water uptake. The sum of the matric and gravitational (elevation) heads is generally called the hydraulic head (or hydraulic potential), which is useful in evaluating the directions and magnitudes of the water-moving forces throughout the soil profile. Methods are available for measuring matric potential as well as total soil moisture potential, separately or together (Black, 1965). Matric potential in the field is measured with a tensiometer, whereas in the laboratory use is often made of tension plates and of air pressure extraction cells.

Tensiometer: If left in the soil for a long period of time a tensiometer follows the changes in the matric suction of soil water. As soil moisture is depleted by drainage or plant uptake, or as it is replenished by rainfall or irrigation, corresponding readings on the gauge occur. Suction measurements by tensiometry are generally limited to matric suction values below 1 atmosphere. This is a result of the vacuum gauge or manometer measuring a partial vacuum relative to the external atmospheric pressure, as well as of the general failure of water columns in macroscopic systems to withstand tensions exceeding 1 bar. In practice the useful limit of most tensiometers is at about 0.8 bar. As described in Section 5.6 the School of Bioresources Engineering and Environmental Hydrology at the University of Kwazulu-Natal designed special tensiometers for this project to measure tension as deep as 5 m, and depending on the depth of the water table, tensiometers were installed at every meter down drilled core holes at the different irrigation sites, except New Vaal (which is too sandy for good ceramic contact). Results vary in the degree of success, with the tensiometers at Kleinkopje 4 being the most successful.

The tensiometer data can be interpreted as follows:

- The higher the tension values above 0 bar, the drier the soil.
- At 0 the soil is saturated.
- Below 0 ponding may occur.

Kleinkopje 1:

At Kleinkopje 1 (Figure 6-35) the one-meter tensiometer initially malfunctioned. However, when auger holes were drilled during the summer and the winter, a visible difference in moisture content could be observed, with the summer period being wetter. At 2m, the tensiometer indicates wet conditions during the summer rain period and drying-out conditions during the winter irrigation period. During September there was again an increase in moisture when the area was flooded due to a malfunctioning pivot. The 3 m tensiometer is very close to the water level and indicates very wet conditions (even ponding conditions). The 4 m tensiometer is below the water level and indicates wet conditions similar to the 3m one.

From these data, it is clear that even at a site with such a shallow water level there is a visible decrease in soil moisture during winter when effective irrigation is being practiced. This will result in salts retained in the upper layers of the soil, as indicated by the soil analyses and the soil water analyses.

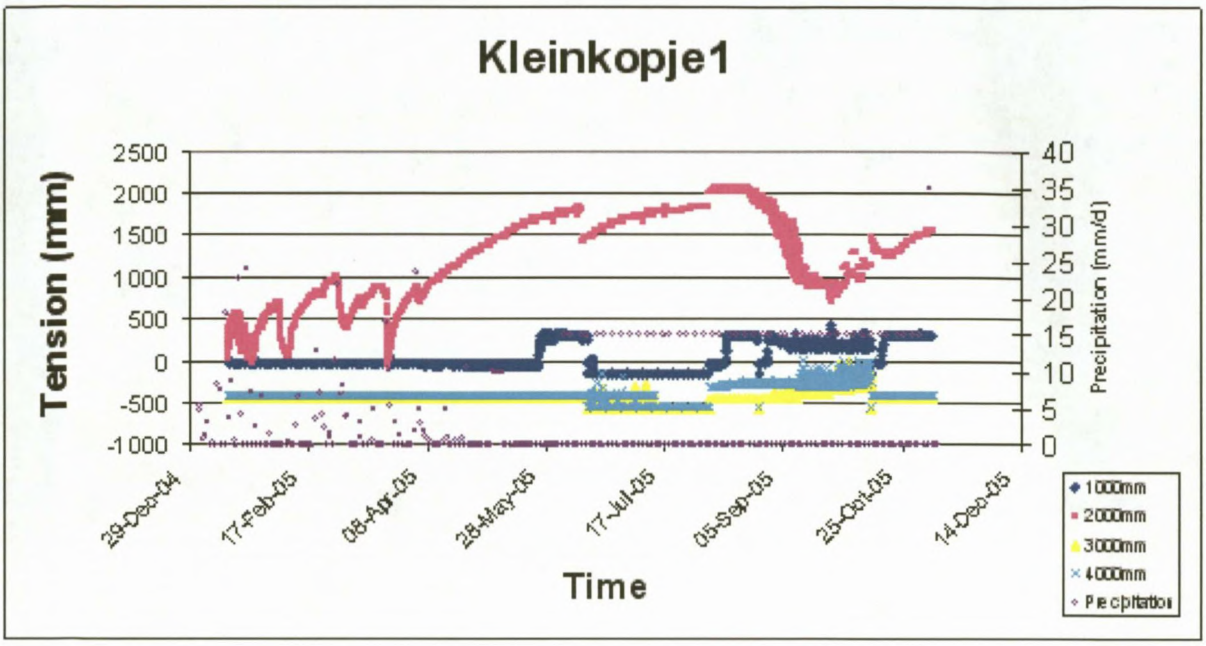


Figure 6-35: Tensiometer data for Kleinkopje 1.

Kleinkopje 4:

At Kleinkopje 4 the results from the tensiometers were much better, with all four tensiometers indicating good results.

Initially the one-meter tensiometer did not work, but after excessive rain contact was achieved. Since then the layer remained fairly wet. The two-meter tensiometer indicates an increase in moisture during the rainy season, and started to dry out slightly during winter. The three-meter tensiometer was installed at the increased clay layer and indicates ponding at this level after the high rainfall events of the summer. This corresponds with observations while digging the observation pits. At the end of July all the tensiometers showed an increase in moisture, with the three-meter one again indicating ponding. It could not be confirmed, but it is most probably because of an increase in irrigation during this time just after the winter crop was planted. At four m the effect of the clay layer can be seen clearly. This layer dries out at a steady rate during winter. This is because of the retarding effect the clay layer has on the downward movement of the water, but also because the water leaks into the aquifer. The leaking will occur because the conductivity value is larger below the clay layer than in the clay itself (See section 6.6.4 on aquifer parameters).

The site shows the importance of the clay layers in the downward movement of the soil water. This will also have an effect on the salts being attenuated in the soil layers above the saprolite zone.

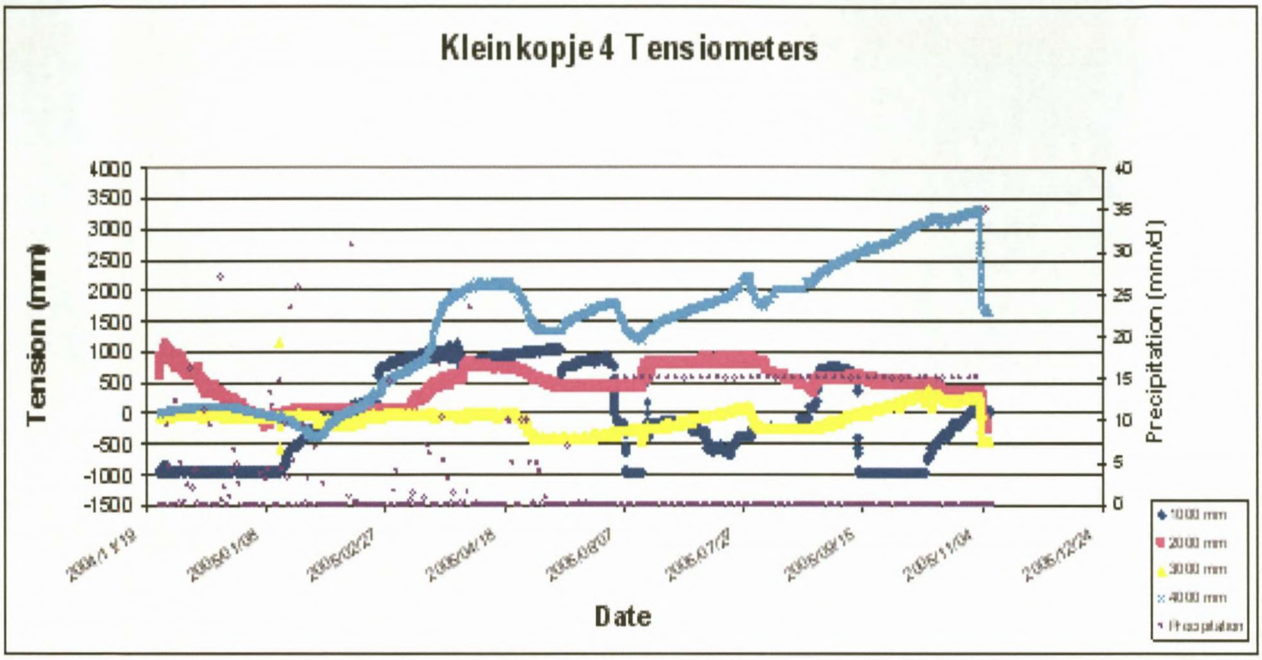


Figure 6-36: Tensiometer data for Kleinkopje 4.

<u>Syferfontein:</u>

Shortly after the tensiometers at Syferfontein were installed in June 2004 the pivot broke down. All the results until March 2005, when the pivot came into operation again, were thus discarded. The soils have a very high clay content at Syferfontein and the tensiometers did not produce satisfactory results. The two-meter one did not function at all. The only feasible conclusion from this is that the topsoil (with a clay content of 60%) also dried out slowly during the winter.

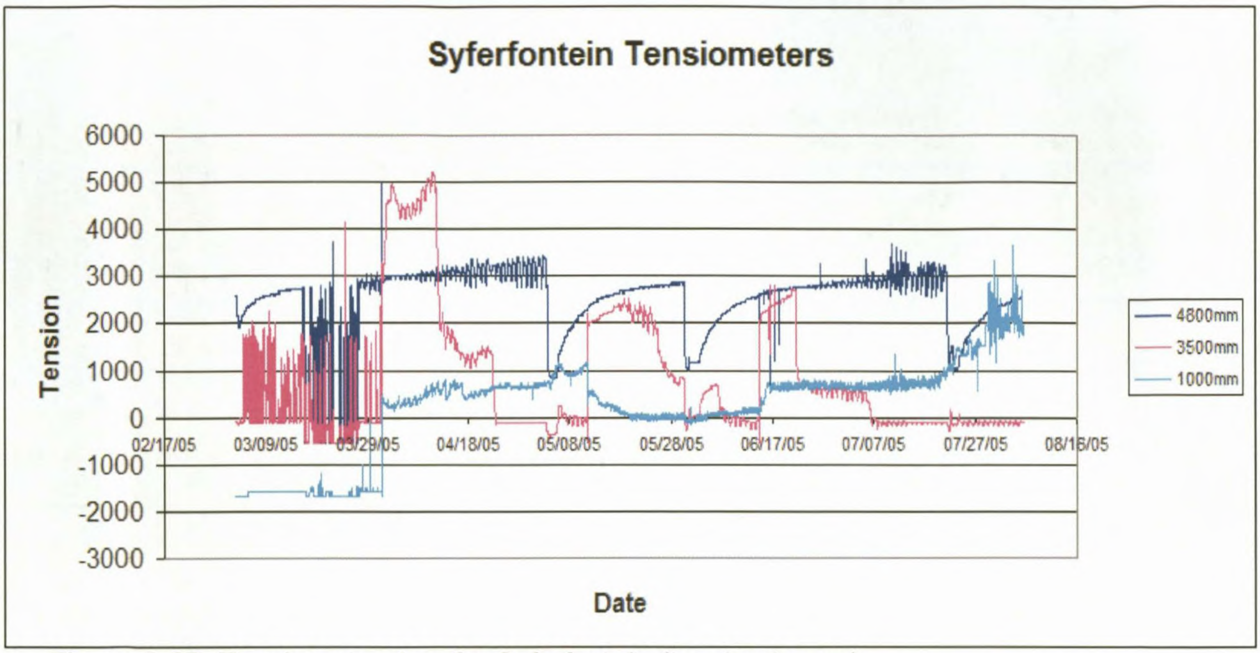


Figure 6-37: Tensiometer data for Syferfontein (tension in mm).

6.6.1.1 Calculation of soil moisture

The pressure potential of water in soil in relation to water content may be portrayed by means of retention curves.The relationship between water content and pressure potential is not unique due to the hysteresis effect in the filling and emptying of soil pores. Changes in pore geometry and water content will occur during swelling of clays. Retention curves determined under transient and static conditions may differ (Hutson, 1983). In practice, these effects are usually ignored and a unique non-hysteretic relationship between water content and pressure potential is assumed. Retention curves are determined in the laboratory by measuring the water content of soil cores at increasing pneumatic potentials. These tests are time-consuming and laborious, prompting the search for simpler methods of estimating retentivity from South African soil types.

Hutson (1983) set up regression equations for most of the soils in South Africa, based on texture. Soil texture refers to the size of mineral particles or the relative amounts of sand silt and clay, ranging in size range from fine to coarse. Fine-textured soils contain more clay size particles and have relatively high porosity but the pores are small and often discontinuous. In contrast, coarse textured soils contain sand-sized particles and have more porosity but bigger pores that are connected. The proportion of sand, silt and clay particles in the soil determine whether a soil is classified as sandy, silty or clayey. Clayey soil has the smallest soil particles, and many small pore spaces. Soils with a high number of clay particles have a very high water-holding capacity and are very fine-textured, making them feel smooth and sticky (like soap) when wet.

In South Africa the International Soil Science Society particle size classification is used, with the addition of a medium sand fraction. The limits are:

- Clay < 0.002mm
- Silt 0.002 - 0.02mm
- Fine sand 0.02 - 0.2mm
- Medium sand 0.2 - 0.5mm
- Coarse sand 0.5 - 2mm

A balanced soil (loam) contains about 40% sand, 40% silt and 20% clay and is preferred for growing crops. The soil particle diameter of clay is < 0.002mm, that of silt between 0.002mm and 0.05mm, sand 0.05mm to 2mm, with gravel >2mm).

Textural classes were defined by Loxton (1961). The textural triangle was adapted from that of the USDA Soil Survey (Hutson, 1983). The textural triangle converts the relative percentage contribution of each separate (by weight) into a textural class or name such as loam, clay, silty clay loam and so on. For example: a soil which contains 45% sand, 25% clay and 30% silt is a loam. Note that silt is determined by difference: % silt = 100% - (45% sand + 25% clay). (see Figure 6-33.)

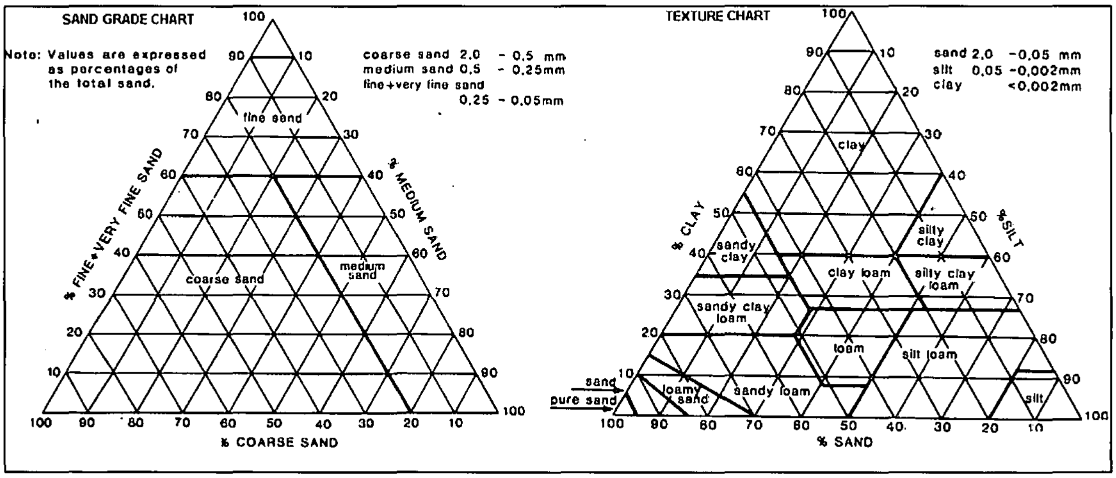


Figure 6-38: Texture chart (Soil classification working group -1991; Hillel, 1982).

Clay mineralogy plays an important role in determining the physical properties of soil (Hutson, 1983). Clays increase the total surface area and are usually the cause for swelling or shrinking. Highly exchangeable sodium levels can lead to extreme swelling and particle dispersion. The structure of most soils changes to some extent during wetting and drying cycles. The extent of this change (or structural stability) depends on the composition of the soil material. Sandy soils in South Africa generally have a high structural stability during wetting and drying, while the stability of soils containing swelling clays or high exchangeable sodium levels have low structural stability. Air-to-water permeability ratio (AWR) measurements were introduced by Reeve (1953) as a method of evaluating structural stability. A completely stable porous material has an AWR of 1 while 20 roughly indicate the instability threshold in soils. These high AWR values may be caused by swelling of the soil.

A large number of published regression equations relate moisture retention to particle size distribution and bulk density (Petersen *et al.*, 1968; Rivers and Ship, 1978; Hall *et al.,* 1977; MacVicar *et al.,* 1977 and Motram *et al.*, 1981).

Soil is composed of solid particles (minerals and organic matter) and pore space (air and water). The characteristics of the soil are determined by the size, distribution and shape of the solid particles in addition to the size and number of pore spaces.

Bulk density is the weight of a given volume of soil, which includes the pore spaces. It can be easily measured by gently pressing a small cylinder into the soil, removing the core and weighing after drying to remove the water contained in the pore space. Average values would be 1.3 -1-75 g per cm^3. Coarse textured soils will usually have a higher bulk density because they have less pore space than fine textured soils. Bulk density is an important property of soils since it affects how easily plant roots can penetrate the soil when they propagate. Real Density is the weight of a given volume of the soil solids only. It would be equivalent to the average density of the soil minerals and the organic matter.

According to Hutson (1983), particle size distribution, organic matter content and bulk density accounts for between 60% and 90% of moisture retention. He combined data from several sources in South Africa to derive equations relating water content at several potentials with different particle size criteria and bulk densities. In this research project, where moisture content data down to the water level was needed, and as it is very difficult to sample intact soil cores to that depth, this method of Hutson is very practical and convenient.

As pressure potential (ψ) decreases, the proportion of the variance of water content (θ) accounted for by regression increases since moisture retention increases. Of the independent variables included in the regression, clay content accounts for the greatest proportion of variance in θ and ψ. Silt content increases in importance as potential increases but bulk density has a negligible influence until saturation is approached. At saturation water content is related solely to bulk density.

Factors that have an influence on soil water retention are particle shape, bulk density, clay mineralogy, organic matter content, structure and degree of aggregation. According to Hutson (1983) some of these factors defy precise quantitative description, and consequently their effect on retentivity may be assessed in qualitative terms only. Using data from a wide spectrum of physical environments he developed a model, in equation form that is based on clay and silt percentages together with bulk densities, which may be applied to South African soils.

This is needed to calculate the salt balance in the soil. The soil texture analyses done on the Kleinkopje and Syferfontein soils (sand, silt and clay content were compared to these regression equations) were derived for stable soils by Hutson (1983) with an air water ratio of 10-100 (Hensley, 2006). The tensiometer data at the irrigation pivots were then used to calculate the soil moisture at the different depths. The water content is calculated as follows:

Eq1: $\theta_{-10} = 0.0558 + 0.0037Cl + 0.0055Si + 0.0303D_b$, with the assumption that θ/ψ_s is linear between V_p and θ_{-10} on the moisture retention curve.

Eq2: $\theta_{-30} = 0.0150 + 0.00384Cl + 0.00572Si + 0.0463D_b$, with the assumption that θ/ψ_s is linear between θ_{-10} and θ_{-30} on the moisture retention curve. This equation is being used where the tension from the tensiometer data is above 1000mm.

Where:

θ = volumetric water content (m^3/m^3)
ψ = moisture potential
V_p = pore volume
D_b = bulk density of soil

The saturated volumetric content of the soil was derived from the bulk density of the soils, using the formula (Hensley, 2006):

$$\theta_s = 1 - (D_b/2.65)$$

From Eq1 and Eq2 the moisture content can be calculated for the pivots in relation to the soil composition obtained from the soil analysis done at Glen (Table 6-19 and Table 6-20

Table 6-19: Kleinkopje 1 (Bainsvlei / Clovelly soil):

Depth (mm)	Si	Clay	Db (mg/m^3)	Eq1: θ_{-10} Estimated θ_v% at ψs= 1000mm water	Estimated % θV_p at saturation	Eq2: Estimated θ_v% at ψs= 3000mm water
1000	25.8	18.6	1.65	31.7	37.7	
2000	25.8	18.6	1.7	31.8	35.8	28.6
3000	24.6	9.2	1.75	27.8	34	
4000	Below the water table.					

Only the 2000mm depth graph rose above 1000mm tension, therefore the θ_{-30} equation was used to calculte the moisture values at 3000mm tension.

Table 6-20: Kleinkopje 4 (Hutton soil):

Depth (mm)	Si	Clay	Db (mg/m^{3})	Eq1: θ_{-10} Estimated θ_v% at ψs= 1000mm water	Estimated % θV_p at saturation	Eq2: Estimated θ_v% at ψs= 3000mm water
1000	25	19	1.65	31.4	37.7	
2000	20	28	1.7	32.1	35.8	
3000	24	23	1.75	32.6	34	
4000	14	23	1.75	27.1	34	23.4

(Only at a depth of 4000mm, which lies between θ_{-10} and θ_{-30}, $\psi_s > 1000$mm).

From these calculations the moisture content at different depths and moisture potential values are *extrapolated and estimated* in Table 6-21 and Table 6-22 (Hensley, 2006) and displayed in Figure 6-39 and Figure 6-40:

Table 6-21: Kleinkopje 1 estimated moisture content:

Depth (mm)	Estimated θv% at different ψs values (mm water)						
	Saturation	500	1000	1500	2000	2500	3000
1000	37.7	34.7	31.7				
2000	35.8	33.8	31.8	31	30.2	29.4	28.6
3000	34	30.9	27.8				

Table 6-22: Kleinkopje 4 estimated moisture content:

Depth (mm)	Estimated θv% at different ψs values (mm water)						
	Saturation	500	1000	1500	2000	2500	3000
1000	37.7	34.6	31.4				
2000	35.8	34	32.1				
3000	34	33.3	32.6				
4000	34	30.6	27.1	26.2	25.3	24.3	23.4

Values were estimated for every 500mm of tension in order to calculate more accurate averages for the different depths (1000mm to 4000mm) to correspond with the porous cup water quality data needed to calculate a salt balance.

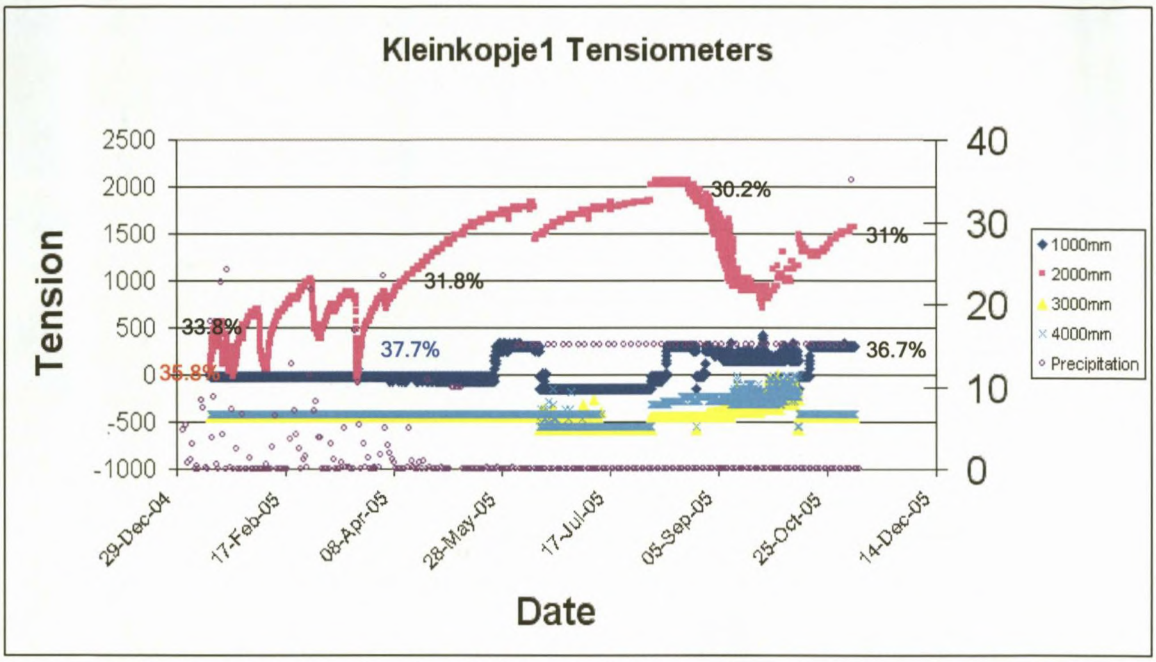


Figure 6-39: Tensiometer data for Kleinkopje 1 with estimated volumetric water content (tension in mm).

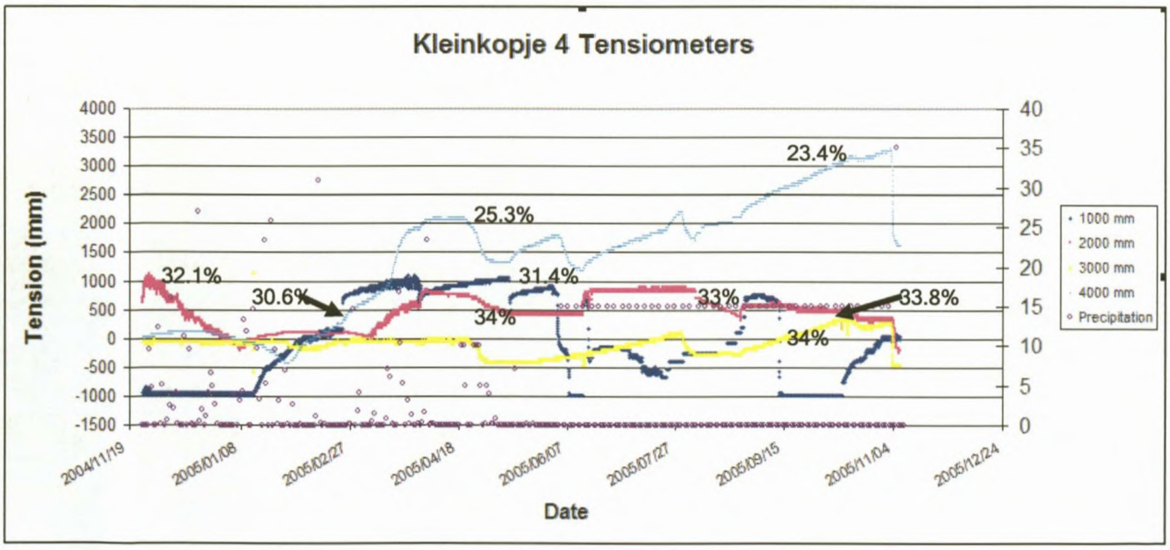


Figure 6-40: Tensiometer data for Kleinkopje 4 with estimated volumetric water content.

From the moisture content values in the tables above (Table 6-21 and Table 6-22), and the tensiometer graph average, the volumetric water content (needed for a salt balance) was calculated at each depth (Table 6-23). The average tension of the tensiometers was calculated against specific periods of time per tension value. The Syferfontein values are included, but will be less accurate because the tensiometers did not function as well as those at Kleinkopje.

To obtain these averages per specific depth, the number of days that the tension was for example saturated, between 250mm and 750 mm was calculated against the 500mm tension moisture content, the number of days between 750mm and 1250mm against the 1000mm tension moisture content up to the highest tensions obtained. These values were then devided between the total period of days to obtain an average for a specific depth.

Table 6-23: Average estimated moisture content with depth.

Depth	**1000mm**	**2000mm**	**3000mm**	**4000mm**
Kleinkopje 1	0.32	0.373	0.34	0.34
Kleinkopje 4	0.358	0.339	0.34	0.28
Syferfontein	0.384	0.35	0.274	0.262

It must be kept in mind that the profile above 1m will be less moist than at 1m. Therefore the conditions above one meter will be much more favourable for gypsum precipitation, and more will be precipitated in relation to what will be in the soil water deeper down in the profile where the moist conditions will be less conducive to the precipitation of the salts.

6.6.2 *Salt Balance of the profile*

One of the critical issues in successful irrigation with the coalmine waters is how much of the salts are retained in the soil profile over the medium term. A salt balance is used to measure the amount of salt that is being introduced into the soil, the amount that is being removed, and the amount currently present within the soil and ground water (Szabolcs, 1986). Salts accumulate in soils where evapotranspiration (combined evaporation from soils and transpiration by plants) exceeds combined precipitation, and will follow the water flow in the event of excessive irrigation and high rainfall events. As saline groundwater approaches the land surface, plants begin to show signs of salinity damage and may die from salty water in the root zone and waterlogging, basements may flood, water levels may rise into landfills, and underground pipes can be damaged.

If a high percentage of the salts precipitate (Annandale *et al.,* 2006) and also adsorb (for example 25% of the retained sulphate, see Section 6.5.3) in the soil, irrigation with the mine waters will not have a significant influence on the groundwater except if these salts leach out rapidly. (see Section 6.6.3 on leaching).

As explained in the previous section, soil is composed of solid particles (minerals and organic matter) and pore space (air and water). The characteristics of the soil are determined by the size, distribution and shape of the solid particles in addition to the size and number of pore spaces. The soil hydraulic characteristics of a vast range of soil, including that of the irrigation sites, were performed by Lorentz *et al.* (2001), using the Van Genuchten, Brooks-Corey and the Campbell parameters. An average of these bulk density values was used in the calculation of the salt balance. (A spreadsheet with the calculations is in Appendix D).

To calculate the salt balance in the profile, the following data are needed:

- Irrigation quantity and quality (from Annandale *et al.*, 2006).
- Bulk density of the soil (Lorentz *et al.*, 2001).
- Volume of water in the soil pores (as discussed in Section 6.6.1).
- Quality of soil salinity (soil leaching data). This is the total salt, which includes precipitated salts and salt in the soil water.
- Quality of soil water (porous cup and water sampling data).

To calculate the salts retained in the soil, the following calculations was made:

*Bulk density * thickness of the layer * sulphate concentration in the soil*

To calculate the percentage salts retained in the soil:

Sulphate retained / total sulphate applied over the period of irrigation

To calculate the sulphate retained in the soil water:

*Sulphate concentration in soil water * thickness of layer * moisture content at that depth*

From these calculations the following results were obtained per hectare of irrigation:

Table 6-24: Salt balance calculations at the irrigation sites.

Site	% Total sulphate applied through irrigation retained in vadoze zone	% of Total sulphate applied through irrigation in soil water	% of Salts retained that are in soil water	Sulphate in soil (ton/ha)	Sulphate in soil water (ton/ha)
Kleinkopje 1	67	56	83	56	47
Kleinkopje 4	77	60	77	48	37
Syferfontein	82	64	78	42	33
New Vaal	86	30	35	18	6

Because the calculations are so sensitive to the input parameters, they cannot be regarded as exact figures, but rather in a range of ± 10 % accuracy. The value at Kleinkopje 1 is lower than the others, because a borehole near the test site drains into the mine underneath, and a large amount of salts in the upper shallow layers was flushed down to the deeper systems (personally observed). On average, between 75% and 80% of the salts are retained in the pore water and the rest precipitates and is sorbed (Table 6-24). Hydraulic, adsorption and attenuation factors prevent the salts in irrigation mine water from being directly and rapidly mobilised down the deeper soil profile and into the aquifer. New Vaal is the exception where a large amount of the salts is retained in the clayey soils deeper down the profile. In Table 6-25 the percentage salt per layer (in depth) in relation to the total salt in the profile is depicted. From this table it is clear that most of the salts in the clayey soil of Syferfontein are retained in the upper 0.6 m. At Kleinkopje 4 the salts have migrated a little deeper, with most remaining at 1-2 m in the moist area above the clayey layer.

Table 6-25: Percentage salt in layers in depth through the profile down to water level.

Kleinkopje 1		**Kleinkopje 4**		**New Vaal**		**Syferfontein**	
Thickness (m)	% salt in layer	Thickness	% salt in layer	Thickness (m)	% salt in layer	Thickness (m)	% salt in layer
0.2	31.5	0.3	15	0.3	0.6	0.3	63
0.2	27.1	0.3	9	0.3	0.2	0.3	25
0.4	10.0	0.4	20	0.4	0.7	0.4	9
0.2	4.1	1	52	1	11	1	0.7
0.5	8.9	0.5	0.1	0.2	2.6	1	0.7
0.5	5.3	0.5	2.8	0.2	5.0	1	1.2
0.5	4.5	1	0.1	0.6	15	1	
1	8.2	0.5	1.1	1	14		
0.5	0.3			3.5	40		
				1	11		

What will happen when irrigation cease at the different sites? How long will it take for the salts to leach out with rain, and at what rate? These questions will be addressed in the next section.

6.6.3 *Leaching of the salts in the profile*

Campbell (2001) states that associations between sulphate retention maxima and zones representing past or present regions of hydrological transition suggests that the accumulation of sulphate in any particular region of the profile is significantly influenced by seasonal variations in the soils` water content and water flow in the soils. In particular, the influx of rainwater during each wet season appears to move the bulk of sulphate present in the upper part of the profile to the top of the saturated zone. The high-intensity, short-duration rainstorms results in the rapid movement of significant volumes of rainwater through the unsaturated zone in these sandy soils. Since sulphate adsorption, especially on kaolinite edge sites, tends to be reversible (Mott, 1981) rainwater passing through the unsaturated zone would cause sulphate to desorb and be transported down to the water table. More stagnant water flow conditions at the water table will cause a net accumulation of dissolved sulphate.

The leaching requirement is the amount of water that must travel through the soil and into the groundwater in order to leach the desired amount of salts. In general one volume unit of fairly low salinity irrigation water can leach 80% of salts from the same volume of soil. This is only a general rule and significant variation is related to the different soil types (Abrol et al., 1988). Irrigation water must serve two purposes:

- Some of the water will be used by plants (transpiration) and some will be lost to unavoidable evaporation. Both processes will raise the salt concentration in the soil.
- The second purpose of irrigation water is to leach the excess salt, created by evapotranspiration, and maintain the salt balance in this way.

However, in the case of irrigation with colliery water, the water quality is such that it will not leach the salts in the soil, but instead result in the accumulation of more salts. The only way to leach the salts is with heavy rainfall events. In order to simulate (and determine) the effect of rainfall events on the leaching of gypsum from the soil, leaching drums were set up in the laboratory (Figure 6-42). The gypsum content in the soil was based on the work done by Annandale *et al.* (2006). According to these calculations approximately 20 tons gypsum / ha will precipitate in the upper layer of soil at the Kleinkopje pivots over 15 years. These simulations and measurements are illustrated in Figure 6-41 (Van der Westhuizen, 2005).

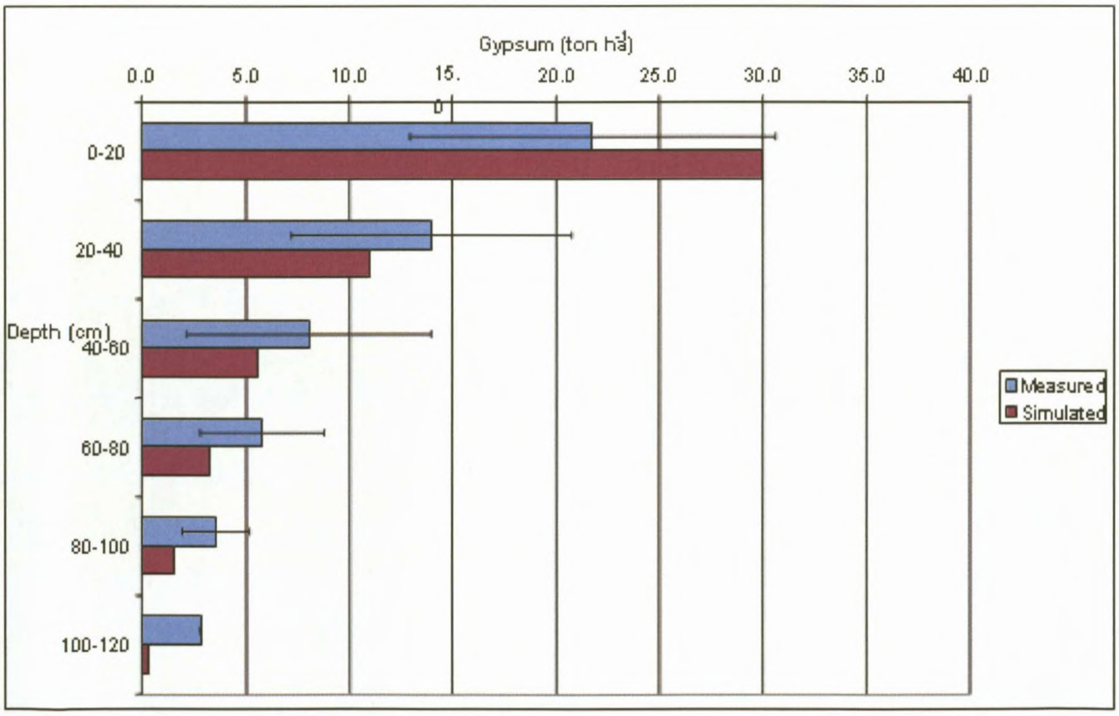


Figure 6-41: Gypsum precipitation calculations at Kleinkopje pivots (After Van der Westhuizen, 2005)

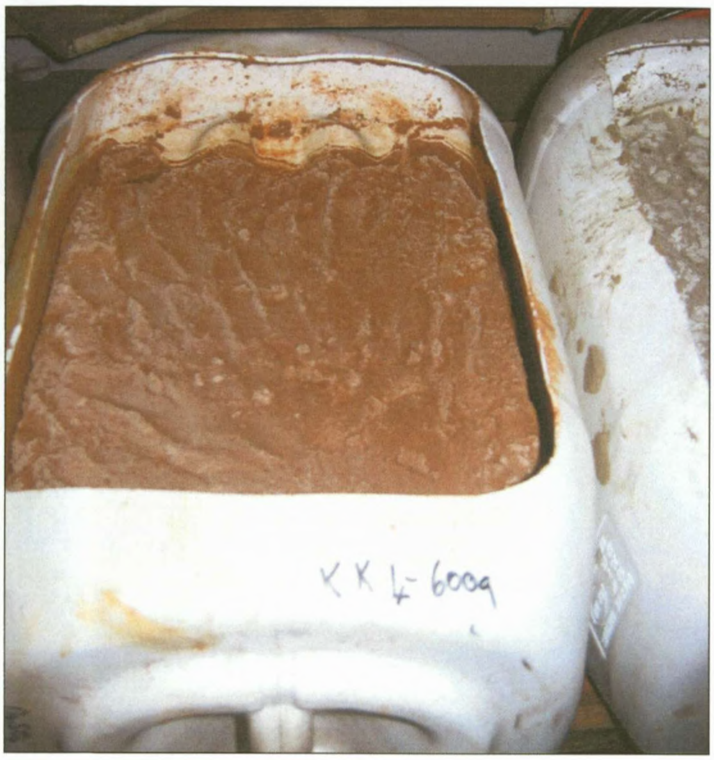


Figure 6-42: Leaching drums with different types of soils and gypsum concentrations.

Different gypsum concentration scenarios were run for the different types of soils at Kleinkopje Pivot 1 (Bainsvlei and Clovelly soils -lower clay content, 5-10%) and Pivot 4 (Hutton soil - higher clay content, average 18%), Syferfontein Pivot (Arcadia soil -high clay content, in the order of 60%) and New Vaal Pivot (sandy soil). For the Kleinkopje pivots three scenarios were simulated i.e. 10 ton gypsum / ha, 20 ton gypsum / ha and 40 ton gypsum / ha, but for Syferfontein and New Vaal only one scenario each was simulated i.e. 20 ton gypsum / ha. Artificial rainfall used was of the same quality that has been measured by Van der Westhuizen (2005). The water had a TDS of 80mg/L (EC of 14 mS/m) with a NaCL value of 40mg/L and a $CaCO_3$ value of 40mg/L.

During each leaching event, 75 mm of rainwater was applied to each drum, and the water analysed. The soil was then dried out under natural conditions, assisted by wind. This process was repeated eight times. After each drying cycle, the soil was loosened as if cultivated by the farmer. This was done to simulate real agricultural conditions.

Calculations with PHREEQC indicate that the leachate is saturated or over saturated with respect to gypsum (Figure 6-43). The exception was during the second last leaching event (12 December 2005) when all the drums were not completely dried out. The moist soil resulted in the leachate being under saturated with respect to gypsum.

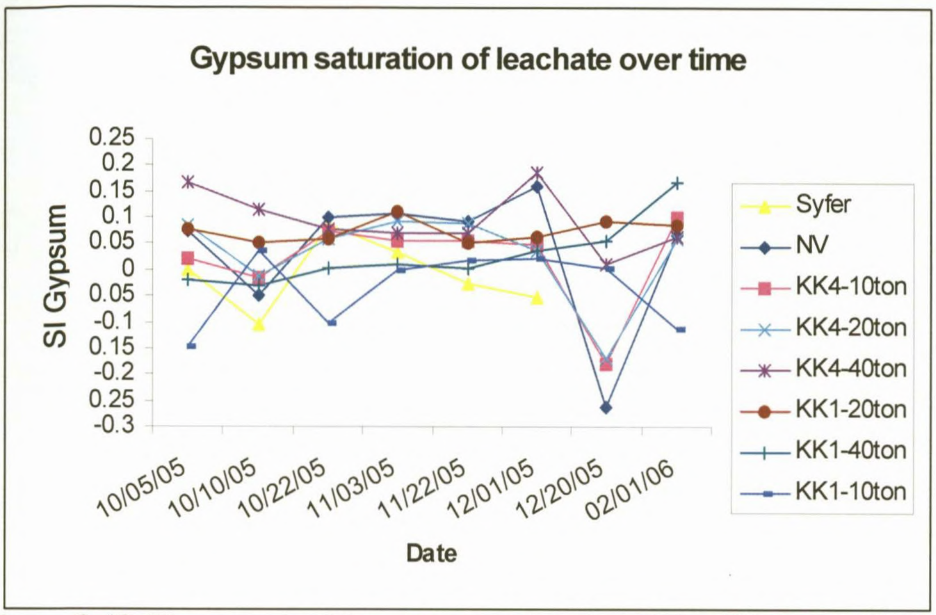


Figure 6-43: Time graph of the gypsum saturation of the different leachates.

Increase in Ca^{2+} and SO_4^{2-} can only occur up to a point, where the aqueous solubility of these ions becomes limited by the solubility of gypsum. The sulphate concentrations in the leachate were all in this range. This means that the maximum quantity of gypsum leached from the soil is bound by the gypsum saturation of the water moving through the soil. Calculating the sulphate (1800-2000 mg/L) and calcium (600-700 mg/L) concentrations in the leachate indicates that, if 20 tons gypsum / ha precipitated in the upper layer of soil, at least 40 - 50 heavy rainfall events (75mm) will be needed to leach the precipitated salts from the soil.

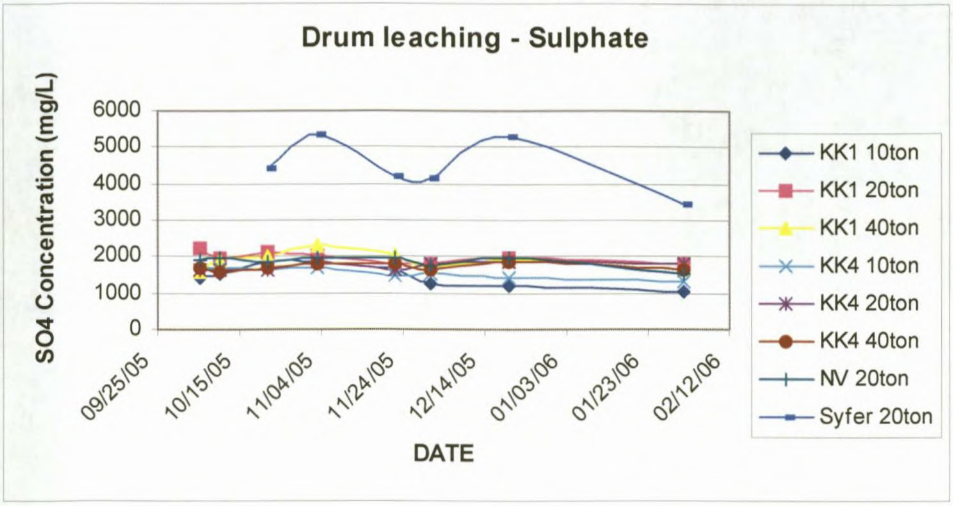


Figure 6-44: Leaching rate of sulphate from the leaching drums.

According to Figure 6-44 the soils at Syferfontein will leach faster than the others. High Na in the Syferfontein water causes high ionic strength, and due to these effects the activity coefficient of the ions decreases, resulting in the higher solubility of Ca and SO_4 before gypsum equilibrium is reached.

It must be noted that this represents the minimum rainfall events needed, as the conditions in the experiment are optimal for leaching.

- Evapotranspiration, which will decrease the volume water moving through the soil, has not been taken into account during the experiment.
- The leaching is also a direct function of the moisture content of the soils. The drier the soil, the more water is needed to flush the salts.
- Recharge, and the subsequent vertical movement of water, are bound by the amount of rain. It was assumed that very little recharge would occur in events of less than 15-20mm. Only high rainfall events will thus effectively leach the salts.

It should be noted, however, that even if gypsum accumulates in the upper meter of the irrigated soils, as predicted by Annandale *et al.* (1999), there would still be downward movement of Mg, SO_4 and other salts, given that Mg will be more exchangeable than Ca in the upper part of the soil profile and that the concentration of SO_4 in the irrigation water is twice that of Ca. Furthermore, the solution that percolates from the base of a gypsiferous zone is saturated with respect to gypsum (under equilibrium conditions), so soluble Ca must also be present in leachate from the zone, i.e. if Ca is not zero. Even if irrigation is managed so that leaching is negligible during the dry season, it is apparent from the data that the significant movement of the solutes caused by irrigation will take place during the rainy season. This means that in the longterm almost all of the Mg, Na, K and Cl, at least half of the

SO_4, and some of the Ca added by irrigation must enter the groundwater system. If sustainable gypsum precipitation does not take place, then nearly all the added Mg, SO_4 and Ca will move to the local aquifer.

In order to form an idea of the time it will take to leach the gypsum retained in the soil after irrigation has stopped, leaching columns were set up with soil from the irrigation sites. The soil was augured down to water level depth at Kleinkopje 1 and 4, and was then placed in 4m leaching columns in exactly the same sequence as it was taken from the profile. The same quality "artificial" rainwater that was used in the previous experiment was then used to leach the soils. The EC was measured after each leaching event and the experiment continued until the leachate quality approached that of the elluent (artificial rainwater) (Figure 6-45).

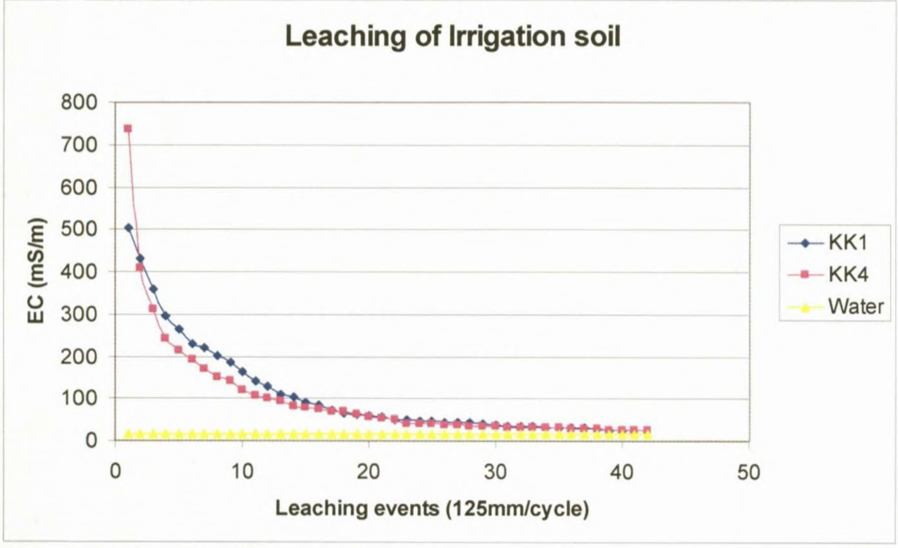


Figure 6-45: EC of the leachate from the irrigated soil.

Under these optimal conditions the columns indicated that at least 30 leaching events of 125 mm each (3750 mm) are needed to decrease the EC down to 38 and 34 mS/m respectively. To decrease it to 16 ms/m (nearly the same as that of the rainfall) 42 leaching events (5250 mm) are needed.

All the important macro elements were analysed for after selected events. The leaching trend, especially for sulphate, is the same as that of the EC (Figure 6-46).

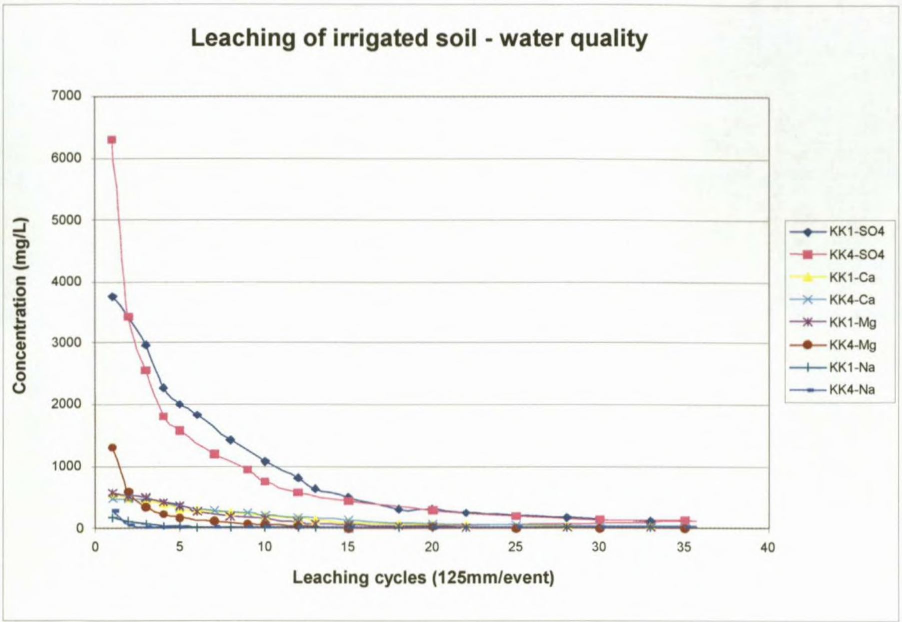


Figure 6-46: Ca, Mg and SO_4 qualities of the leachate over the period of leaching.

To compare the volume of rain needed to the time it will take to leach the salts from the soil profile, a few assumptions had to be made:

- The leaching is also a direct function of the moisture content of the soils. The drier the soil, the more water is needed to flush the salts.
- Recharge and the subsequent vertical movement of water, are bound by the amount of rain. Very little recharge will occur in events of less than 15-20mm. Only high rainfall events will thus leach the salts. An average of rainfall available for leaching (if this assumption was upheld) since 1929 was calculated and relates to 338mm/a if daily evapotranspiration is also subtracted (see ET Calcs in Appendix D). It is also assumed that all the flow is diffusive flux (which will leach the salts uniformly) and not macropore (preferred pathway) flux, which will only leach areas immediately surrounding the preferred flow areas.
- Daily evapotranspiration has to be compared to the rainfall in order to determine how much water will pass the root zone and will be available for leaching. From the ET figures for maize, wheat and pastures, obtained by Green (1985), it is assumed that the evapotranspiration is the same throughout the crop period, which is not correct.

The total ET (mm) for these crops at the Highveld is as follows:

Crop	**ET**	**Time span**	**Total days**
Maize	550	15 Dec - 14 April	119
Wheat	570	15 June-13 Nov	150
Pastures	1300	Jan -Dec	365

And for New Vaal (ET in mm):

Crop	**ET**	**Time span**	**Total days**
Maize	730	15 Dec - 14 April	119
Wheat	645	15 June-13 Nov	150
Lucerne	1500	Jan -Dec	365

The evaporation in the hot summer months (also the rainy season) will be much higher than during winter. The assumption was made that there is a linear relationship between temperature and ET (average temperatures obtained from the SA Weather Bureau). A spreadsheet on all these calculations can be seen in ET Calcs in Appendix D. The average daily evapotranspiration figures are tabled in Table 6-26.

Table 6-26: Daily calculated ET values at the Highveld and New Vaal.

HIGHVELD					
Maize	Month	Daily ET	**Pastures**	Month	Daily ET
	December	4.7		January	4.1
	January	4.9		February	4.0
	February	4.7		March	4.0
	March	4.7		April	3.5
	April	4.2		May	3.2
Wheat	May	Daily ET		June	2.7
	June	3.1		July	2.7
	July	3.1		August	3.2
	August	3.6		September	3.7
	September	4.2		October	3.8
	October	4.3		November	3.8
	November	4.5		December	4.0

NEW VAAL					
Maize	Month	Daily ET	**Pastures**	Month	Daily ET
	December	6.2		January	4.9
	January	6.5		February	4.7
	February	6.2		March	4.5
	March	6.0		April	3.9
	April	5.2		May	3.6
Wheat	May	Daily ET		June	3.0
	June	3.5		July	3.2
	July	3.5		August	3.6
	August	4.1		September	4.3
	September	4.7		October	4.5
	October	4.9		November	4.5
	November	4.9		December	4.7

With all these assumptions in mind, it will take at least 15.5 years (5250 mm/ 338 mm/a available on average after small rainfall events and evapotranspiration were subtracted from annual rainfall) to leach the soil profile at the Highveld with rain after irrigation has stopped. At New Vaal it will take 44 years if the same crop (maize and wheat) is planted on the same type of soils as in the Highveld, because the ET is much higher and the rainfall is less (only 630 mm average against the 720 mm at the Highveld). However, the measured gypsum load in the sands at New Vaal is only 20 ton/ha against the 48 - 56 ton/ha at the Kleinkopje sites and 42 ton at Syferfontein (see spreadsheet on salt balance in Appendix D.). From the salt leaching experiments and the illustration of sulphate leaching from the drums in the time series graph in Figure 6-44, it is clear that the salts in the New Vaal sand profile will leach at the same rate as the Highveld soils at Kleinkopje. It can thus be assumed that the New Vaal soil profile will also leach in 44*(20/56) years, i.e. 16-18 years.

To test these values, they can be compared with a vertical K-value calculation. If assumed that porosity is 35%, there will be 0.525 m^3 per m^2 of water for the first 1.5m of the profile, where most salts are currently retained. If the vertical K is $1*10^{-4}$ m/d for diffusive flow, it will take 0.525 / $1*10^{-4}$ days for the water with the salts to move through the profile, which will be 14 years.

It must be kept in mind that these leaching figures are derived from the absolute optimal conditions, with 100% diffusive flux through the soil profiles. In reality it will take much longer (and with a non-linear decrease in gypsum) because of the macropore flow. According to Table 6-34 in the following section 25% of the water applied through irrigation will reach the water level. This will mean that under the same conditions (wet irrigation conditions) and with an annual rainfall of 750 mm, it will take 30 years to leach the gypsum. The conditions in the soil will however be drier under normal cultivating conditions, and recharge will maximum be 5-6% (Usher *et al.*, 2006). Then it will take more than a hundred years to leach the sulphate from the soil. *In the following section (Section 6.6.4) calculations will show that most of the recharge through the profile is along preferred pathways.*

6.6.4 *Identification of the aquifer parameters and flow zones through interpretation of point dilution, slug and pumping test data (See Sections 5.9 to 5.11).*

6.6.4.1 Kleinkopje 1:

This borehole had very low salinity water with a background value almost below the detection limit of the EC-measuring instrument. As a result, only 20g of NaCl (circulated in the volume of water of the borehole) was enough to increase the EC of the tested section by about 250% during the point dilution test. The water level was at 2.45 m and the test conductive to a depth of 12m.The point dilution test clearly indicates *a high flow zone at 6 m,* because of the dilution that occurs at this level (Figure 6-47), and also one at 8-9m.

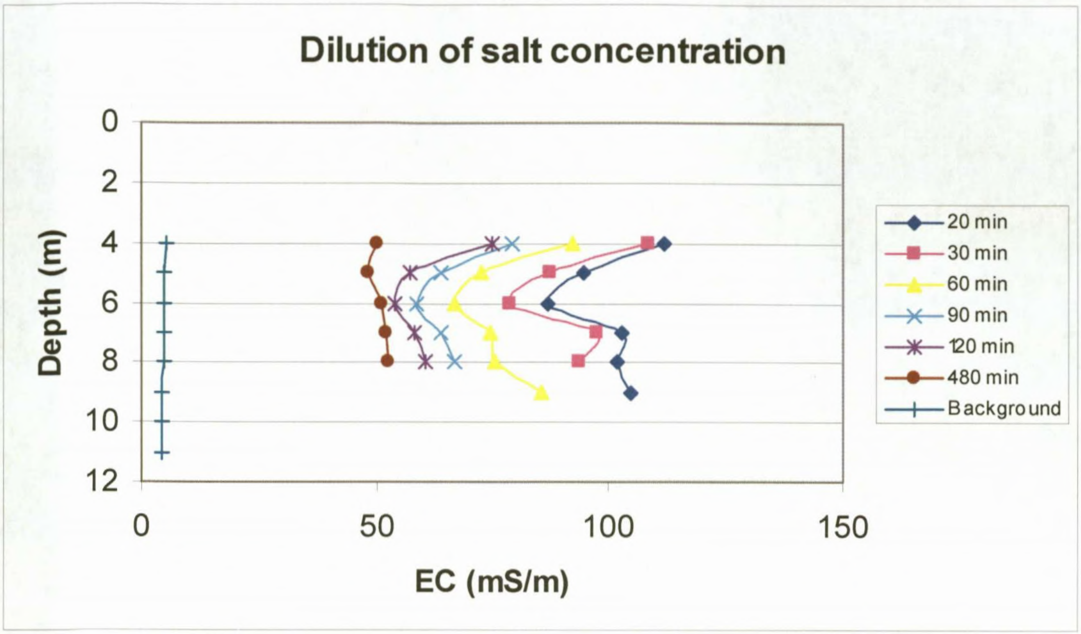


Figure 6-47: Graphs of the decrease in concentration over time at KK1.

The values in Table 6-27 indicate the conductivity values of zones of higher flow (preferred pathways or fractures), and *not of the matrix* (or aquifer) as a whole for this section of the profile. The high flow zone at 6 m confirms what has been encountered while digging the test pit at this site when high flow was encountered at a depth of 4m. The values above the water level were obtained from the falling head tests. The transmissivity value of the aquifer, as determined by the numerous pumping tests performed at this site, ranges from 0.2 - 0.3 m^2/d, which relates to matrix K-values of <1m/d.

Table 6-27: Conductivity values for different flow zones through the profile at KK1 (with the flux in m/d).

Depth (m)	K (m/d)	Flux q
1.5	0.05	0.001
3	0.03	0.003
4	127.10	0.318
5	19.36	0.048
6	32.81	0.082
7	21.91	0.055
8	24.17	0.060
9	32.69	0.082
10	25.67	0.064
11	28.95	0.072
12	18.44	0.046

6.6.4.2 Kleinkopje 4:

The water level in the borehole was 2.03 m and the profile was tested to a depth of 15m. The background EC-value of this borehole at the top 5m was almost half of the rest of the borehole. This may indicate the existence of at least two aquifer systems where by, fresh water is flowing in the upper section. 250g of NaCl was added to significantly increase the concentration from the background value during the point dilution test. Three layers with different velocities could be distinguished from the result. These are: above 5m which is characterised by a lower velocity, from 7 - 10m which has a higher value, and between 10 - 15m which has an intermediate velocity value (Figure 6-48).

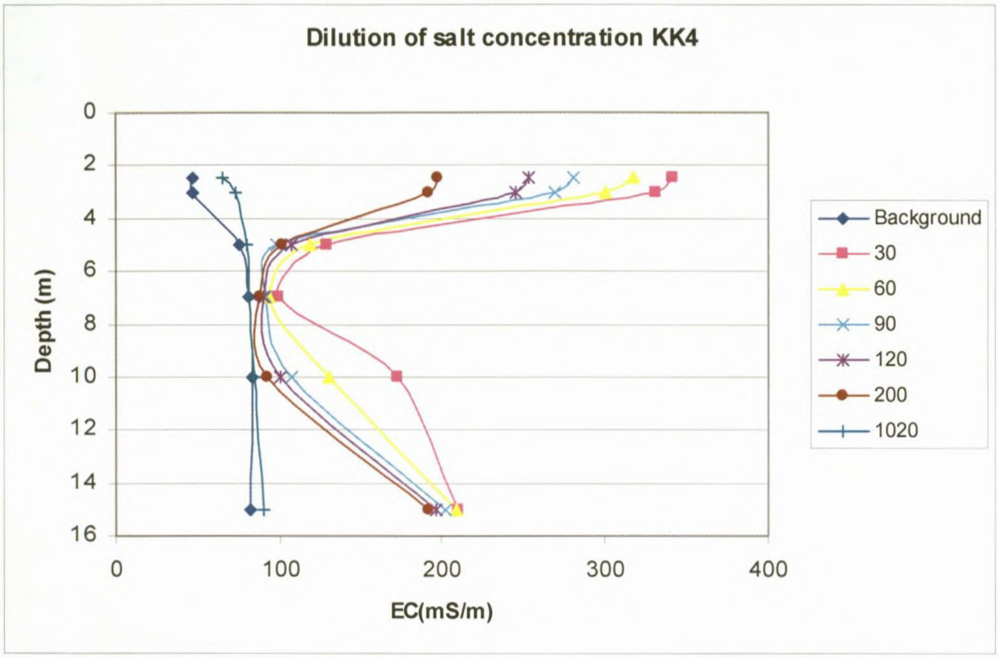


Figure 6-48: Graphs of the decrease in concentration over time at KK4.

The values in Table 6-28 indicate flow zones with higher conductivity values (preferred pathways or fractures), and *not of the matrix* (or aquifer) as a whole for that section of the profile. Low conductivity values occur in the soil above the water table (obtained from the falling head tests), basically indicating no flow or very low flow zones in the upper soil. The relatively low conductivity value of the clay layer at 3m confirms the reason for ponding at this depth, as indicated by the tensiometers. The high flow zone at 7m has been confirmed during pumping tests when water could be heard and seen running into the borehole at a depth of 6-7m after the water table level was draw down below this level. The transmissivity value of the aquifer, as determined by the pumping tests at this site, ranges from 0.2 - 0.3 m^2/d, which relates to an average aquifer K-value of <1m/d (See Appendix D *Pumping tests,* to confirm these values).

Table 6-28: Conductivity values for different flow zones through the profile at KK4 (with the flux in m/d).

Depth (m)	K (m/d)	Flux q
1.3	0.06	0.005
2	0.58	0.002
2.5	22.57	0.056
3	4.76	0.012
5	57.44	0.144
7	111.12	0.278
10	29.17	0.073
15	35.20	0.088

6.6.4.3 Syferfontein:

The test was conducted from the water level at 3.36m to a depth of 20m. NaCl was added to increase the solution by roughly 250%. There was not much dilution over time, which indicates that the groundwater velocity was very low through the whole profile. It took more than 66 hours for the tracer to be diluted to its initial background concentration. There was also not much difference in concentration along the profile over time, which indicates that the groundwater flow velocity is more or less the same throughout the section (Figure 6-49). Because of the low velocity value, aggravated by the high solution concentration added, movement of the solution downwards due to density gradient was observed. To interpret the Darcy velocities, the movement of the tracer by density gradient had to be compensated for.

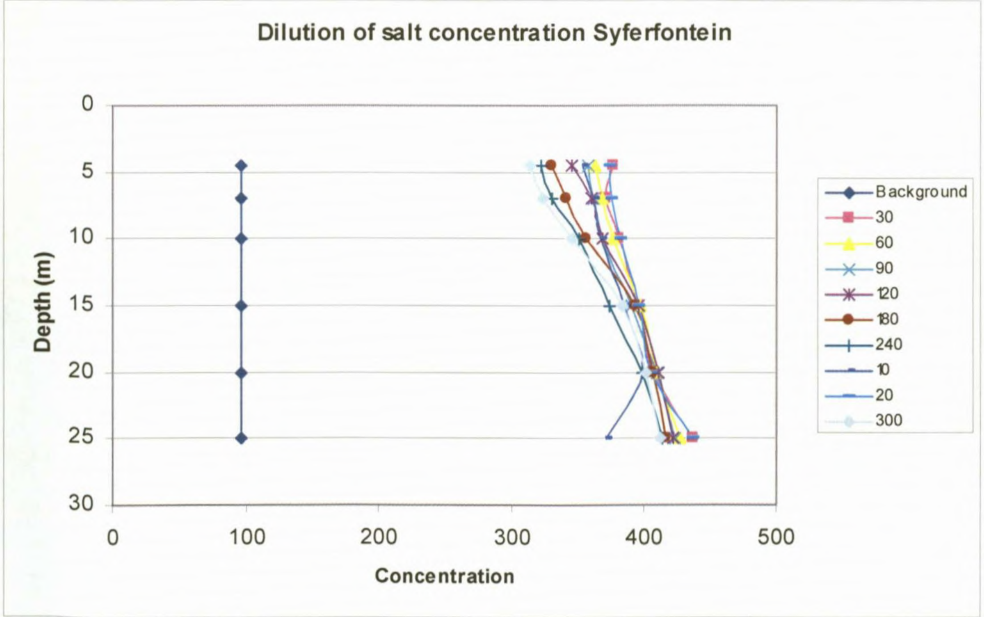


Figure 6-49: Graphs of the decrease in concentration over time at Syferfontein.

The groundwater flow velocity is fairly uniform throughout the borehole, except at 4.5m where there was an elevation in the conductivity value. This is not clearly illustrated in the graphs in

Figure 6-49, but is portrayed in the calculations (obtained from the point dilution test) in Table 6-29. Some of the water that moves down the upper soil profile will move lateral along this zone, but not as much as at the Kleinkopje sites.

Table 6-29: Conductivity values for different flow zones through the profile at Syferfontein (with the flux in m/d).

Depth (m)	K (m/d)	Flux q
1	0.086	0.0002
2.5	6.55	0.016
4.5	39.48	0.091
7	6.53	0.016
10	5.64	0.014
15	3.66	0.009
20	2.44	0.006
25	0.95	0.002

6.6.4.4 New Vaal:

There was not much difference in concentration along the profile over time, which indicates that the groundwater flow velocity is more or less the same throughout the profile in depth. Unfortunately the flux of the clayey layer between 2.4 m and 4m could not be determined with this test. (The water level is below the clayey layer and could thus not be determined with the point dilution test. The auger holes used for the falling head tests were not deep enough due to the sand caving in).

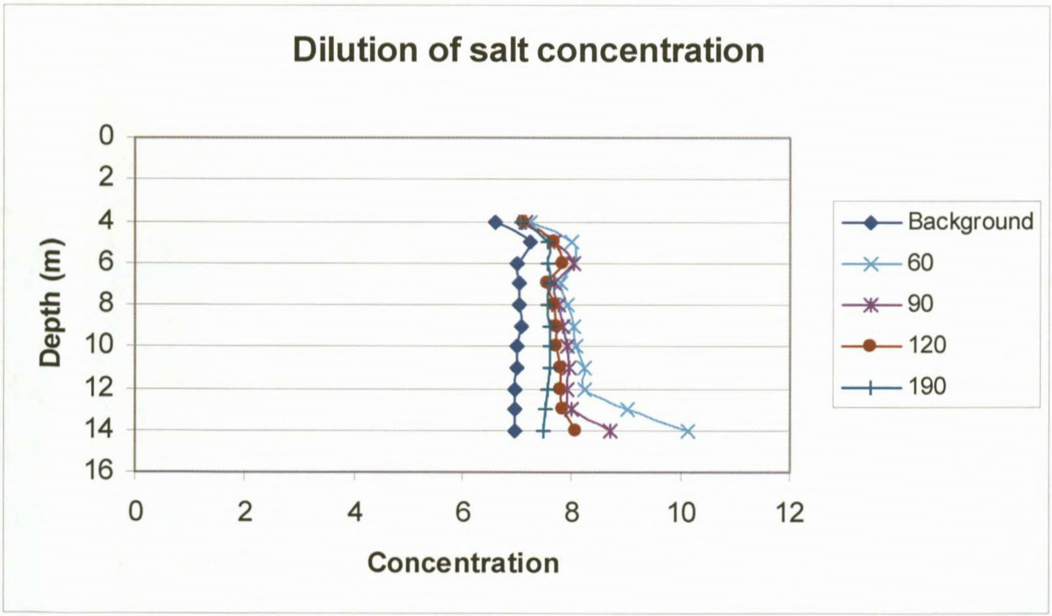


Figure 6-50: Graphs of the decrease in concentration over time at New Vaal.

However, the areas immediately above and below the clayey layer shows elevated hydraulic conductivity values (Table 6-30), indicating preferred flow zones, as observed while digging the inspection pits.

Table 6-30: Conductivity values for different flow zones through the profile at New Vaal.

Depth (m)	K (m/d)	Flux q
1	32	0.320
2.5	50	0.500
4	50	0.501
7	39	0.390
9	13	0.130
14	17	0.177

The lower conductivity values deeper down the profile is due to higher clay content in the soil deeper down (See Section 6.3.2).

These tests indicate lateral flow zones with higher conductivity (fractures or weathered zones), which will have an influence on the quality of water moving down towards the water level and from there into the aquifer. *To reach the water table, the water that moved past the root zone will follow different paths and flow mechanisms to reach it.*

6.6.5 *Determination of flow at the Irrigation site*

6.6.5.1 Introduction

If the flow through the unsaturated zone is bimodal (i.e. diffuse plus preferential flow), the chloride content in the soil water of the unsaturated zone will be different from the chloride content in the groundwater. If the chloride in the groundwater is less than the chloride in the soil water, preferential flow paths exist (Selaolo, 1998 and Gehrels, 1998). This is the case at all the researched irrigation sites. The chloride mass balance method is thus ideal to calculate the flows at these sites.

6.6.5.2 Chloride mass balance and moisture fluxes

The chloride mass balance method is one of the techniques that are often used to estimate moisture fluxes through the unsaturated zone, thereby enabling the assessment of recharge to groundwater basins. The chloride mass balance method has been used to evaluate recharge processes in a wide range of semi-arid environments (Eriksson and Khunakasem, 1969; Allison and Hughes, 1978; Edmunds and Walton, 1980 and Sharma and Hughes, 1985). Of the tracer techniques available, Cl balance techniques appear to be the simplest and least expensive method for recharge estimation (Allison *et al.*, 1994). No sophisticated instrumentation or dependence on the measuring of specific runoff events is required, and when used, groundwater estimates of the method is independent of whether recharge is focused or diffuse (Bazuhair and Wood, 1996). The method is useful because long-term average precipitation and chloride concentrations in rain and groundwater entail less uncertainty and are generally less expensive to acquire than physically based parameters commonly used in analysing recharge via water balance approaches.

Chloride is used for recharge estimation because of its conservative nature and the relative abundance in precipitation. The application is based on a comparison of the chloride deposition rate at the soil surface with the concentration in the soil water or groundwater. The Cl concentration increases relative to the concentration of rainwater as a result of interception, soil evaporation and/or root water uptake by the vegetation.

The theory is that solutes will be transported downwards through the unsaturated zone at rates that depend on precipitation amounts. Some of the solutes may be removed from the soil water by a variety of secondary processes, such as plant root uptake, mineral precipitation and adsorption. Conversely, some of the solutes may also be released by the decay of dead plant material, by mineral dissolution, or by desorption (Edmunds *et al.*, 1988). A prerequisite in the use of a chemical tracer is that only tracers that are not subject to chemical reactions, and for which there is no net release or storage from the soil matrix on their way down, are considered.

The chloride balance method, developed by Eriksson and Khunakasem (1969), compares total chloride deposition at the surface with the soil water concentration below the active root zone or the concentration in groundwater. Under diffusive or piston flow conditions, Cl increases in the root zone, until a constant value is reached below the root zone (Allison, 1988). Under steady-state conditions of piston flow, the flux of Cl at the surface is equal to the flux of Cl below the active root zone, and the conservation of mass leads to (Eriksson and Khunakasem, 1969):

$$P\,Cl_p = R\,Cl_{sw}$$

Where:

P = mean annual precipitation

R = recharge (mm/a), and

Cl_p = mean Cl concentrations (mmol/l) in precipitation

Cl_{sw} = mean Cl concentrations (mmol/l) in soil water

Sharma and Hughes (1985) provide a slightly more complex estimation of recharge. They introduce a **bimodal model** including a bypass flow component. If it is assumed that soilmoisture movement occurs through the soil matrix as well as through preferred pathways, then the total recharge can be evaluated as a two-component system. Soilmoisture transport in such a flow regime consists of a slow diffusive and quick preferential flow component. Preferential flow may well extend beyond the root zone. Bypass flow in the root zone may become more diffuse in the percolation zone, but it is also possible that it persists all the way down to the water table. If the profiling depth is limited to within the unsaturated zone, only the diffuse recharge component is estimated.

The basic assumptions of the method are that:

- There is no source of chloride, other than that from precipitation in the soil water or groundwater.
- The chloride ion behaves conservatively and is thus not adsorbed by nor is it leached from vegetation, unsaturated zone sediments and/or aquifer formations (Edmunds *et al.*, 1988).
- Diffuse and/or preferential flow often needs to be critically examined. Soil moisture and solutes may be transported through the unsaturated zone by preferred pathways (macro-pores).

Under preferential flow or bypass flow conditions some of the precipitation water (with relatively low chloride concentration) will flow directly along the preferred pathways to below the root zone. This bypass flow component, unaffected by evapotranspiration, dilutes the soil water that has been concentrated by transpiration, resulting in relatively low concentrations in the percolation zone with respect to the concentrations encountered in the root zone. Assuming conservation of mass in such a bimodal flow situation, total recharge (R_T) can be partitioned into two components as (Sharma and Hughes, 1985):

$$R_T = R_{sw} + R_{pp}$$

and

$$R_T{*}Cl_{gw} = \mathrm{R_{sw}.{*}Cl_{sw}} + R_{pp}{*}Cl_{pp}$$

where R_{sw} is recharge attributed to diffuse flow (mm/a); R_{pp}, is recharge attributed to preferential flow (mm/a), Cl_{gw}, Cl_{sw} and Cl_{pp} are the Cl concentrations in mmol/l of groundwater, soil water and bypass flow, respectively. Cl_{pp}, is assumed equal to the Cl concentration of precipitation. **When $\mathrm{Cl_{sw}}$ is close to $\mathrm{Cl_{gw}}$, the total recharge is approached by the diffuse recharge component. Conversely, when $\mathrm{Cl_{sw}}$ is higher than $\mathrm{Cl_{gw}}$ diffuse recharge is not the only recharge component and bypass flow occurs as well.**

If the chloride concentration of the preferential flow component (Cl_{pp}) is nearly identical to the chloride concentration of the precipitation, then enrichment of soil moisture solutes by plant uptake becomes negligible.

For these equations, it is assumed that the two flow components of water are thoroughly mixed upon groundwater recharge to the aquifer. Rapidly decreasing chloride concentrations below the root zone may be an indication of preferential flow. If the chloride concentrations become constant with depth, the moisture flux can then be calculated.

6.6.5.3 Bimodal Flow calculations for the irrigation sites

The chloride values at all the different irrigation sites showed a decrease in chloride values with depth, indicating bimodal flow (Sharma and Hughes, 1985). The values of the chloride with depth are illustrated in Table 6-31. These values were obtained from the porous cup data, the monitoring data as well as from Annandale et al, 2006. The values were averaged over time.

Table 6-31: Chloride values with depth at the irrigation sites (mg/L).

Site	**Weighted irrigation water Cl value**	**Cl value of groundwater outside irrigation area**	**1m depth Cl value**	**3m depth Cl value**	**Cl value at WL**
Kleinkopje 4	42	20	130	100	33
Kleinkopje1	13	20	48	42	23
Syferfontein	24	28	72	55	28
New Vaal	34	8	79	130	41

The calculations were derived according to chloride values at 1m (just below root zone), at the 3m level and at the water level (van Tonder, 2006). (These calculations are illustrated in the spreadsheet named "Irrigation flux" in Appendix D). This implies:

1. Diffusive flow (Q_v) at the root zone level. At this level there is an increase in chloride concentration due to evapotranspiration.
2. Bimodal (or bypass) flow, i.e. vertical as well as preferred pathway flow (Q_{Bp}) at 3m. This component portrays the pollution flux that reaches the water level. The chloride value has decreased from the value just below the root zone, and can only be attributed to dilution due to preferred flow, where water that is not evapotranspirated (water that moves directly through along pathways) mixes with diffusive flow water.
3. Lateral flow (Q_L) at water level. This indicates the groundwater component of water (lower Cl) that flows laterally which plays a role in the mixing fraction of the salts.

The calculations are as follows:

1.

$$Q_v = \frac{Cl_{irrig}}{Cl_{Rz}} * \frac{Rain + Irrigation}{365 days}$$

Where:

Cl_{irrig} = chloride value in the rain
Cl_{rz} = chloride value at 1m, just below the root zone
$Rain$ = total annual rain
$Irrigation$ = total annual irrigation

2.

$$Q_{Bp} = Cl_{3m} * [(Q_v - Cl_{rz}) * Q_v] / \frac{Cl_{irrig}}{Cl_{3m}}$$

Where:

Cl_{3m} = chloride value at 3m depth

3.

$$Q_L = \left[\left(\frac{Cl_{3m}}{Cl_{wl}}\right) * Q_1\right] + \left[\left(Cl_{3m} - Cl_{wl}\right) * Q_V\right] / \left(Cl_{wl} - Cl_{outside}\right)$$

Where:

Cl_{wl} = chloride value at water level
$Cl_{outside}$ = chloride value of aquifer outside the pivot area

From these formulas the vertical and the lateral flux components that contribute to the mixing values of the chloride could be calculated (Table 6-32).

Table 6-32: Percentage flux that contributes to the chloride mixing process to give groundwater Cl concentration.

Site	Q_v+Q_{Bp} (bypass)	Q_L (lateral)
Kleinkopje 4	16.3	83.8
Kleinkopje1	13.6	86.4
Syferfontein	1.8	98.2
New Vaal	27.3	72.7

These values have a major impact on the feasibility of irrigation on these sites at the short to medium term. The saline water that moves down through the soil profile contributes approximately 15% or less to the mixing process of the water. This causes dilution and explains the lower salinity qualities measured down the soil profile (as samples with depth in the porous cups). The low value obtained at Syferfontein (1.8) may be due to the fact that irrigation ceased at this site for nearly two years and that the system has not reached steady state, with the lateral component contributing a lot more than should be the case if irrigation continued.

The actual fluxes ($m^3/d/m^2$) for the three components Q_v, Q_{Bp} and Q_L calculated are as follows (Table 6-33):

Table 6-33: Actual fluxes ($m^3/d/m^2$) at the irrigation sites.

Site	Qv (m3/d/m2 =K diffusive)	Q_{Bp} (K bypass)	Q_L
Kleinkopje 4	7.23E-04	2.80E-04	5.17E-03
Kleinkopje1	3.34E-04	5.77E-05	2.48E-03
Syferfontein	7.58E-04	3.07E-04	5.75E-02
New Vaal	9.65E-04	0.00E+00	2.57E-03

(**Note:** The values in both Table 6-32 and Table 6-33 are not fixed values, but should be seen as ranges of what the different fluxes will be - the calculations are sensitive to various parameters).

- The bypass component of the flux (Q_{Bp}) at Syferfontein is larger than at the other sites (Table 6-33). The reason for this is that the clay normally cracks very quickly near the surface during the drying out process by the sun and wind, resulting in large cracks, which serve as conduits for water. During thunderstorms, most of the water infiltrates quickly before the cracks close up because of swelling. This has been observed during leaching experiments in the laboratory, and on numerous occasions in the field. At Syferfontein, the Arcadia clays are not very deep (0.2m -1.0m) and cracks will extend into the weathered (clayey) dolerite and shale below.

From these fluxes the % flux moving down into the groundwater in relation to the water applied to the pivot sites, as well as the actual volume of water that reaches the groundwater, were calculated as illustrated in Table 6-34.

- Also portrayed in the table is the K-value derived from these fluxes ($Q_V + Q_{Bp}$) at each of the sites.
- The value for Kleinkopje 1 is small in comparison with the other sites (9%). This is due to the fact that water is lost due to drainage down the borehole into the mine.

Table 6-34: % Flux that reaches groundwater.

Site	% Flux of total water apllied that moves down to WL	K-value	Total water that reaches WL (m^3/ha/d)
Kleinkopje 4	24.07	0.001004	10.0
Kleinkopje1	9.39	0.000391	3.9
Syferfontein	25.55	0.001066	10.7
New Vaal	24.47	0.000965	9.7

The salinity increase in the monitoring boreholes does not always reflect the downward movement of the water. This strengthens the belief that most of the monitoring boreholes are constructed incorrectly. The boreholes known to be constructed correctly (PV1BH2 at Kleinkopje 1, PV4BH2 at Kleinkopje 4 and OBD6D at Syferfontein) show an increase in salt concentration as portrayed by the downward fluxes, whilst the other boreholes e.g. PV1BH7 at Kleinkopje 1, PV4BH6 at Kleinkopje 4 and OBH5 at Syferfontein show unrealistically low values of salts in the aquifer (see

Table 6-35) and is graphically illustrated in Figure 6-51. The borehole at Syferfontein situated outside the pivot, but next to the dyke (OBH2) running through the pivot, shows elevated values, which implies that some of the water drains along the dyke. At New Vaal, the high flux value is due to the sandy nature of the soil. Monitoring (see Section 6.2.2.1) indicates an increase in sulphate in the Borehole PV5 in the middle of the site. ***It is thus very important to know what is being measured at a monitoring site.***

Table 6-35: Sulphate values at irrigation sites (values are tabled downwards in time from the start of irrigation until 2006).

	Kleinkopje 1		**Kleinkopje 4**		**Syferfontein**		
Time	PV1BH7	PV1BH2	PV4BH6	PV4BH2	OBH6D	OBH5	OBH2
1	3	3	5	10	126	40	133
2	2	6	1	7	116	50	131
3	3	12	5	2	126	46	138
4	4	18	1	3	131	39	166
5	2	26	1	115	177	39	139
6	3	53	1	55			
7	1	89	1	203			
8	0	135	5	240			
9	0	197					
10	2	275					

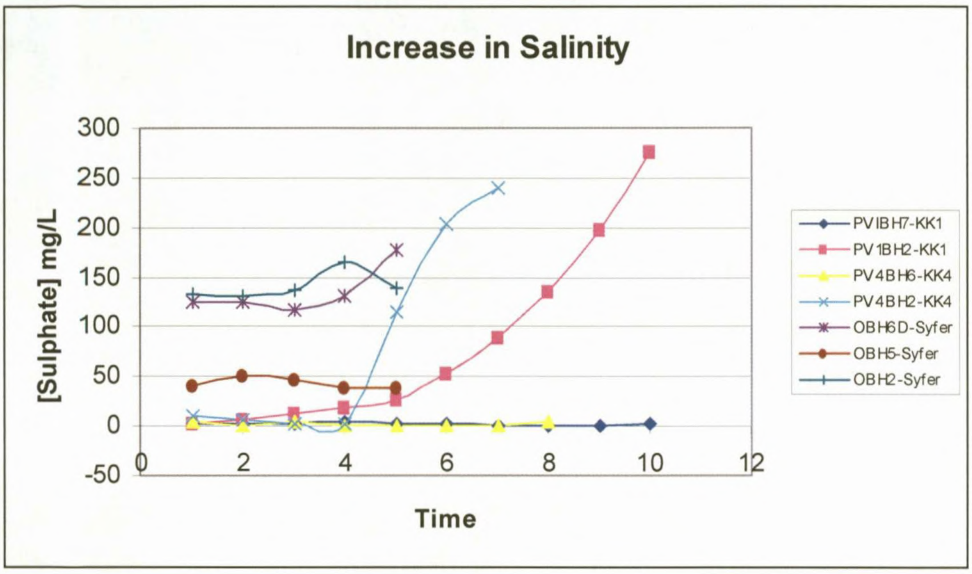


Figure 6-51: Increase in sulphate concentration in well-constructed boreholes.

6.6.6 *The influence of clay in the unsaturated profile on the soil water that reaches the water level*

A very important aspect of the research at the irrigation sites is to determine the influence of the clay on the downward movement of the soil water, and what the unsaturated hydrulic conductivity and saturated hydrulic conductivity values will be.

The relation of the unsaturated K and moisture can be derived from the well-known equation of Van Genuchten and can be illustrated in a very simple form (Botha, 1996) as (also see Section 4.1.2 on Unsaturated flow):

$$K(\theta) = Ks(\frac{\theta - \theta_r}{\theta_s + \theta_r})^{5/2}$$

Where:

θ_r = residual moisture content

θ_s = saturated moisture content

$K(\theta)$ = unsaturated K

Ks = saturated K

To help geohydrologists obtain an estimated unsaturated K-value that will be applicable to the deeper layers below the root zone, a spreadsheet was set up to calculate the unsaturated K-value according to the equation above. To determine the $K(\theta)$ (unsaturated-K) value for a specific moisture content (θ) derived from a tensiometer reading at an irrigation site (See Section 6.6.1), the following is thus needed (see spreadsheet "Unsaturated K" in Appendix D):

1. Residual moisture content
2. Saturated moisture content
3. Saturated K- value

The unsaturated K-value at the irrigation sites will differ from that under normal field conditions in the sense that the soil will always have a higher moisture content, resulting in swelling of clays (if present), thus decreasing the flux, and subsequently the unsaturated K-value.

1. It was decided to use the θ_{-1500} regression equation (thus at 15 bar matric pressure) from Hutson (1983) as a default value to determine the residual moisture content, as suggested by Van Genuchten (1980).

According to the regression equations derived by Hutson (1983) in relation to the soil texture (sand, silt and clay content) this can be calculated from:

$$\theta_{-1500} = 0.0602 + 0.0032Cl + 0.0031Si - 0.026D_b$$

2. The saturated volumetric content of the soil can be derived from the bulk density of the soils, using the formulae (Hensley, 2006):

$$\theta_s = 1 - (D_b/2.65)$$

(Where 2.65 is the average density of soil minerals).

3. Saturated K:

To determine the Ks for different clay percentages at the irrigation sites, the diffusive flux obtained from the calculations for each site in Section 6.6.5.3 and illustrated in Table

6-33was plotted against the clay content at each site (Figure 6-52). From this a relationship with a correlation of 74% was obtained:

$$y = 0.00008\, x + 0.000971$$

Where:

x is the clay content and **y** is the diffusive flux (saturated K-value).

These K-values are very low (10^{-4} m/d) and indicate that vertical movement in the moist irrigation soils is very slow. This equation was calculated for and will be valid for average clay contents up to 40%, but with individual layers up to 65%.

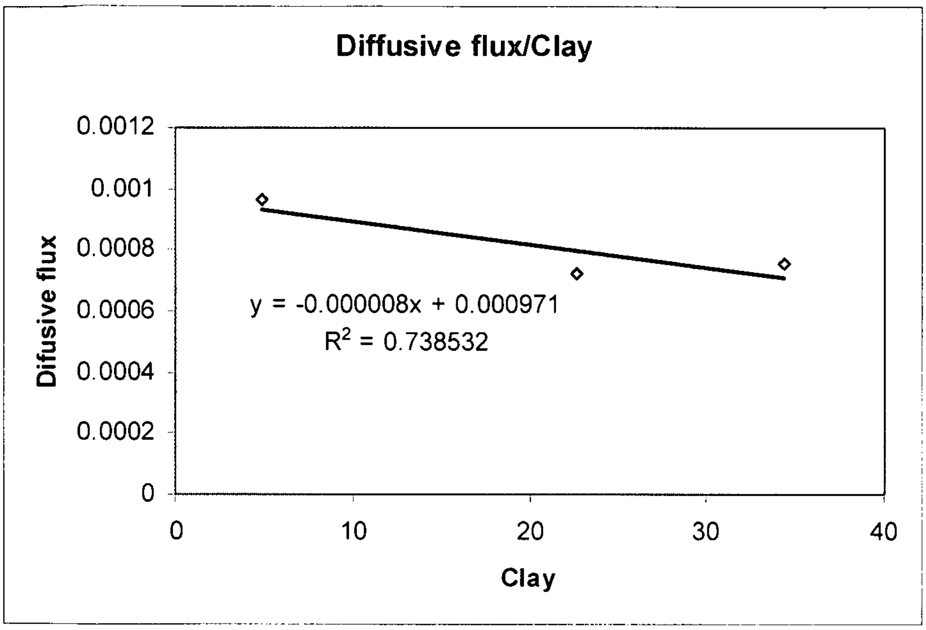


Figure 6-52: Clay percentages against the diffusive flux.

- Work by Campbell (1985) revealed an equation where clay and silt fractions were used to calculate the saturated-K. The equation reads:
  - $Ks = 2*10^{-3}e^{-4.26\,(ms+mc)}$

(Where m_s is the silt content and m_c the clay content in fractions).

- This equation was further developed by van Tonder *et al.* (2002) for borehole protection zones in the Bainsvlei area outside Bloemfontein and reads as follows:

$$Ks = 30*Exp(-0.3*Clay)$$

This formula is suited to normal field conditions where the soil does not have a high moisture content, and the prediction of saturated K-values will be too high for irrigation soils where the high moisture content will cause swelling of the clays, thus reducing the flux.

These three equations were used in calculating the unsaturated K for different clay values and for a silt value of 20%, which is a representative value for the soils at the irrigation sites, and is illustrated in Table 6-36. From this it is clear that the values obtained by van Tonder *et al.* (2002) for the Bainsvlei soils are high for soils with low clay content, whilst for high clay content the results are low in comparison with the other two methods. The values calculated from the irrigation sites and those calculated by Campbell are very similar, as can also be seen from Figure 6-53.

Table 6-36: Ks and unsaturated K-values for different clay values (silt = 20%).

	Ks			**Unsat K**		
Clay %	Bainsvlei - van Tonder	Irrigation - Vermeulen	Campbell	Bainsvlei - van Tonder	Irrigation - Vermeulen	Campbell
10	1.49E+00	8.91E-04	5.57E-04	3.87E-01	2.31E-04	1.45E-04
20	7.44E-02	8.11E-04	3.64E-04	1.17E-02	1.28E-04	5.73E-05
30	3.70E-03	7.31E-04	2.38E-04	3.41E-04	6.73E-05	2.19E-05
40	1.84E-04	6.51E-04	1.55E-04	9.37E-06	3.31E-05	7.89E-06
50	9.18E-06	5.71E-04	1.01E-04	2.36E-07	1.47E-05	2.61E-06
60	4.57E-07	4.91E-04	6.62E-05	5.17E-09	5.56E-06	7.49E-07

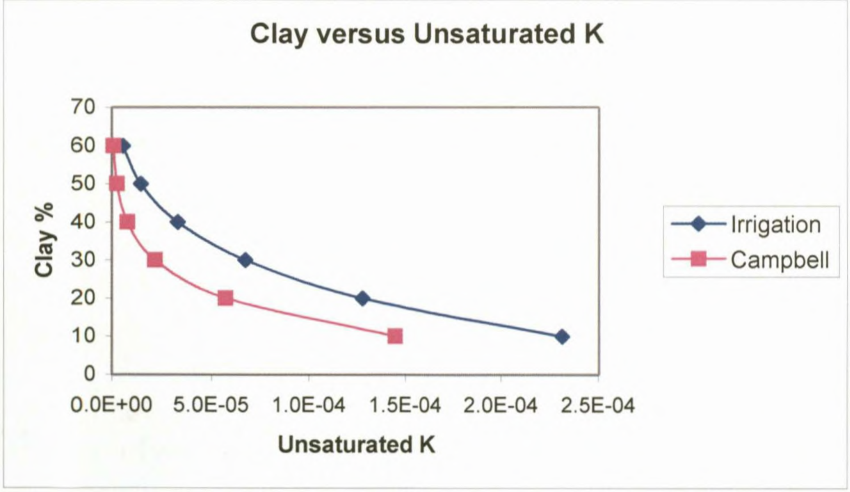


Figure 6-53: Graph of clay percentage versus unsaturated K.

- Another equation by Naney, which is based on the bulk density value of the strata (Naney *et al.*, 1983) to determine the saturated K-value is:

$$Ks = 110.16*D_b^{-22.2} \text{ m/d}$$

(This equation is also included in the spreadsheet "Unsaturated K" in Appendix D).

6.7 Conclusion

Geochemical modeling has indicated that the soil water in the top one meter is saturated with gypsum, and precipitation should occur. In the deeper moist layers the water is still undersaturated with regard to gypsum. The salt balance calculations revealed that 80% of the sulphate applied during irrigation since 1999 (2001 at other sites) has been retained in the soil profile (also as gypsum), most of it in the upper two meters. 80% of this retained sulphate is in the soil water. After irrigation ceases, it will take more than 15 year to leach the sulphate from the soil profile under optimal conditions. Due to bimodal flow and low recharge it can be more than 100 years.

The chloride values at all the different irrigation sites showed a decrease in chloride values with depth, implicating bimodal flow. Twenty five percent of the total volume of water applied through irrigation reaches the water level. There is a direct correlation between clay content of the soil and the diffusive component of the bimodal flow. Due to the moist conditions at irrigation sites, swelling of the clay results in a very low vertical conductivity value of 10^{-4} m/d. This correlates well with the findings of Campbell (1985).

Due to lateral flow in the weathered saprolite zone, dilution occurs (lateral flow contributes approximately 85% towards the dilution process). Water will move along the weathered zone, and part of the salinity will move deeper down into the fractured aquifer, some will daylight or seep into adjacent strata. This means that the release of salinity into the groundwater is a very slow process, which makes irrigation a viable option over the short to medium term.

It is very important to construct the boreholes at irrigation sites correctly. Otherwise a false picture of what really happens regarding the increase in salinity in the underlying aquifer emerges.

7 IRRIGATION AT OPENCAST COLLIERIES (SPOILS)

7.1 Scenarios considered for spoils irrigation

The range of potential interactions in spoils is highly variable; the fact that the on-site observations will not provide a complete picture, several methods can be carried out by applying a series of laboratory investigations was undertaken, including the following:

- Leaching columns of spoil material (spoils is waste material from the mine and can be potentially acid generating and non-acid generating)
- Humidity cells of spoil material (*potentially acid-generating and non-acid generating scenarios were run)*
- Columns within the spoils

The different scenarios considered by these tests therefore included:

- Irrigation with high quality water
- Irrigation with mine water
- Irrigation with re-circulated mine water
- Inundation of spoils through over-irrigation or irrigation where water could not drain away.

In addition to these alternatives, geochemical modelling was used to illustrate factors of fundamental importance.

7.2 Laboratory testing of spoils irrigation

7.2.1 *Humidity cells*

Humidity cell tests are performed to evaluate the long-term acid-producing potential of mine waste rock, tailings or residual ore. The test simulates the accelerated weathering of the sample by passing moist air through the sample chamber, followed by dry air; moist air is used for three days, followed by dry air for three days, and distilled water on the seventh day. The leachate is analysed for pH, conductivity, sulphate, acidity and dissolved alkalinity. This one-week cycle is typically run for 20 weeks. Samples are usually selected to represent the various lithologies at the mine, along with a range of ABA and/or NP/AP values. Therefore, humidity cell results can be used to identify or confirm the AMD risk associated with a range of ABA values.

7.2.1.1 Methodology

A degree of standardisation has been attempted in the USA, with the adoption of the ASTM standard methodology. In Designation: D5744-96 Standard Test Method for Accelerated Weathering of Solid Materials using a Modified Humidity Cell (ASTM, 1996), a cell 203mm (8.0 in.) in height by 102 mm (4.0 in.) diameter is specified for material crushed to 100% passing 6.3 mm (crushed core or waste rock and coarse tailings).

In a typical test, a seven-day cycle is employed: three days of dry air, three days of humid air, followed by leaching on the seventh day. The next cycle is started on the 8th day of the test by carrying out the humidity cell tests as long as possible (as discussed in detail in Chapter 5). It is normal for data to be quite erratic over the first few cycles, before consistent results are obtained. This is due to the removal of readily soluble components from prior oxidation and weathering. It is not unusual for humidity cell tests to continue for several months, or even more than one or two years (Lawrence and Day, 1997).

The different weekly methodologies were as follows:

- Cells 1 and 4 were leached each week by the addition of mine water (first order analogue to irrigation)
- Cells 2 and 5 were leached each week by the leachate from the columns themselves, made up to 500 ml by mine water (to illustrate the effect of recirculation)
- Cells 3 and 6 were leached each week by the addition of deionised water (Response of spoils under natural conditions, which forms the baseline for comparison)
- An additional two cells were filled with water and sealed off to similute flooded opencast pit conditions.

7.2.1.2 Results

The key objectives of laboratory kinetic tests are (a) long-term stable reaction rates under kinetic conditions and (b) depletion times for acid-generating, acid-neutralising, and metal-leaching minerals. Test interpretations therefore focus on calculating these values. Recommended equations by Morin and Hutt (1997) are listed in Appendix D.

7.2.1.2.1 Acid-generating spoils

The humidity cells were run for the standard ASTM 20-week period to determine reaction rates and sequences in the potentially acid-generating spoils (obtained from Middelburg Mines). Duplicate cells for the scenarios of clean water addition, mine water irrigation, recycling and flooding were run.

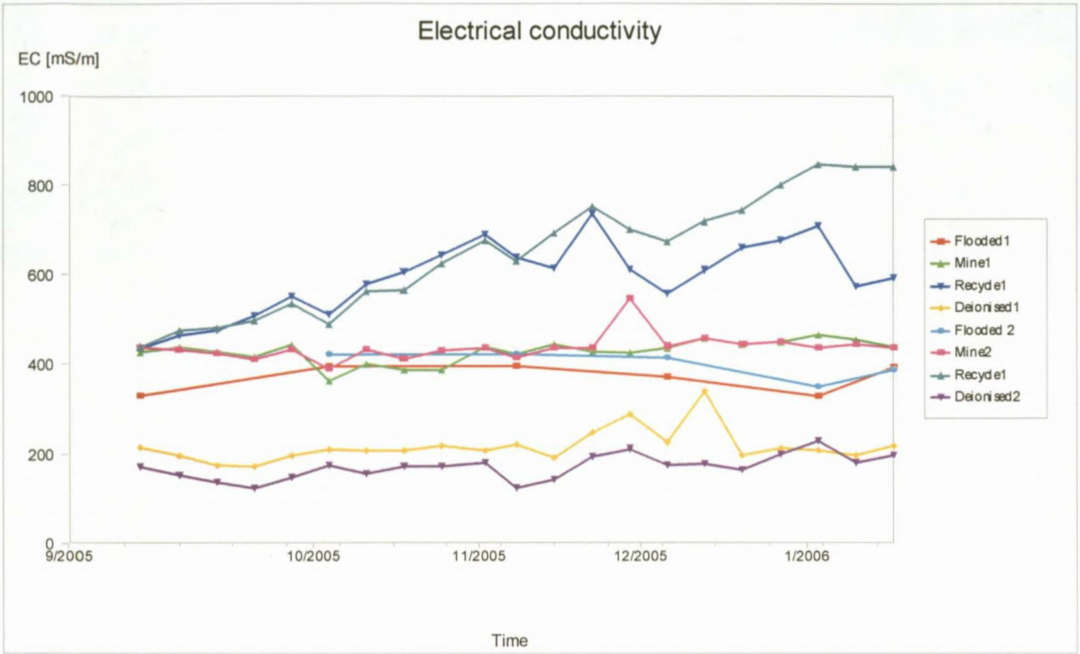


Figure 7-1: EC of all cells over the testing period.

Figure 7-1 shows that the EC changes over time. The differences observed are very important, as they show the impact on concentrations of leachate under different regimes, and illustrate that the inundation would result in a stable chemistry. Clean water irrigation will give the lowest concentrations, mine water irrigation will give relatively stable values, and recycling causes the progressive degradation of water quality to very high salt loads, while the flooded values show a constant concentration.

Figure 7-2 shows the pH changes over time. The progressive acidification in all the cells except the flooded ones is important in terms of expected long-term behaviour.

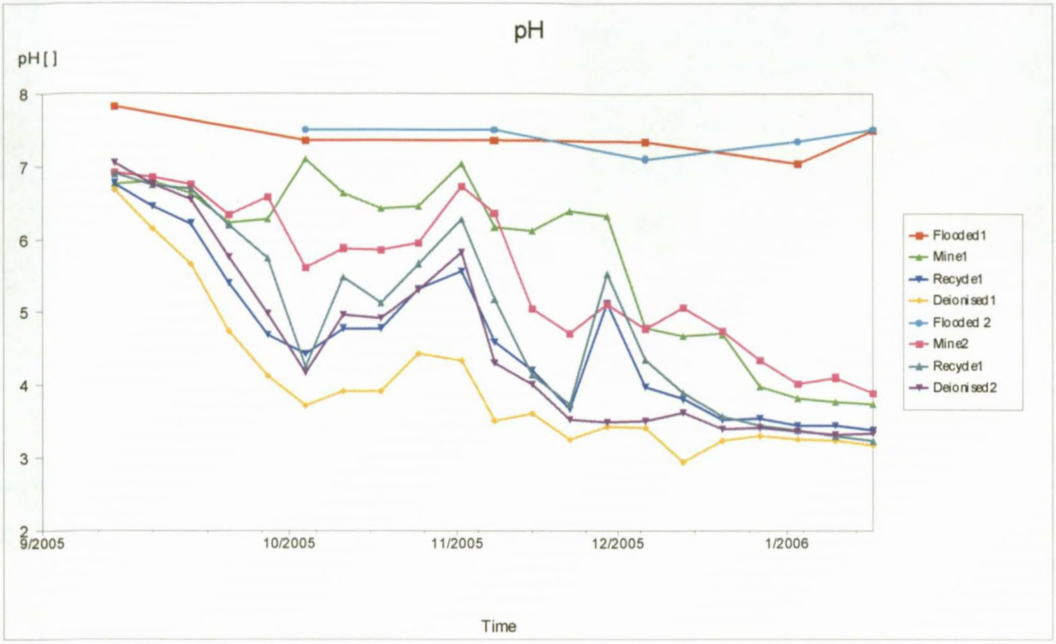


Figure 7-2: pH of all cells over the testing period.

The pH and EC response of each scenario is given by Figure 7-3 to Figure 7-6.

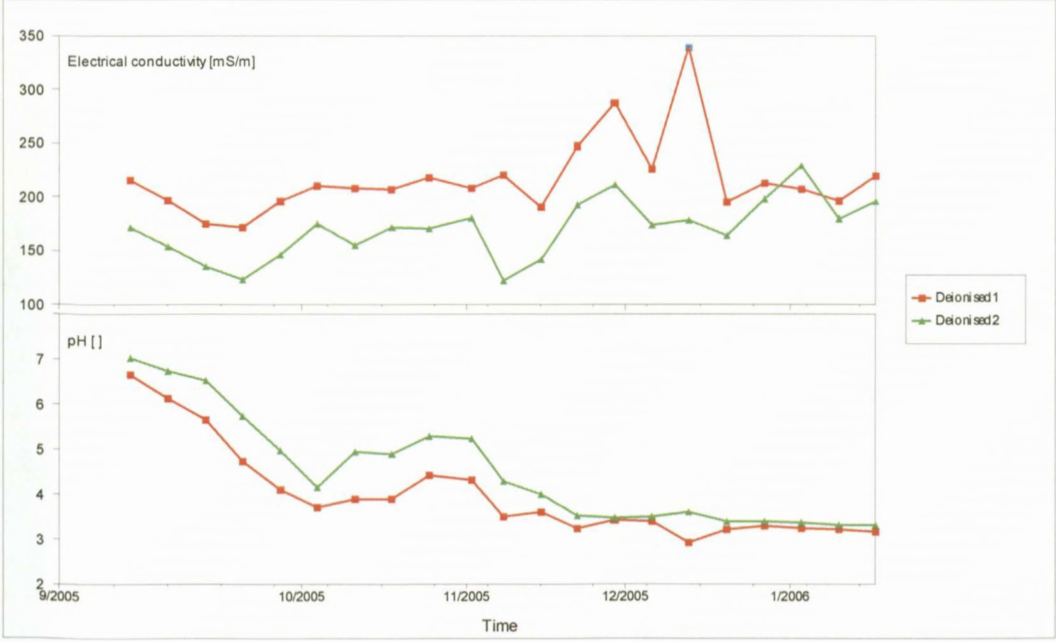


Figure 7-3: EC and pH of spoil humidity cell over time (deionised water addition).

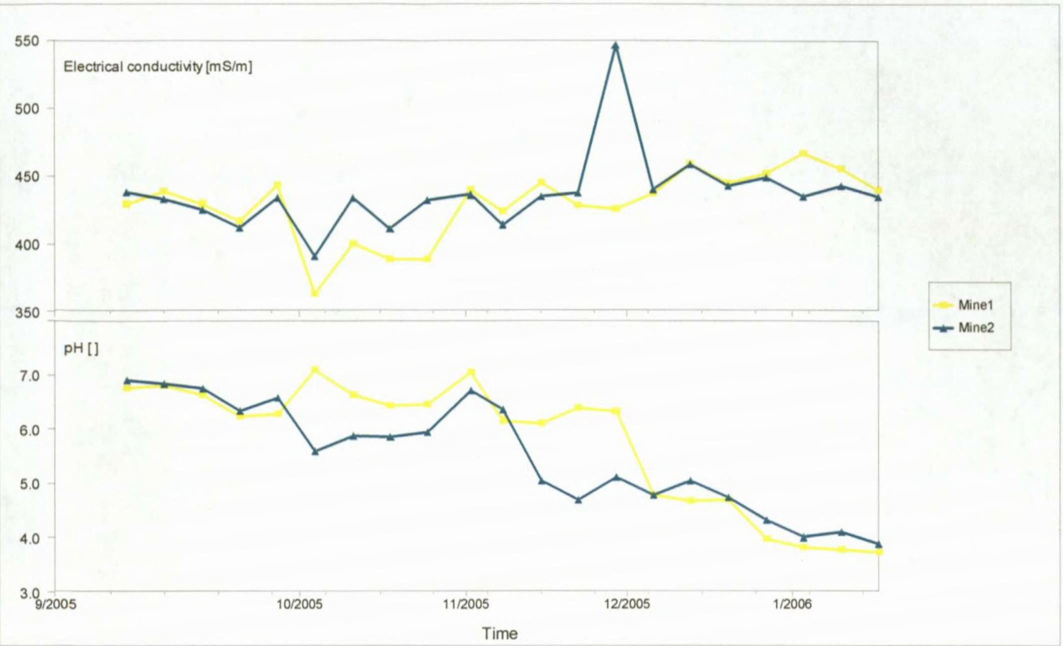


Figure 7-4: EC and pH of spoil humidity cell over time (mine water addition).

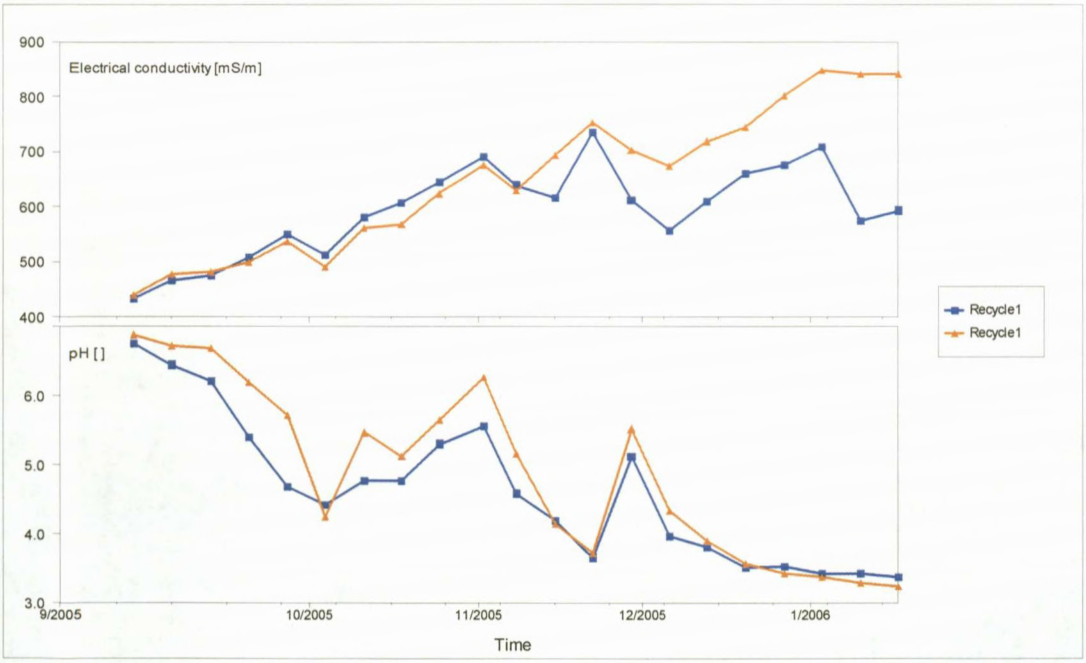


Figure 7-5: EC and pH of spoil humidity cell over time (recycled water addition).

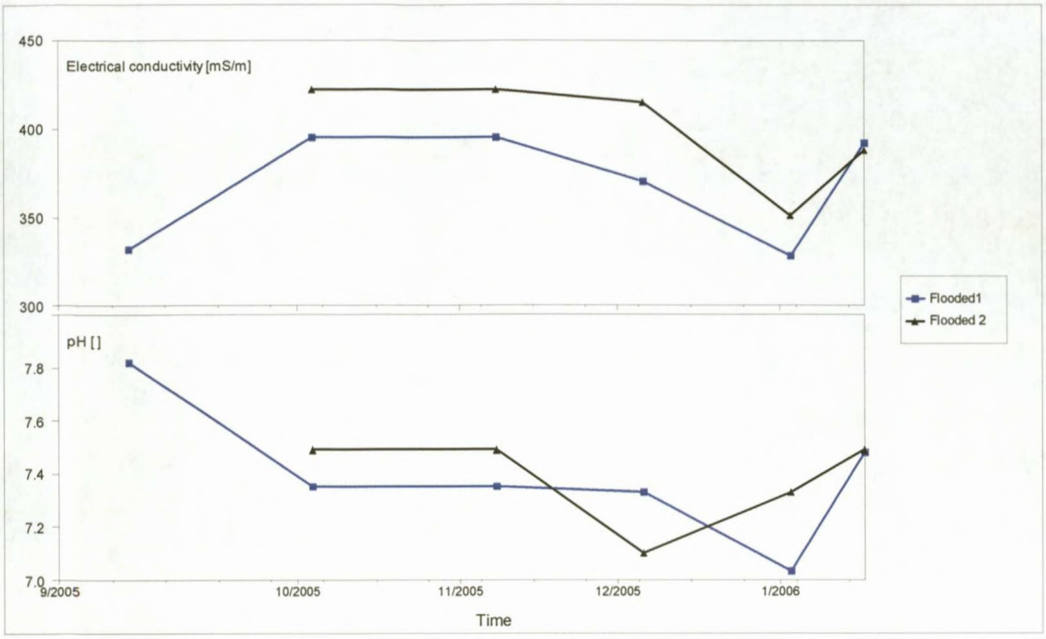


Figure 7-6: EC and pH of spoil humidity cell over time (cell flooded)

The sulphate response is of even greater interest and shows that, when the recycled water contains significant ions other than Ca and SO_4, the sulphate can increase to very high values over time. The other ions increase the ionic strength, thereby resulting in the activity coefficients decreasing so that the equilibrium point for gypsum saturation becomes very high (see also Figure 7-12).

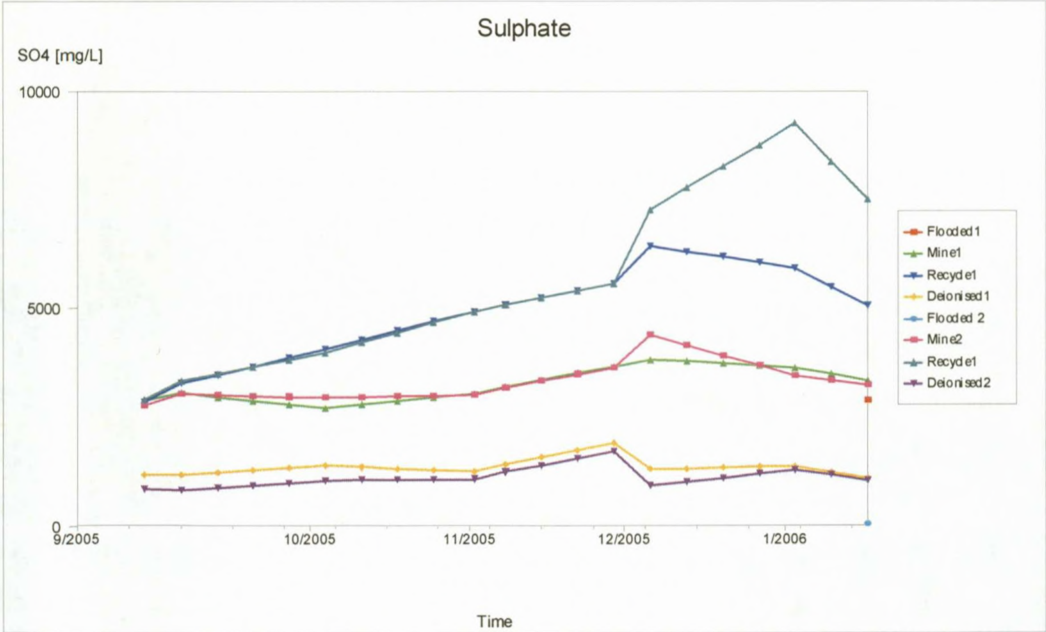


Figure 7-7: SO_4 of all cells over the testing period.

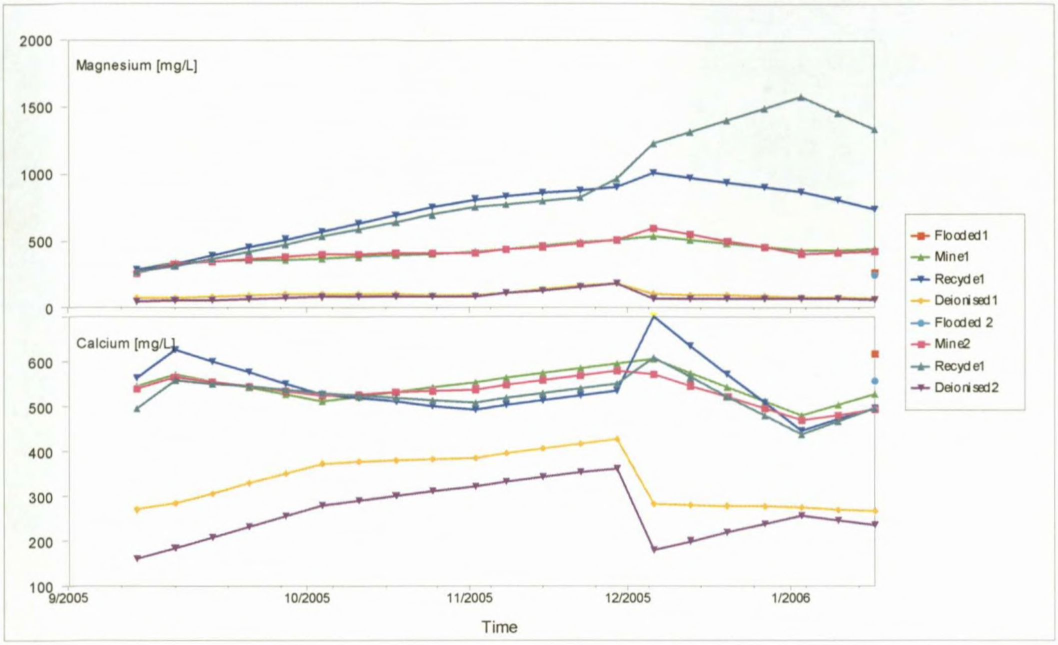


Figure 7-8: Ca and Mg over the testing period

As acidification occurs, the alkalinity of the waters decreases, as expected (Figure 7-9).

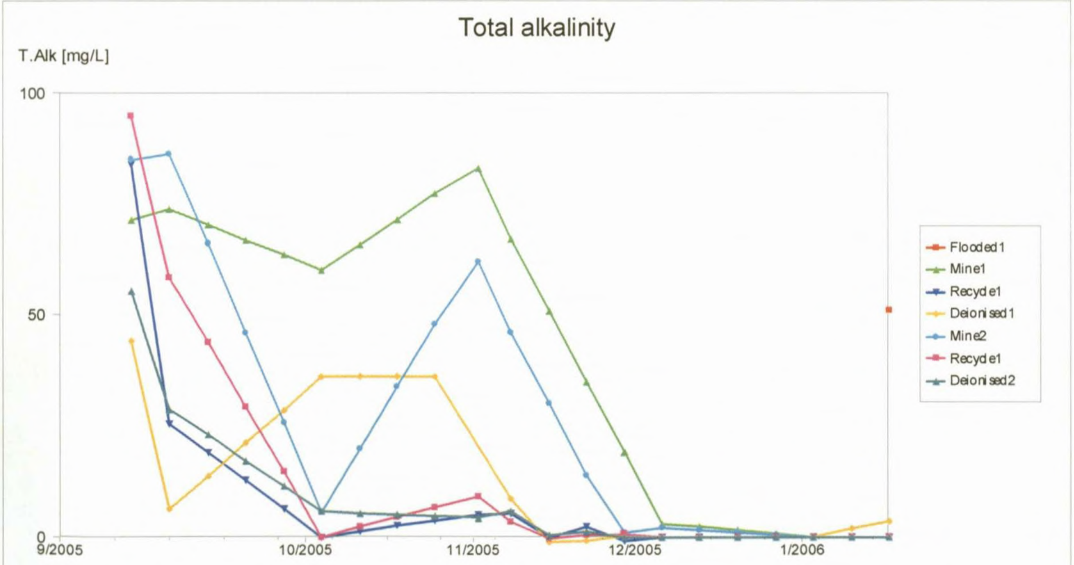


Figure 7-9: Alkalinity decrease as acidification occurs.

The pH-drop is expected to correlate with the consumption of the available neutralising potential. This is shown on Figure 7-10. It is also clear from Figure 7-11 that the available sulphide outlasts the available NP by far, and if these cells are a good analogue for field conditions, long-term acidification can be expected. It must be noted that the standard equations for determining depletions are not valid where the effluent is mine water or recycled leachate, and that the reported values are approximations based on well-constrained assumptions.

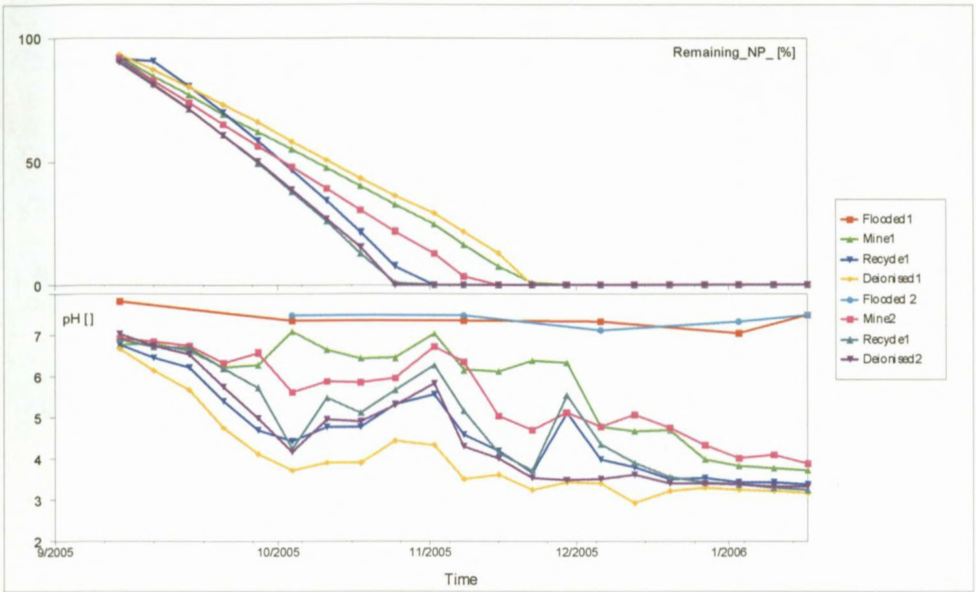


Figure 7-10: Depletion of NP and pH over time.

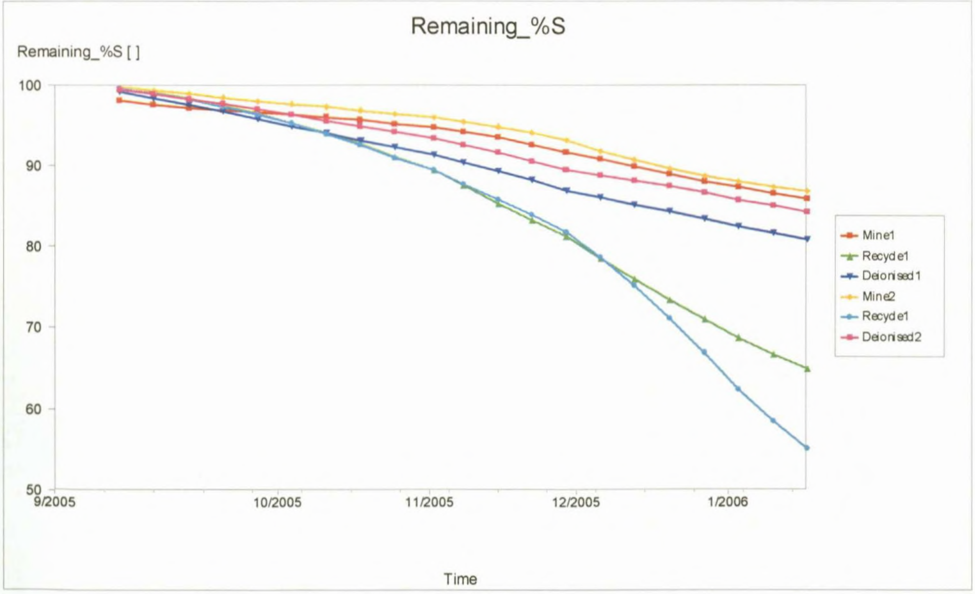


Figure 7-11: Depletion of NP vs. %S remaining.

The saturation indices for different parameters were determined by PHREEQC. It is clear that the upper sulphate and calcium concentrations are limited by gypsum saturation. This is also clear in considering the calcium and magnesium values given in Figure 7-8. It is clear that, in the recycled cell, the Mg keeps increasing, but Ca remains relatively constant due to gypsum saturation.

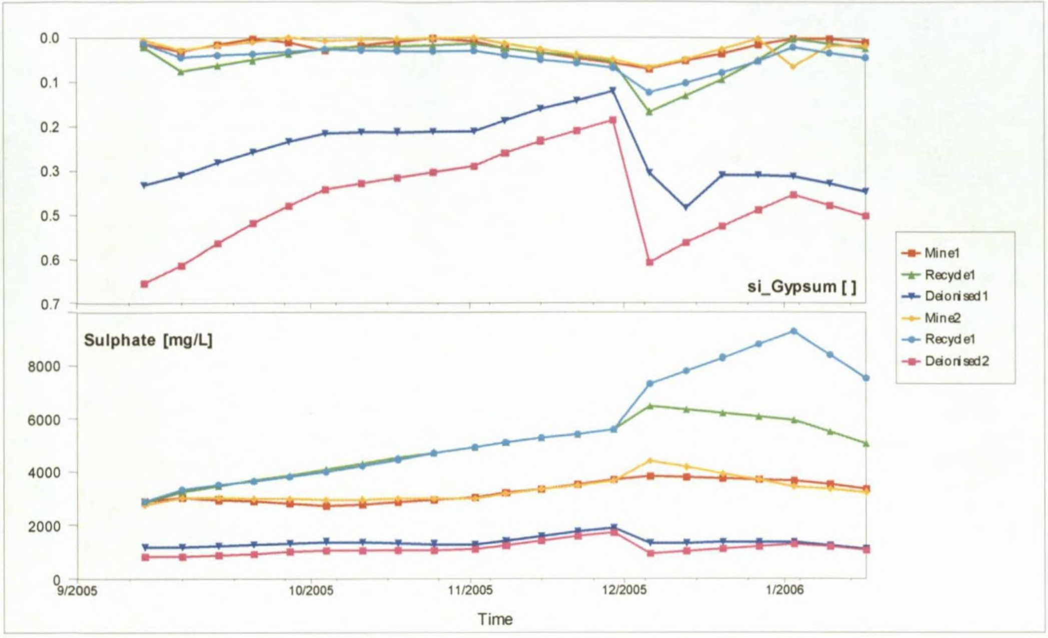


Figure 7-12: Sulphate vs. saturation of gypsum.

The calcite saturation in Figure 7-13 and Figure 7-14 as a function of the pH shows that the calcite is rapidly and consistently below saturation. As the pH drops, calcite becomes insufficient to buffer the generated acidity and remains undersaturated as the pH drops.

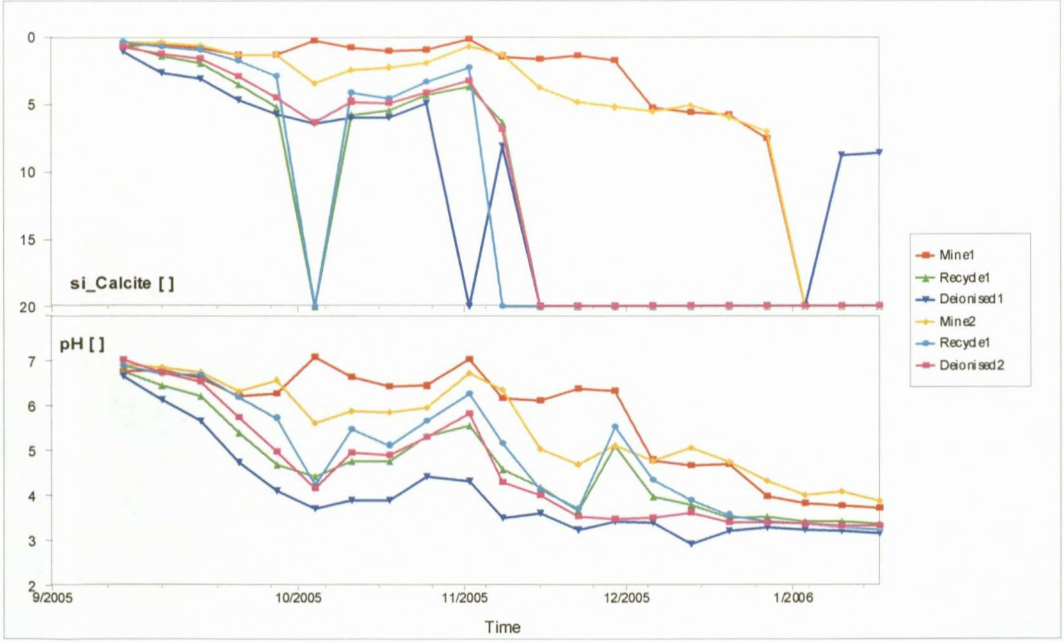


Figure 7-13: Decrease in calcite saturation vs. pH.

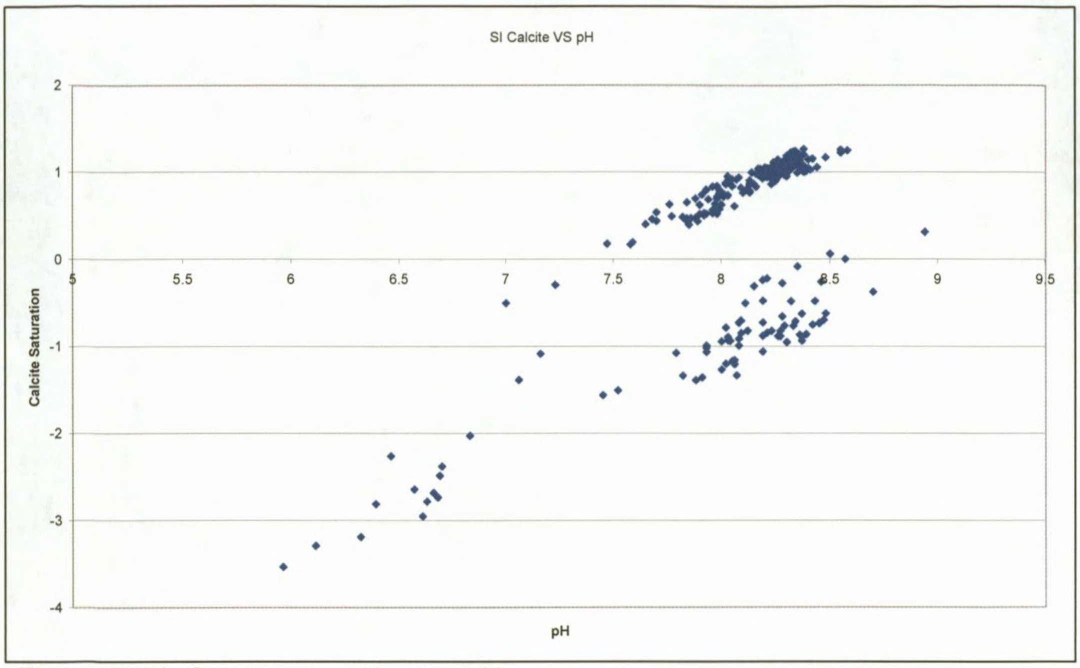


Figure 7-14: Calcite saturation vs. pH.

7.2.1.2.2 Non-acid-generating spoils

The humidity cells were intially run for the standard ASTM 20-week period to determine reaction rates and sequences in the potentially non-acid-generating spoils (obtained from Optimus Pit). After consideration, the test period was extended for an additional six weeks to investigate the possibility of significant changes. Duplicate humidity cells were also run for the scenarios of clean water addition, mine water irrigation, recycling and flooding.

Figure 7-15 shows the EC changes over time. The observed differences were compared to acid-generating spoils, as they show the impact of the different regimes more clearly and illustrate that inundation would result in a stable chemistry. Clean water irrigation give very low concentrations, while mine water irrigation will again give relatively stable values, and recycling causes an even more marked degradation of water quality, which would result in extremely high values compared to clean water irrigation.

Figure 7-16 shows the pH changes over time. The stable pH, showing increases over time after which it stabilises, is in stark contrast with the potentially acid-generating spoil cells.

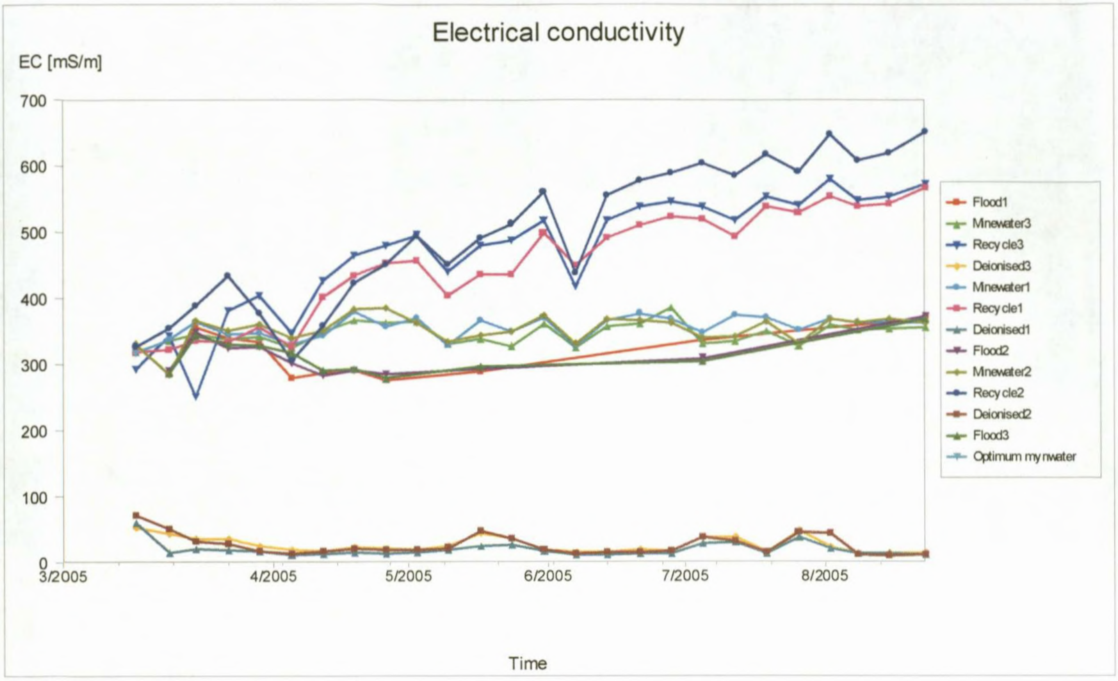


Figure 7-15: EC of non-acidic cells over time.

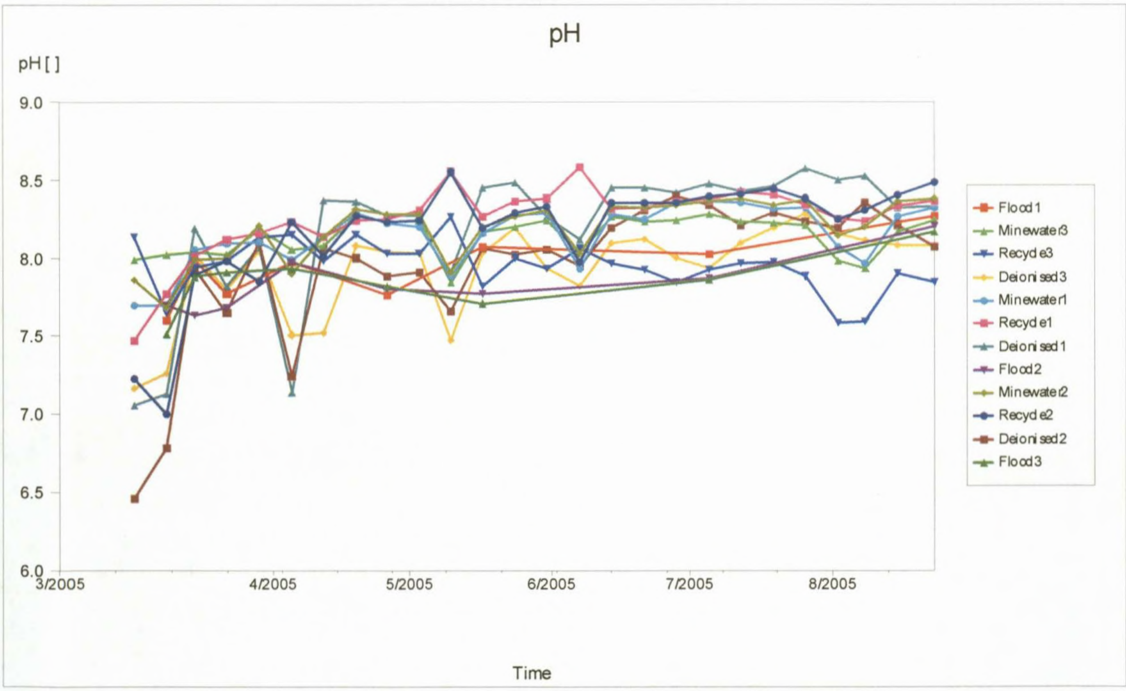


Figure 7-16: pH of non-acidic cells over time

The pH and EC responses of each scenario are given by Figure 7-17 to Figure 7-21.

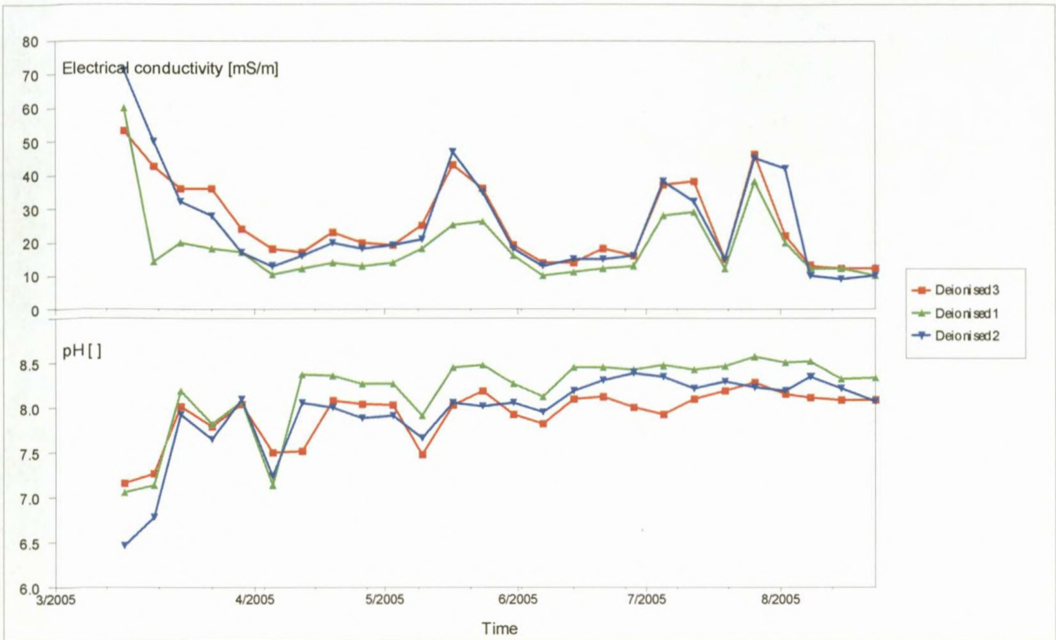


Figure 7-17: EC and pH of spoils humidity cell over time (deionised water addition).

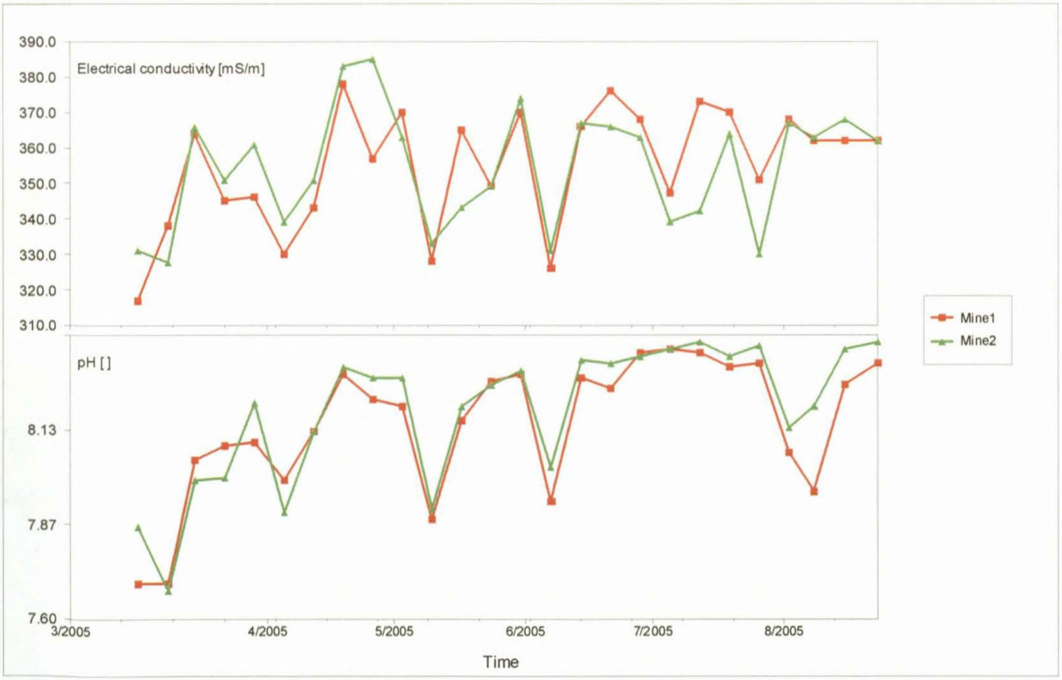


Figure 7-18: EC and pH of spoils humidity cell over time (mine water addition).

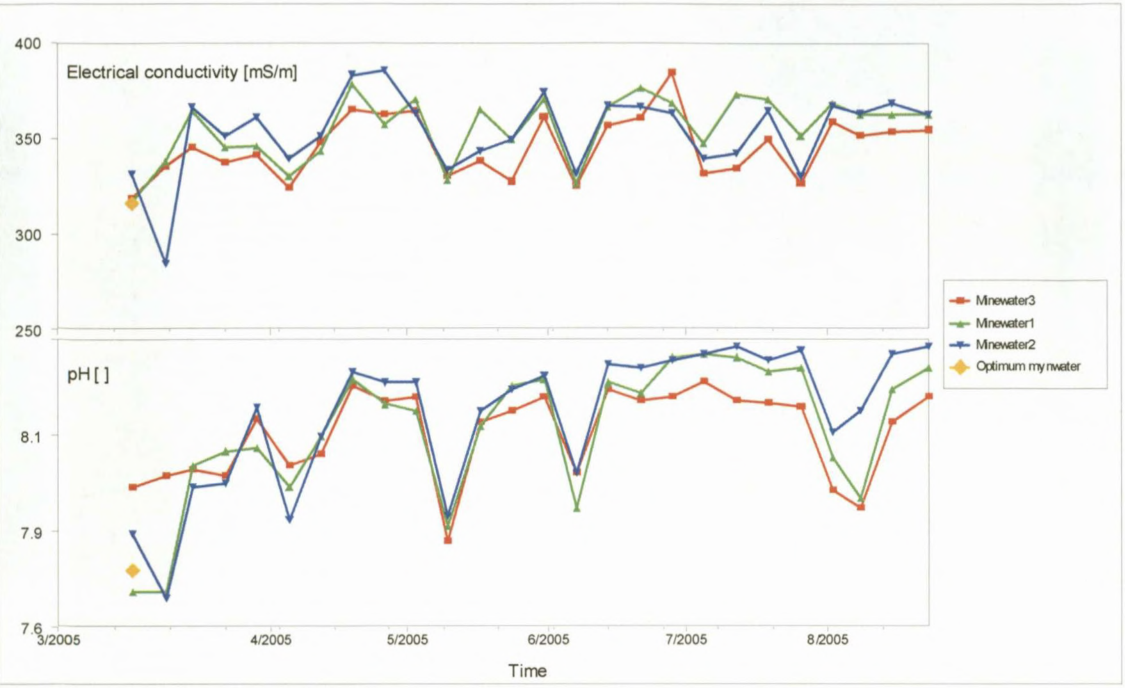


Figure 7-19: EC and pH of spoils humidity cell over time (mine water addition).

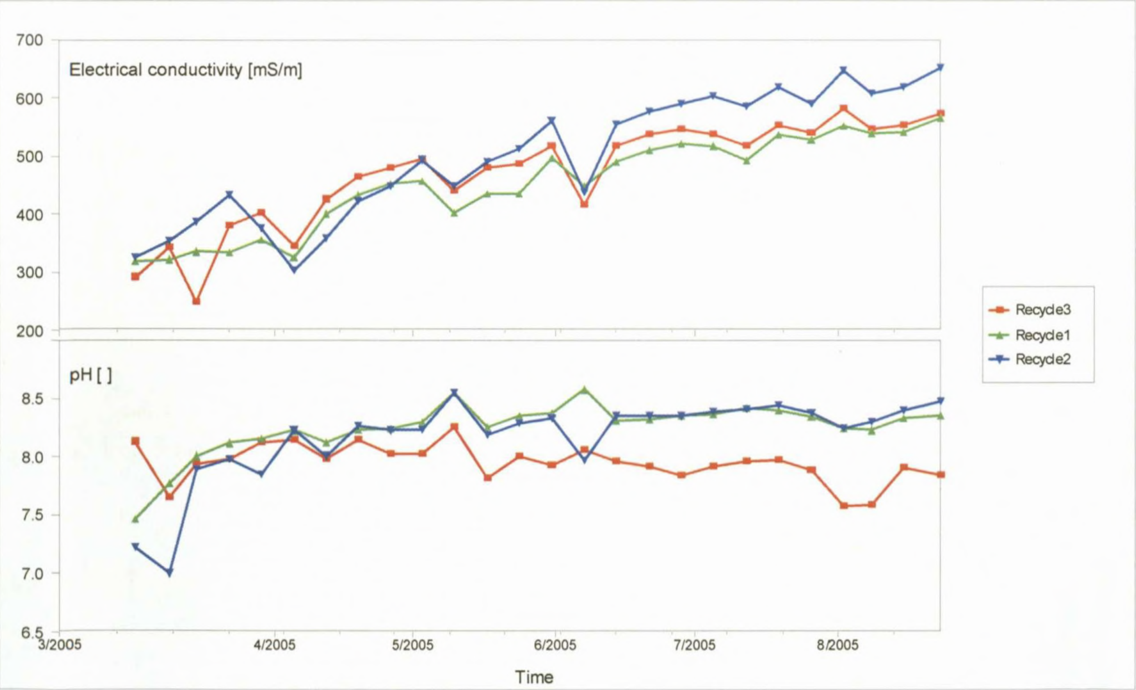


Figure 7-20: EC and pH of spoils humidity cell over time (recycled water addition).

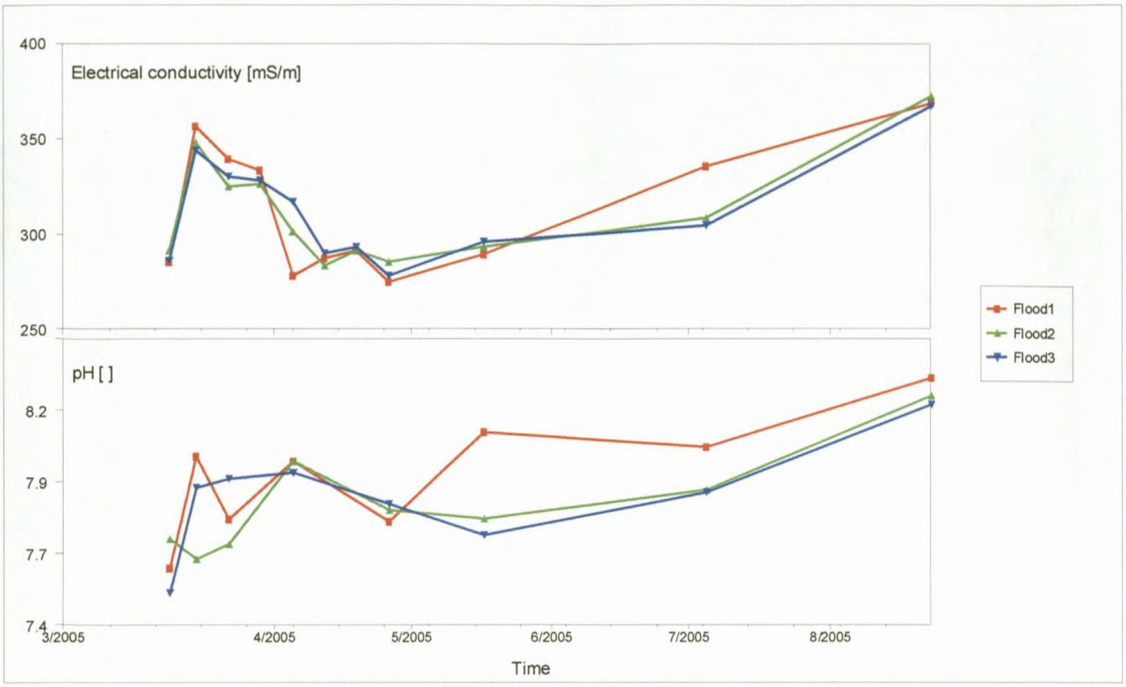


Figure 7-21: EC and pH of spoils humidity cell over time (cells flooded).

From closer scrutiny of the different scenarios it is clear that, where the spoils are non-acid generating, irrigation with mine water causes a severe deterioration in quality, compared to clean water irrigation. Recycling the water results in a ten-fold increase of acid generation over clean water irrigation, as opposed to a factor of three to four for the acid-generating spoils.

The sulphate concentrations for the different scenarios are shown on Figure 7-22. The sharp contrast between the eventual sulphate in these cells and the acid-generating cells is worth highlighting. The flooded cells and mine water cells have similar values, showing that, where the spoils do not generate significant sulphate, no other ions are released, and if throughflow rates are sufficiently high, the effect of secondary minerals is such that sulphate values will be in almost the same order as the input quality. The upper limits for each value are two to three times less than for the acid cells.

The calcium and magnesium values show the stabilising effect of gypsum solubility on calcium and the steady increase in magnesium. The values recorded for recycling, for example, are two to three times lower than for the acid-generating cells.

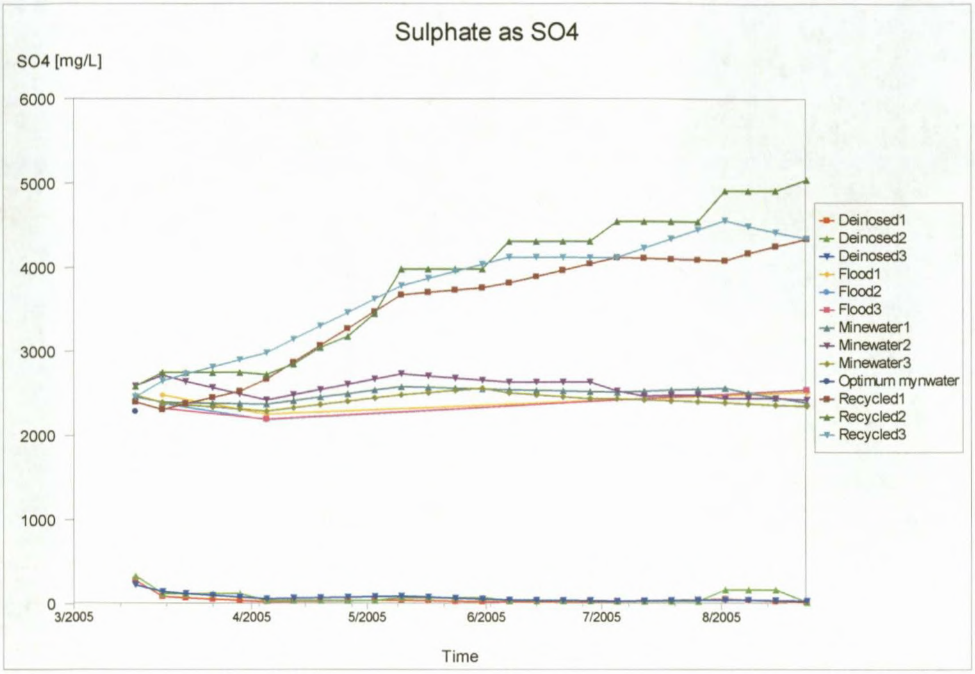


Figure 7-22: Sulphate concentrations for the non-acid-generating spoils humidity cells.

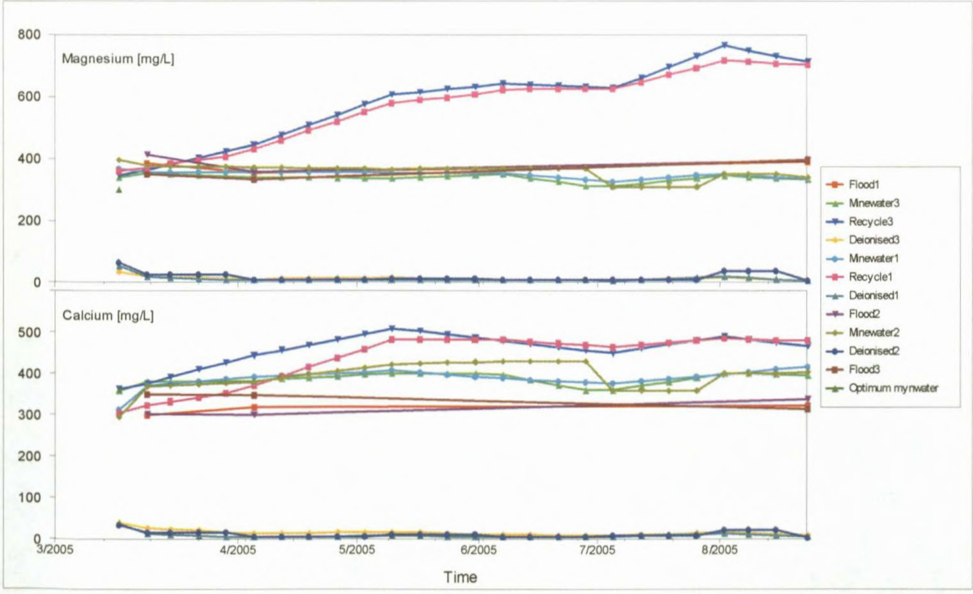


Figure 7-23: Ca and Mg values for non-acid cells.

The depletion of the neutralising potential in these cells is far lower, as expected, with almost none of the available NP depleted during the period of testing (Figure 7-24). It is important to note that the depletion occurs over the extended 26-week period rather than the standard 20-week ASTM testing period.

The increase in pH over the testing period supports this, and indicates the importance of placing spoils irrigation only on non-acid-generating spoils.

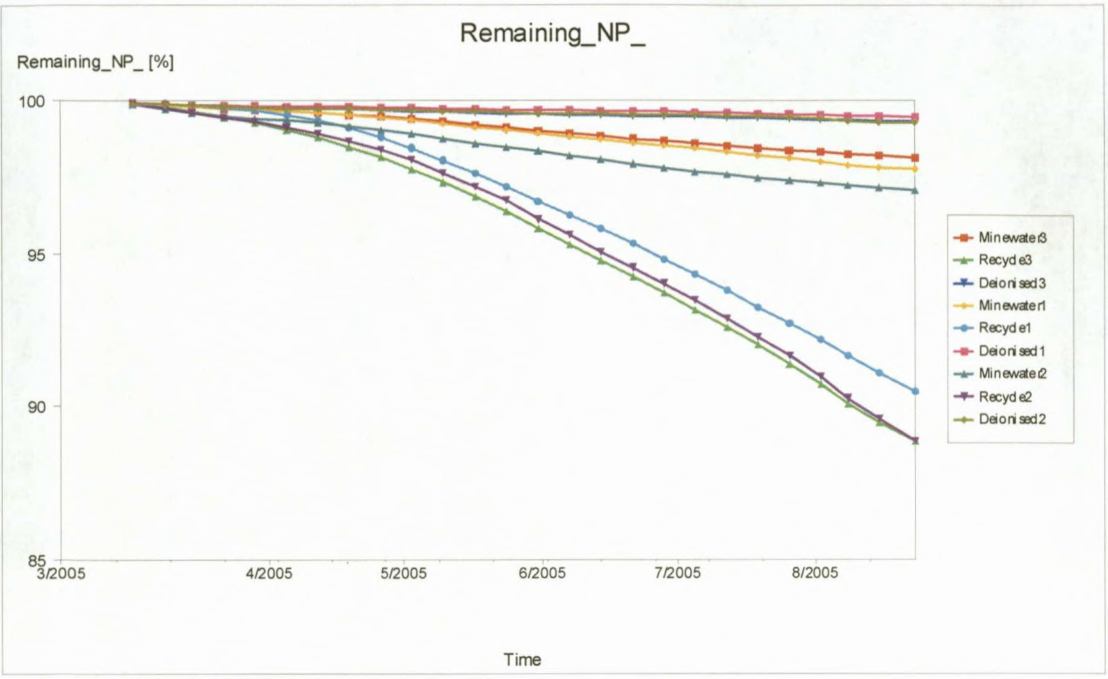


Figure 7-24: NP depletion in non-acid-generating spoils over time.

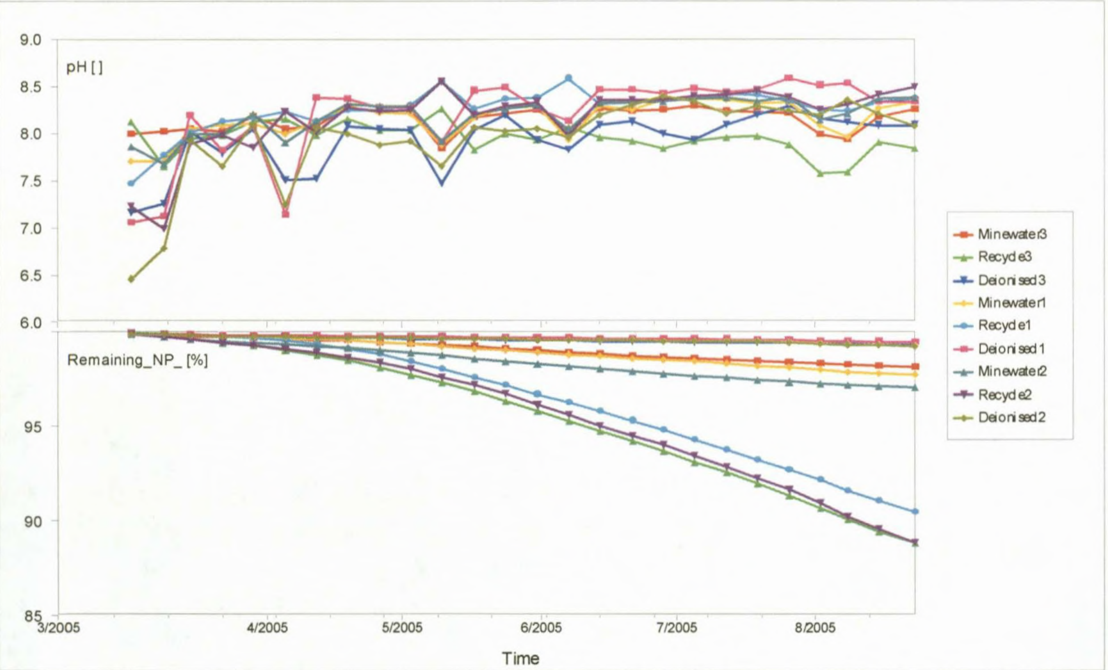


Figure 7-25: pH and NP depletion.

The saturation state of these waters was determined using PHREEQC. This shows that, over the testing period, the gypsum saturation maintains sulphate and calcium concentrations at relatively low values compared to the acidic cells. It is important to note that the mine water is gypsum-saturated, as the spoils are initially. This is maintained with all mine water (Figure 7-26).

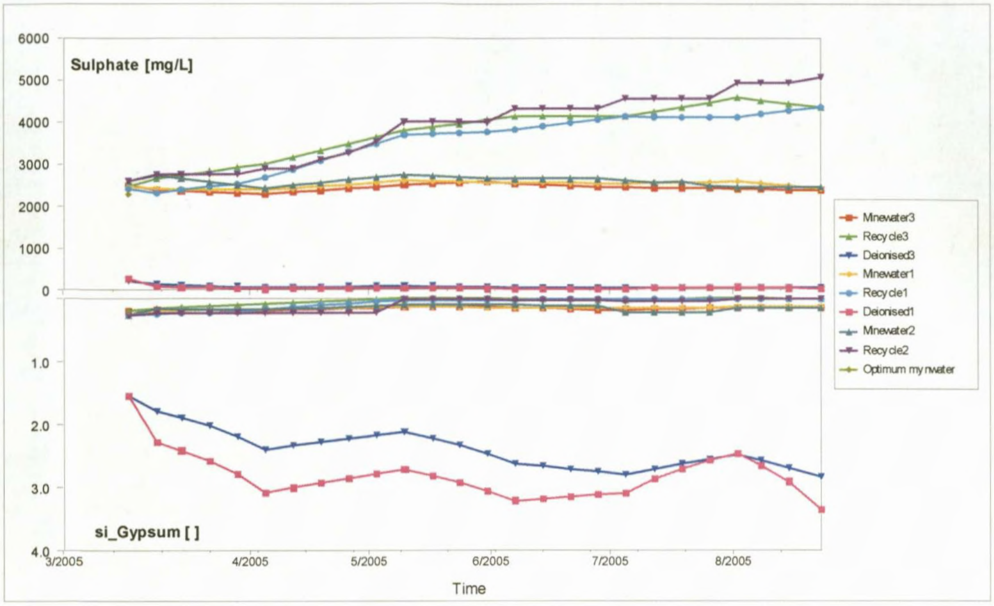


Figure 7-26: Sulphate concentrations and gypsum saturation over time

The saturation of carbonates shows that, in contrast to the acidic cells, calcite and dolomite are at or above saturation throughout the reactions (Figure 7-27). The fact that these values remain at or above equilibrium shows that the system is not under stress from an acidification perspective, even for the extended testing period.

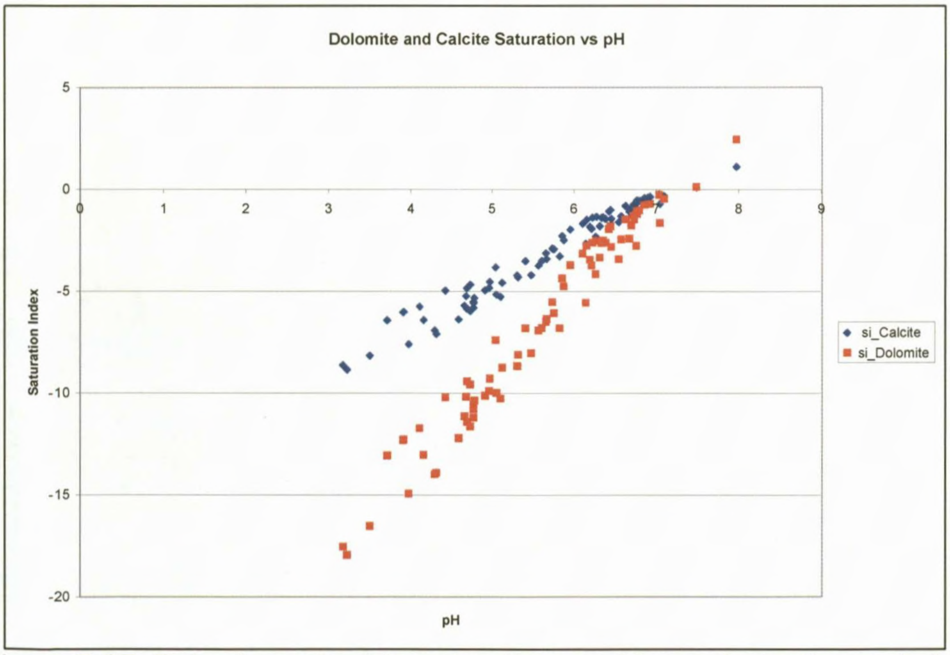


Figure 7-27: Dolomite and calcite saturation vs. pH over the testing period.

7.2.2 *Leaching columns*

7.2.2.1 Methodology

Three duplicate sets of 2 m columns with a diameter of 160 mm were packed with raw spoils obtained directly from the mines. After thorough mixing, equivalent amounts of spoils were sequentially loaded into each column by hand.

The columns were loaded until each contained 50 kg of material. Initially the cells were leached with 5 litres of water to completely inundate the column and leach out the accumulated oxidation products.

The different weekly methodologies were as follows:

- Columns 1 and 4 were leached by the addition of 1 litre of mine water each week.
- Columns 2 and 5 were leached by the the leachate from that column, made up to 1 litre by mine water each week.
- Columns 3 and 6 were leached by the addition of 1 litre of deionised water each week.

The EC and pH of each column were measured weekly with full analyses of the leachate in each column every four weeks.

It is very important to note that the water to spoils ratio in the columns is far lower than in the humidity cells. The reaction progress is therefore much slower and the secondary mineral influence becomes more pronounced (Morin and Hutt, 2001). These columns are, however, a better real-time analogue to the field, since the water:spoils ratio and rates of water addition were adapted to mimic field conditions.

7.2.2.2 Results

7.2.2.2.1 Initial data (Potentially non-acidic spoils)

Acid-base accounting was performed on the spoils obtained from the Optimum site to obtain an indication of the acid-generating potential of the spoils. Results are given in the Table 7-1 below:

Table 7-1: ABA results from spoil columns.

Initial pH	Final pH	Acid Potential (Open)	NP	NNP (Open)
		kg/t $CaCO_3$	kg/t $CaCO_3$	kg/t $CaCO_3$
7.66	3.50	1.84	10.49	8.65
7.33	2.76	3.51	4.76	1.26
7.56	3.41	13.09	14.43	1.34
7.67	4.14	4.86	16.41	11.56

From the results, it is clear that, under open conditions such as those in the laboratory, the spoils would be expected to have some potential to acidify, but this potential is relatively low. Furthermore, according to accepted criteria of ABA interpretation, the spoils fall into the uncertain zone, where ABA alone cannot give a high-confidence assessment of the acid generation from the spoils. The result is that the initial leachate has very high concentrations of different ions, particularly sulphate and the associated Ca and Mg from buffering by calcite and dolomite.

Initial leachate results are given in Table 7-2.

Table 7-2: Initial leachate results from columns.

No.	Date	pH	EC	Ca	Mg	Na	K	MAlk	Cl	SO4
WEEK1										
LC1	**29-Mar-05**	7.24	657	560	1237	104	55.8	464	238	5581
LC2	**29-Mar-05**	7.46	588	551	1249	91	51.2	296	232	5632
LC3	**29-Mar-05**	7.83	505	486	1078	80	42.1	278	55.4	5227
LC4	**29-Mar-05**	7.21	664	557	1291	89	49.8	329	237	5678
LC5	**29-Mar-05**	7.76	660	662	1238	87	54.7	214	247	5856
LC6	**29-Mar-05**	7.28	659	576	1329	81	48.7	322	208	5740

The mine water used to "irrigate" the spoils was obtained from the Lapa Dam at Optimum, with the quality indicated by the table below:

pH	EC	Ca	Mg	Na	K	MAlk	F	Cl	SO4
7.97	298	426.8	327.5	121.2	26.3	231	0.64	25.7	2373

7.2.2.2.2 Results

The EC and sulphate variations over time revealed a very interesting phenomenon, namely that, where clean water irrigation is employed, the values decrease over time. The reason for this lies in the fact that the spoils were oxidised prior to the experiment. Since they represent the results of the *in-situ* spoils at Optimum, it can be expected that oxidation occurred over time in these spoils and the secondary products from oxidation reactions and the subsequent neutralisation would be contained in the spoils.

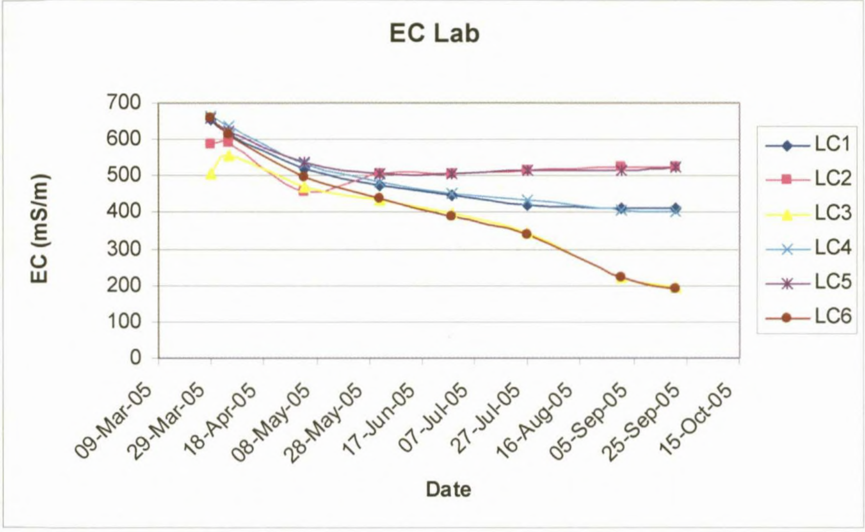


Figure 7-28: EC variations in columns over time.

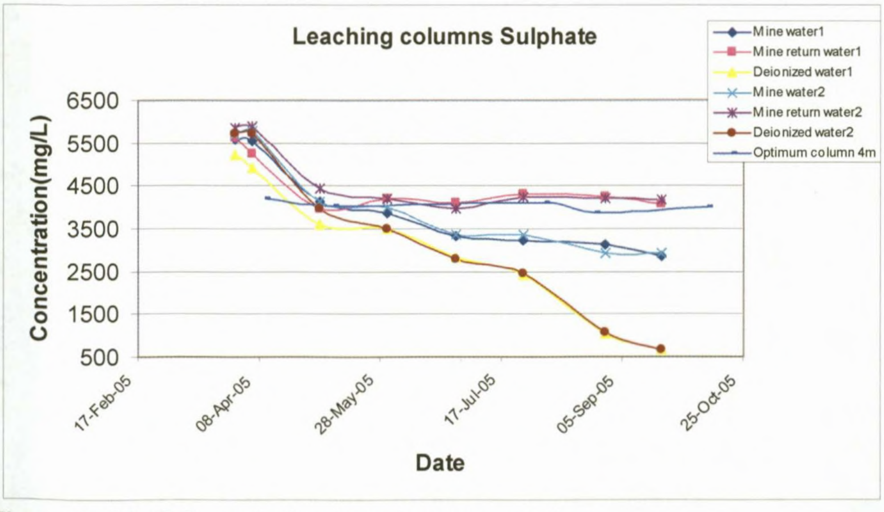


Figure 7-29: SO_4 variation in columns over time.

These findings are mirrored in the results of the Ca and Mg provided in Figure 7-30 and Figure 7-31

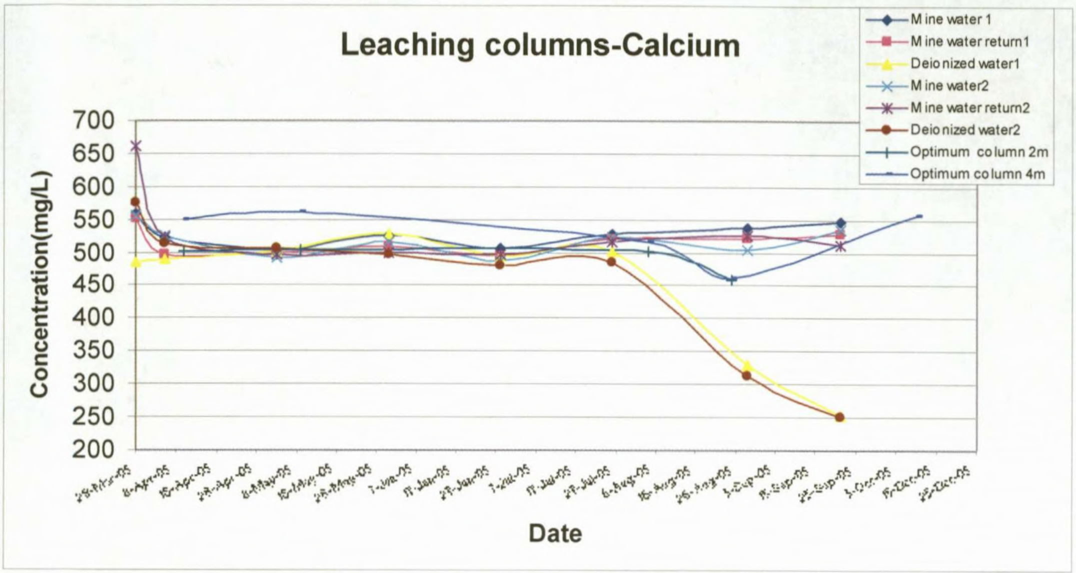


Figure 7-30: Ca variation in columns over time.

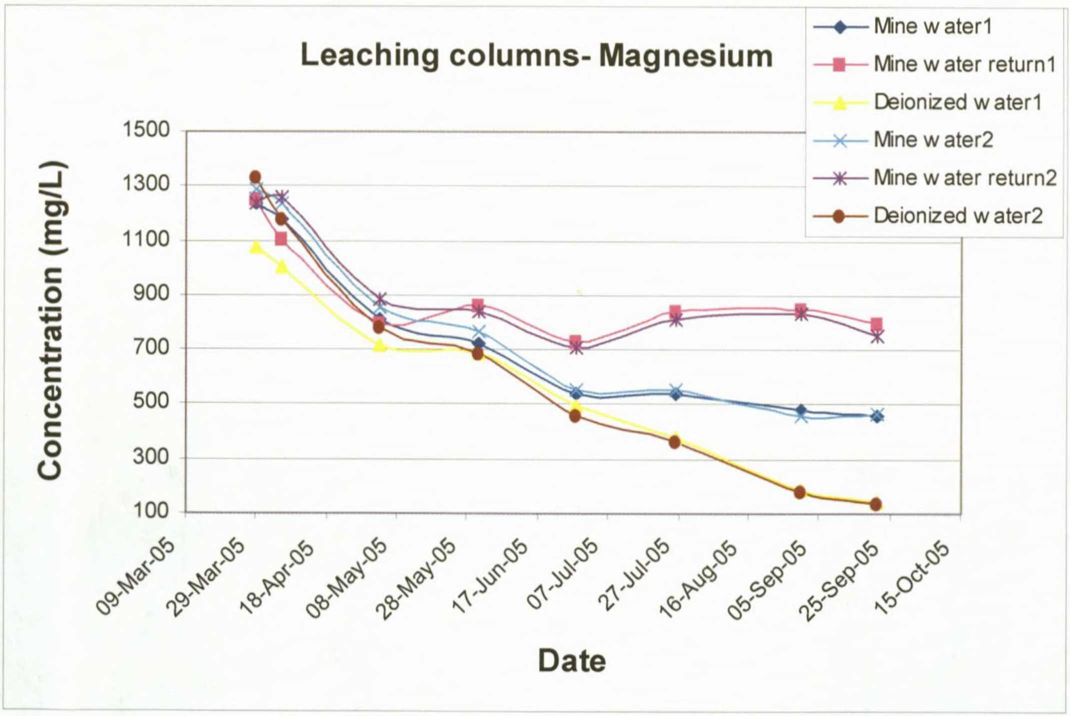


Figure 7-31: Mg variation in columns over time.

The gypsum saturation over the same period is of interest and shown below:

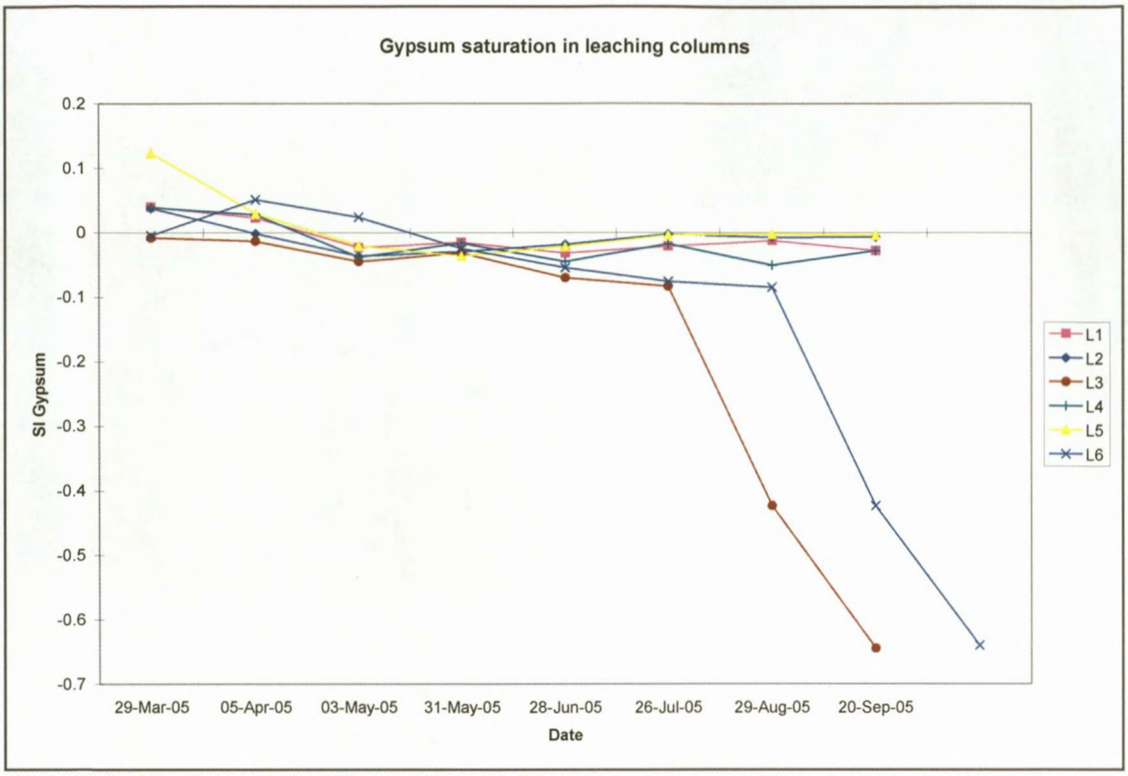


Figure 7-32: Gypsum saturation in leaching columns over time.

It can be seen from the above that the deionised cells become undersaturated as secondary products are flushed out, but where leachate is recirculated or mine water used, the values remain close to saturation.

Figure 7-33: Sulphate concentrations and gypsum saturation in columns.

As can be expected in these columns, the carbonates are not stressed in the reaction period and calcite and dolomite are at or above expected equilibrium.

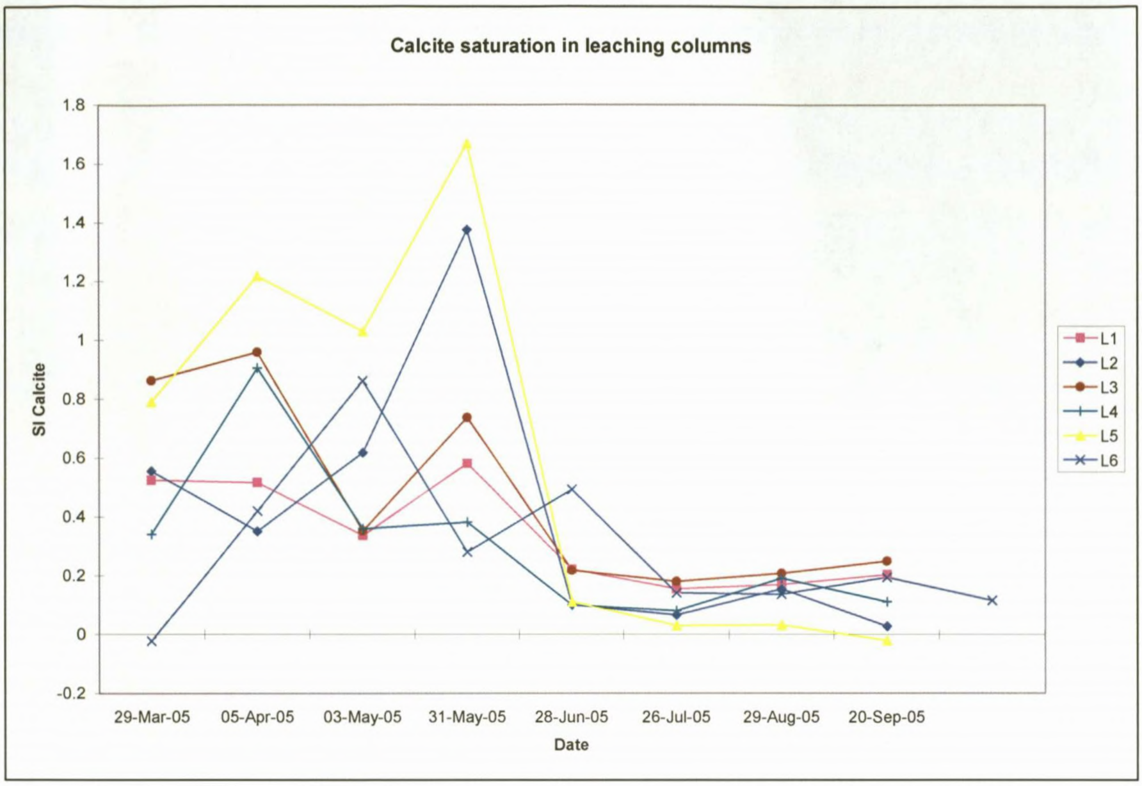


Figure 7-34: Calcite saturation in columns.

7.2.2.3 Potentially acidic spoils

The column tests were repeated with potentially acid-generating spoils. All the caveats outlined for the previous columns hold in this case as well. The most important are the ratios between the rock and water and the resultant limited reactivity of the system. Columns are excellent real-life analogues, but are limited, as they cannot provide the entire reaction sequence within the usual test period.

Acid-base accounting was performed on the spoils used in the leaching columns to obtain an indication of their acid-generating potential. Results are given in Table 7-3.

From the results, it is clear that, under open conditions such as those in the laboratory, these spoils are expected to acidify.

Table 7-3: ABA results from the spoil columns.

Initial pH	Final pH	Acid Potensial (Open)	NNP (Open)
		kg/t CaCO3	kg/t CaCO3
7.62	2.700	76.796	16.22
7.43	2.580	32.806	-20.34
7.84	2.150	58.377	-22.15
7.45	1.790	57.209	-37.52

A few parameters are shown to contrast with the equivalent humidity cells. In the pH variation, neutral conditions are established and maintained in the short term (Figure 7-35). This indicates that, although the potential for acidification exists, this is not immediately manifested. This is borne out by the results of geochemical reaction modelling in Section 7.2.4.

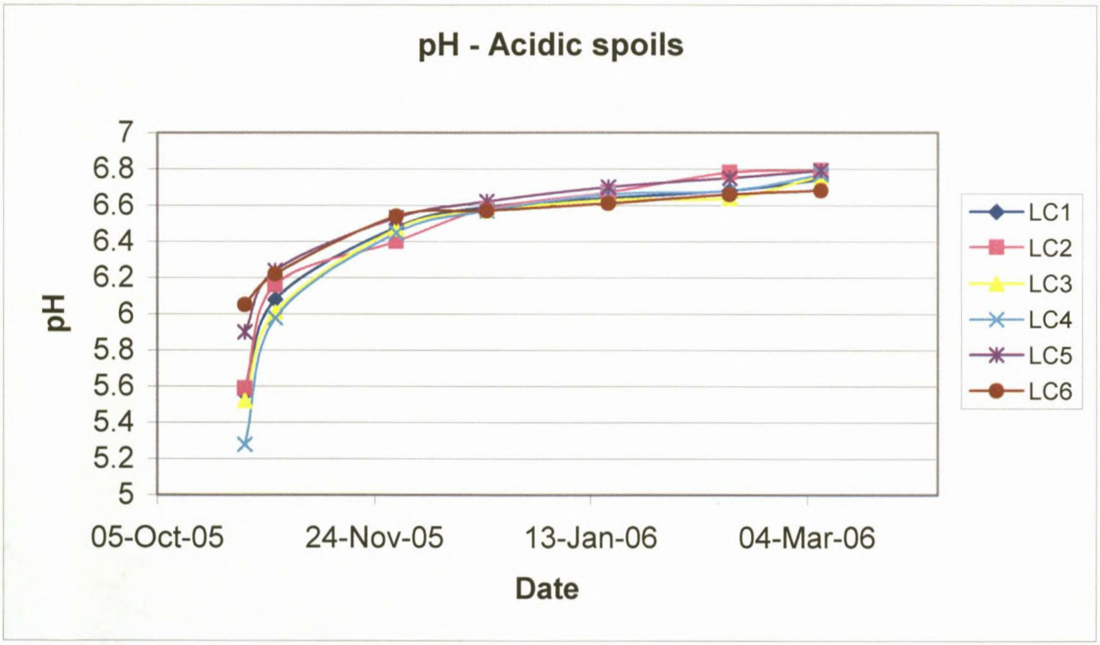


Figure 7-35: pH recovery in columns over time.

The EC (Figure 7-36) and sulphate (Figure 7-37) shows that, as in the previous columns, there are initial high concentrations that decrease as the accumulated reaction products are flushed out of the system. This fact alone makes columns less than ideal for understanding what would happen in the very long term during spoils irrigation. It does indicate, however, that the initial salt loads in such a system would be very high, with stabilisation occurring in time.

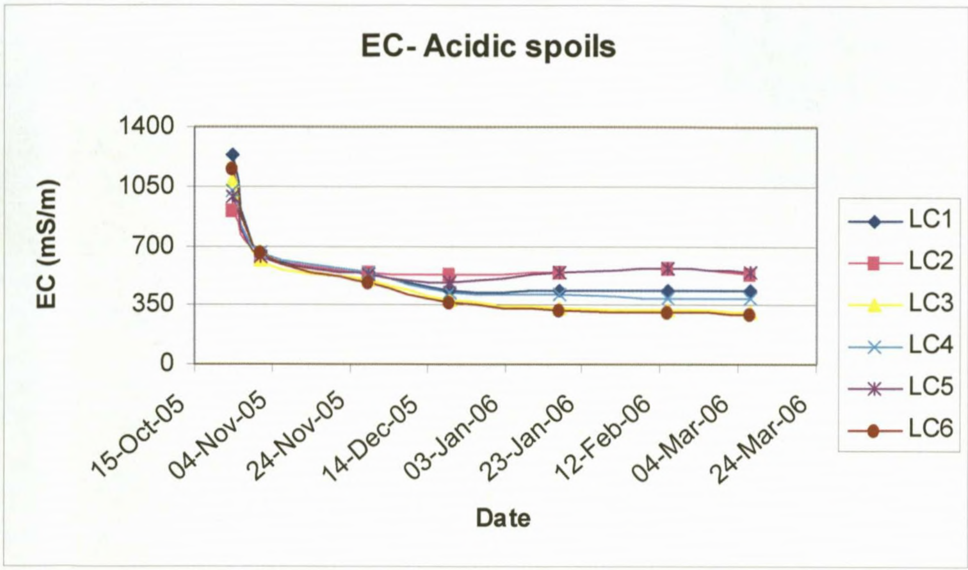


Figure 7-36: EC in columns over time.

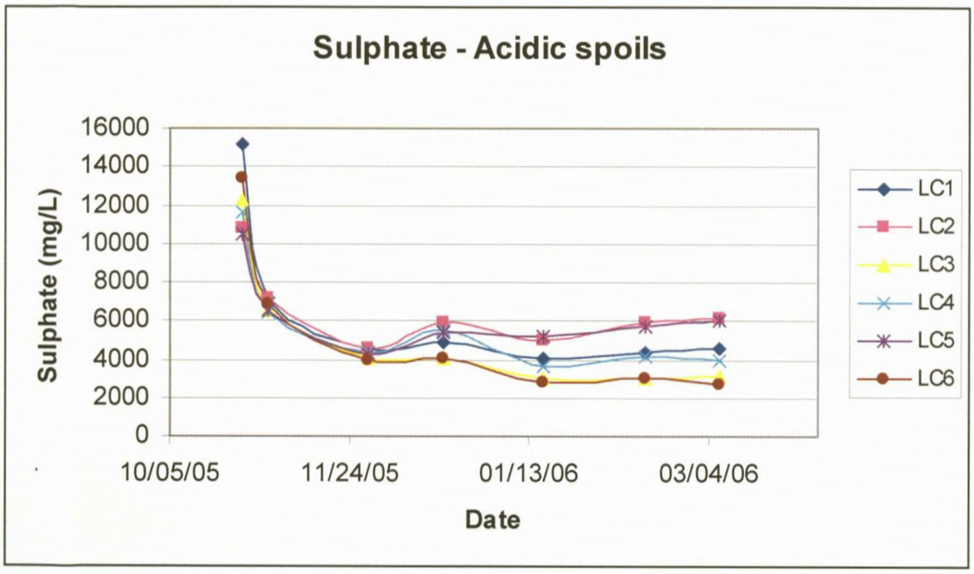


Figure 7-37: Sulphate concentrations.

7.2.3 *Field leaching columns*

A deep trench was dug in the spoils (Figure 7-38) at one of the pivots at Optimum to install leaching columns of 250 cm in diameter. Three columns were buried vertically in the trench, one at 5m, one at 4m and one at 2m. The columns were sealed at the bottom, and filled with 30cm of silica gravel to prohibit the leachate water in the bottom with the spoils reacting chemically. A small tube with a perforated bottom was installed in each of the columns for sampling purposes (Figure 7-39 and Figure 7-40).

The columns were then filled with spoils in the same sequence as they occur in the pit from which they were dug, and compacted. Unfortunately the 5 m column leaked, and only the 4 m and 2 m were sampled over time.

Two 4m experimental columns were installed in a hanger at the University of the Free State, also filled with spoils from the pit, and with small taps at the bottom to drain water. The aim was to leach irrigation water through the one, and de-ionised water through the other after the spoils have compacted, in order to determine the hydrochemical and hydraulic interactions through direct observation and measurements.

Figure 7-38: Pit in the spoils, illustrating the heterogeneity of the spoils.

Figure 7-39: Installation of leaching columns.

Figure 7-40: Installed leaching columns at Optimum pivot.

7.2.3.1 Results

The results indicate that very high initial sulphate and salt loads can be expected (Figure 7-41). This was consistent with the findings in the laboratory columns. The differences between the 2m and 4m depths should be noted and are a result of both the mine water addition at the surface and, more importantly, the greater pre-irrigation reaction in the shallow depths where pyrite oxidation can more easily be accomplished due to optimal oxygen and moisture contents at these shallower depths.

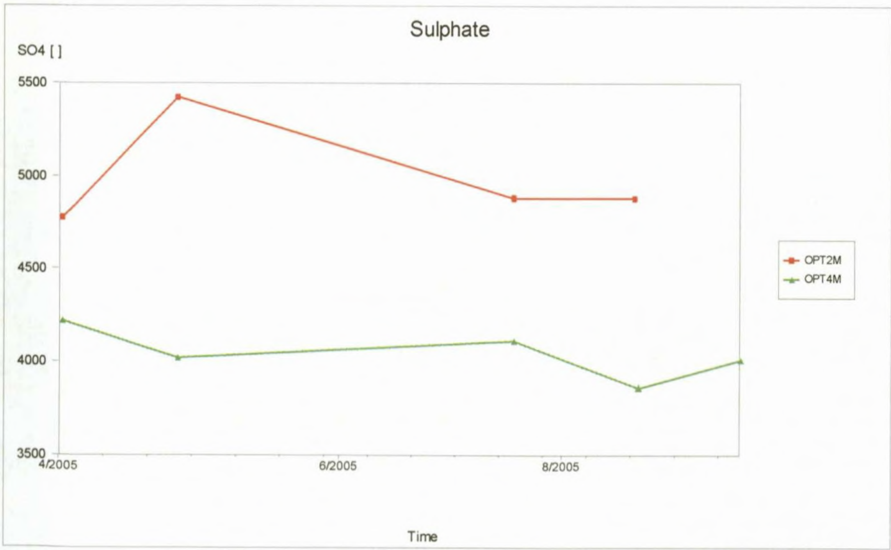


Figure 7-41: Sulphate values from field columns over time (mg/L).

The pH response was similar to that observed in the laboratory columns, and showed that neutral conditions will exist until the available NP has been depleted.

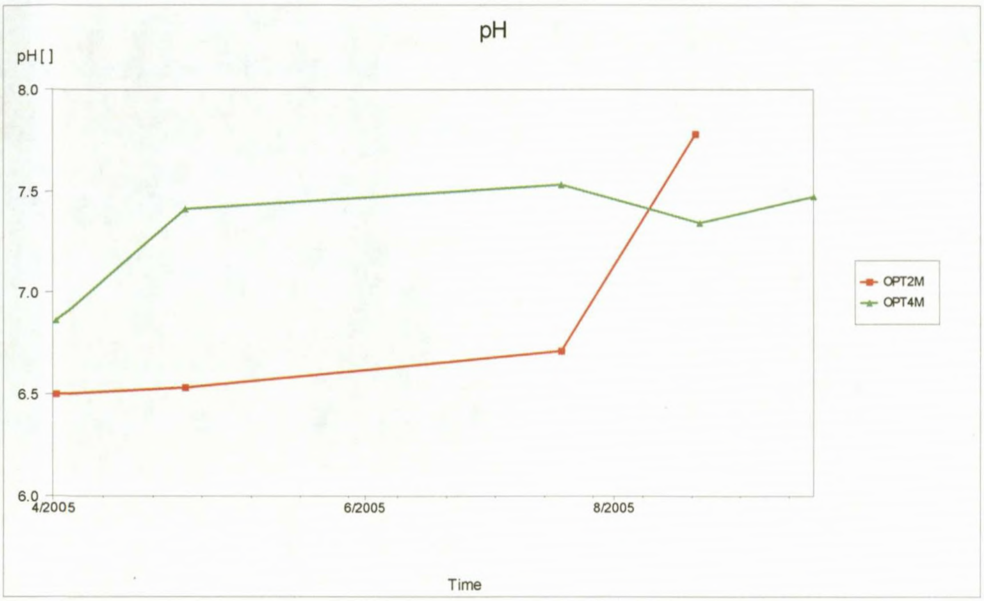


Figure 7-42: pH in field columns over time.

The gypsum saturation profile over time was consistent with the explanation of pre-existing oxidation products, and it is clear that the columns were initially oversaturated with gypsum, which moves to equilibrium over time.

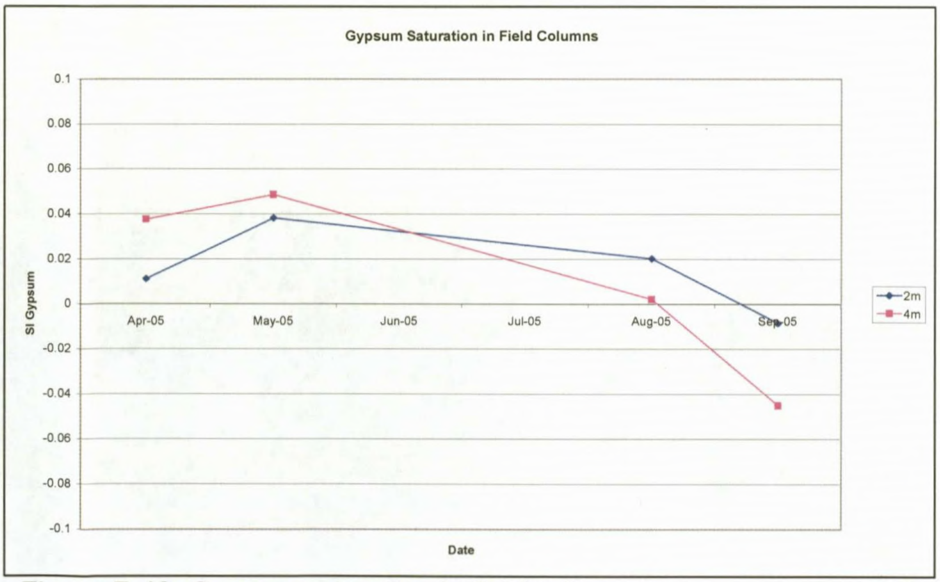


Figure 7-43: Gypsum saturation in field columns.

A comparison of the field columns with laboratory data showed a fairly good correlation, but suggested a large amount of pre-existing reaction products in the 2m column, which correlates well with the initial values in the laboratory. Due to the lower water ratios, this will persist for a lengthy period.

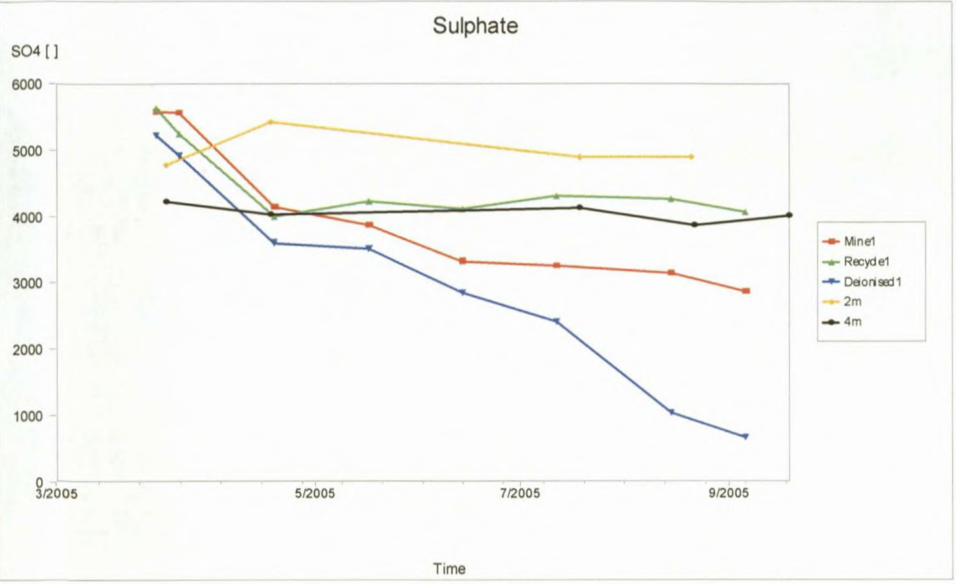


Figure 7-44: Comparison of field and laboratory sulphate values.

7.2.4 *Discussion*

The laboratory and field experiment results are vital for understanding different scenarios in the field. The humidity cell results provide a broad indication in terms of the expected full reaction sequence, therefore providing the best experiments for the most likely fundamental interactions.The laboratory columns are useful as they provide a better understanding of the true rates at which the processes occur and thus provide a closer “real-time” analogue of the field situation, although the volumes of water added reflect a far longer time of irrigation than is usually the case in the field. The good comparison with the field situation is encouraging in this regard.

7.3 Hydraulic response of the spoils

At the Optimum Spoils, tensiometers were installed to measure the soil moisture variation over time. Unfortunately the deeper tensiometer at 4m malfunctioned and only data from 0.8, 2 and 3 m could be interpreted. From the high rainfall period during late summer it is clear that the spoils were quite wet, especially at 2m where the tension was close to zero. After the rain has stopped, and irrigation was applied twice a week at 10mm per cycle (and later at 15mm), the spoils started to dry out and the tensions at the different depths increased, especially at 3 m. Even the 0.8 m tensiometer started to dry out during July to August but once again increases in wetness when more irrigation (15mm) was applied. This indicates that controlled irrigation during wintertime will not enhance increasingly moist conditions, which is conducive to sulphate generation (See Section 7.4.2.3 for modelling of irrigation with reduced recharge). The drop in tension and the subsequent increase in moisture at the end of October are attributed to the fact that the pivot broke down above the tensiometer installation, resulting in flooding in the area for more than a week. Since then, when the rainfall started again, all three depths remained constant in moisture content, which is the same as during late summer.

From these data it is clear that during summer time, especially when rainfall is high, there is an increase in moisture in the spoils. If controlled irrigation were applied during winter, it would not have a negative effect on the surroundings (winter pastures need a lot less water to grow effectively). Less irrigation over a larger area will thus be the answer in reducing excess water at opencast collieries.

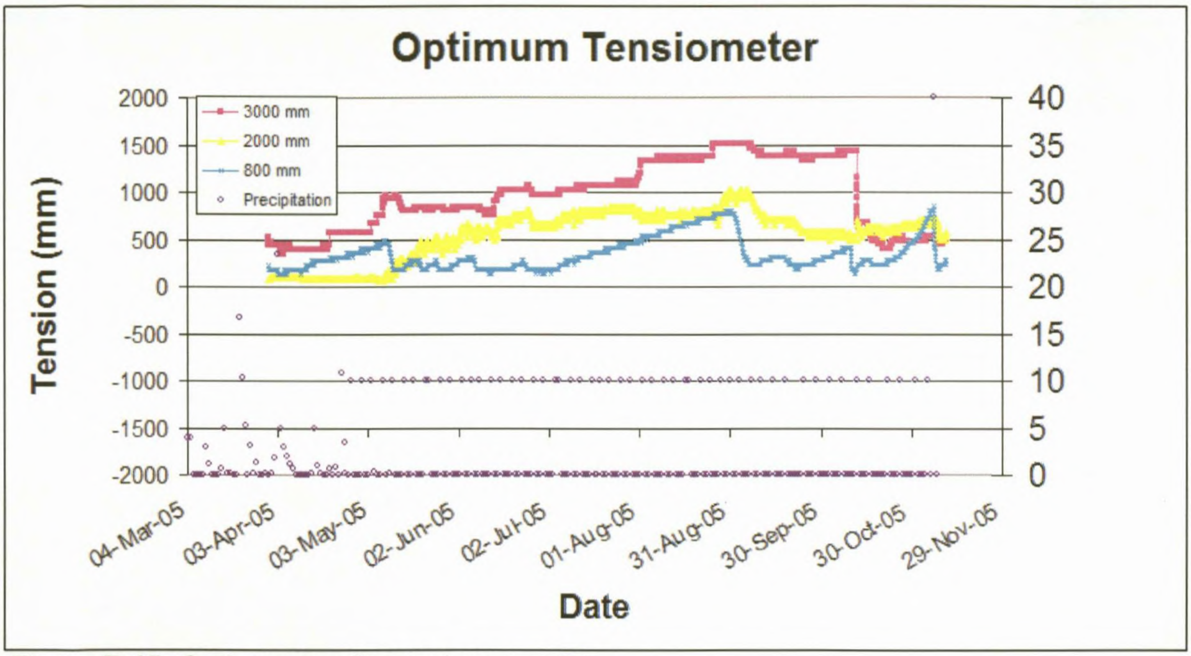


Figure 7-45: Optimum spoils tensiometer data.

7.4 Geochemical Modelling

Geochemical modelling can be used for various reasons, such as:

- To characterise and interpret current contaminant load.
- Environmental assessment (source and receiving environment).
- To predict future contaminant concentrations and loads.
- To assess future treatment needs.
- To compare management and decommissioning options.

To support this, Lichtner (1996) states: "Computer models can provide, if not a direct quantitative description, at least a far better qualitative understanding of the geochemical and physical processes under investigation than might otherwise be possible."

The geochemical model, PHREEQC (Parkhurst and Appelo, 2001) was used to assess the minerals that exert control over the observed water quality. The results were entered into PHREEQC, so that an indication of the saturation state of each sample, relative to common minerals within the South African coalfields, could be determined. The approach was the widely recognised saturation index determination, wherein the saturation state of each water is compared to the theoretical solubility of the minerals, as defined by its K_{sp} value.

Work in other coal mining areas in South Africa indicates that the carbonate minerals, calcite and dolomite are important controls on the pH in water, and that secondary minerals such as gypsum and ion hydroxides are important in controlling the concentrations of these species.

The evaluations for these waters are presented in the sections below.

To obtain a generalised indication of what could occur at a typical opencast spoils site, a case study from Usher (2003) is discussed. Geochemical modelling was applied, using PHREEQC to speciate the water and determine saturation indices. At the encountered colliery, gypsum saturation acts as a control on the maximum sulphate concentrations, whereas calcite and dolomite are the principal buffering agents as far as pH is concerned. Eary *et al.* (2003) used a similar approach, in terms of ABA, saturation considerations and simplified modelling, to characterise the hydrochemistry of a coal mine.

Geochemist's Workbench (Bethke, 1996) was used to obtain a profile of the expected water quality over time. The data used in this simulation are derived from the average acid and base potentials for the ABA boreholes and extensive mineralogy on the 73 core borehole samples. From this detailed mineralogy, the principal minerals are characterised as quartz, kaolinite, illite and montmorrilinite, with lesser quantities of K-feldspar, calcite, dolomite, pyrite and Ca-plagiocase minerals. The data used in this simulation are derived from the average acid and base potentials for the ABA boreholes and detailed mineralogy on the samples. The values used are: AP: 2.8% pyrite; NP: 2% dolomite; clay (kaolinite with some illite) in excess, in the presence of oxygen and water. The results demonstrate the expected sequence of events, but there were no detailed determinations of the reactive surface area. Oxygen is only fully available on the outside of rocks in the spoil. The rocks are saturated with water on the inside and pyrite does not oxidise. For oxidation to take place inside a rock, it has to disintegrate through weathering. This could take many years, depending on specific circumstances. Based on these principles, the conclusion is that the outside of a spoil boulder (at excess acid potential and above the water table) could acidify within a matter of less than ten years, while its inside would still be alkaline. Trenches dug into existing spoil as part of research for a WRC project by Usher *et al.* (2003) confirm this observation.

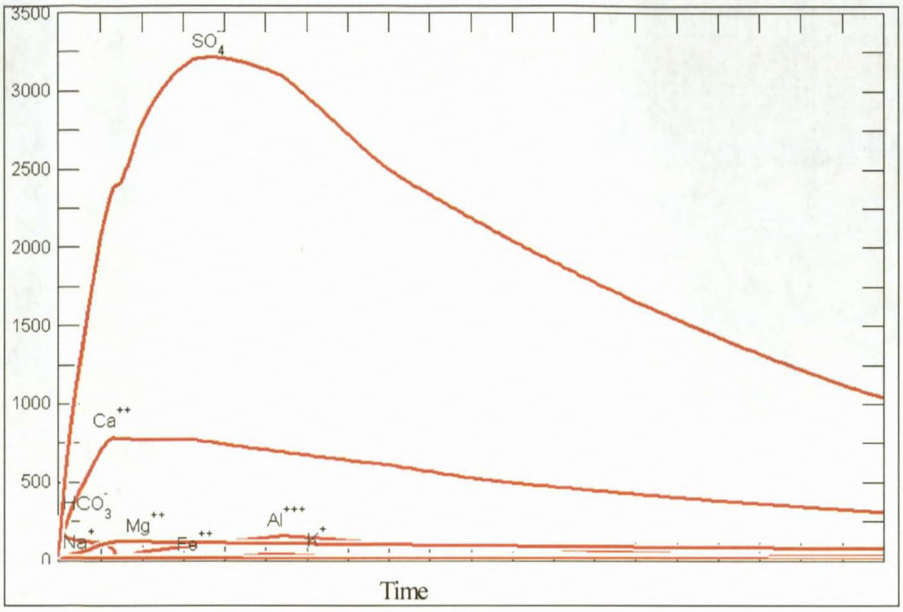


Figure 7-46: Expected concentration profile over time (using the average mineral assemblage determined by this study and an aquifer transmissivity of 1 m^2/day).

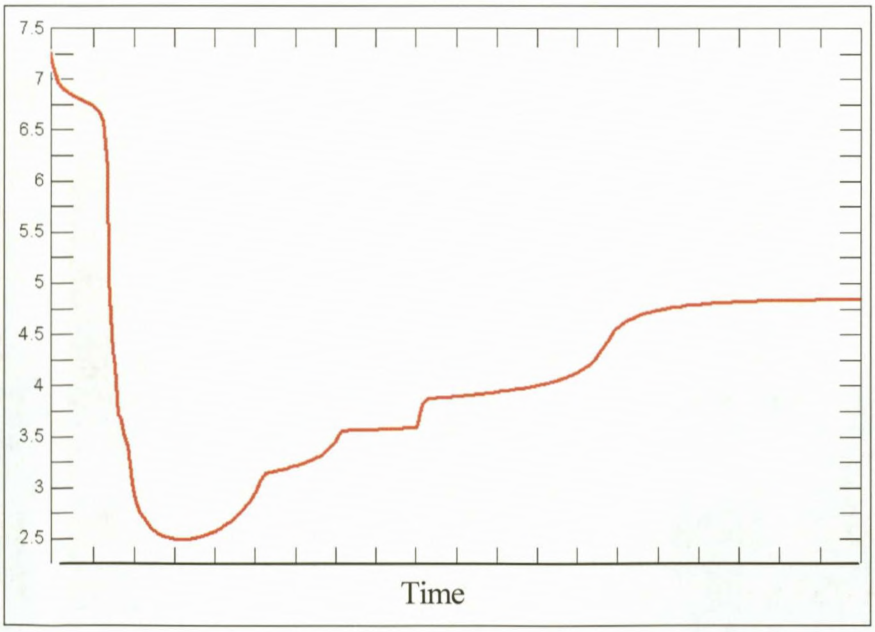


Figure 7-47: Expected pH profile over time.

It is worthy mentioning that within 12 months of this study, excess mine water flowed from the control area. The quality of this water was in excess of 3 000 mg/L SO_4 at a pH of around 2.5. It is clear that using a properly constrained conceptual model in conjunction with other data can lead to more accurate predictions of water quality, even when key parameters have not been measured. An important caveat is that the time graph is not specific; the profiles indicate the expected evolution, but not its timing.

For any particular spoils area, it is possible to generate similar hydrochemical evolution diagrams, if the correct data are collected.

7.4.1.1 Neutralisation of AMD

The expected mechanism of AMD neutralisation in the spoils is of great importance, since it will show the effect of irrigation with mine water.

The system attempts to buffer acidity, generated by AMD, as far as possible. In both the underground and opencast areas, minerals such as calcite and dolomite, which occur within the Karoo lithogies as cementation material or veinlets (observed in shales, coal and sandstone) and the alkalinity of the influent water, provide the necessary buffering (Usher, 2003).

Calcite neutralisation reaction (calcite dissolution by sulphuric acid):

$H_2SO_4 + CaCO_3 = CaSO_4 + H_2O + CO_2$

Dolomite neutralisation reaction (dolomite dissolution by sulphuric acid):

$2H_2SO_4 + CaMg(CO_3)_2 = CaSO_4 + MgSO_4 + 2H_2O + 2CO_2$

In the opencast, the influent water consists of rainfall and fairly inert groundwaters with limited alkalinity, while the irrigation mine water may be either devoid of, low, or high in alkalinity, such as at Syferfontein.

The concentrations obtained, also provide a vital understanding of the expected system response. Depending on where along the early part of the reaction path the system is when sampled, completely different ion ratios will be obtained. In the early part of the reaction path, the system contains a typical Na-HCO_3 water, showing an enrichment in sulphate relative to bicarbonate (*Figure 7-48*). The sodium content remains constant, with the water becoming progressively more calcic as the reaction proceeds. As the reaction continues in the longer term, sulphate and calcium will be constrained by gypsum precipitation for as long as calcium is released by calcite buffering. When this ceases, the system rapidly acidifies and sulphate concentrations rapidly rise, since no more gypsum can be produced to remove sulphate from solution (Usher, 2003).

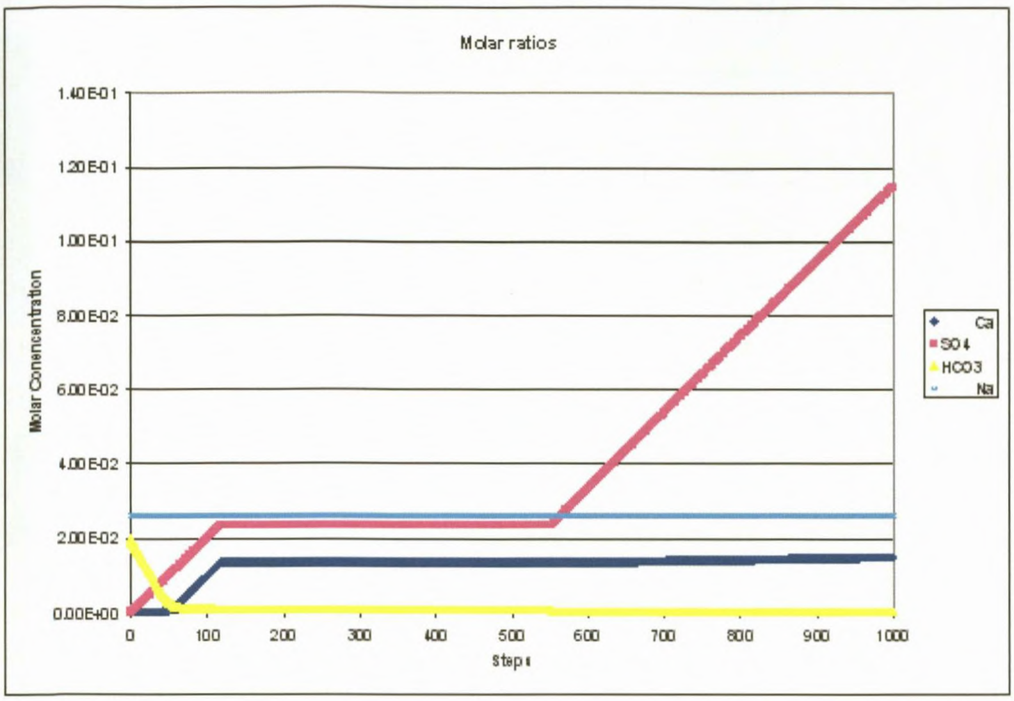


Figure 7-48: Molar concentrations throughout the reaction path.

7.4.2 *Reaction modelling*

Simplified reaction modelling was performed to elucidate the most important factors likely to be responsible for water quality changes in spoils. Variations in spoils geochemistry and irrigation were considered.

7.4.2.1 Base case

A relatively simple base case of spoils irrigation using Geochemists Workbench was modelled. The major reactive minerals are considered to be pyrite as acid generator, and calcite with a minor proportion of dolomite as carbonates acting as neutralisers. Associated with these minerals are a large proportion of quartz, clay minerals in the form of illite with some montmorrilinite, and feldspars (K-felspar as major specie). The expected recharge from irrigation was added to the system in the form of pure water. Oxygen and carbon dioxide were initially allowed to equilibrate with the atmosphere and it was assumed that a free exchange of gases could occur in the system.

For the first simulation, a slight excess of pyrite is assumed, with calcite and dolomite making up an almost equivalent mass of neutralising capacity.

Assumptions have to be made regarding the reaction surface areas. Consequently the values for concentration should be regarded as illustrative guides of expected behaviour. Time periods should also be regarded as relative and not absolute.

The expected water concentrations over time (Figure 7-49), the associated mineral saturation variation for the carbonates and gypsum (Figure 7-50 and Figure 7-51), the depletion of reactive minerals (Figure 7-52), and the associated pH-response are provided (Figure 7-53). This is the baseline against which all the variations are considered and the comparison to analogous laboratory simulations must be viewed with these data. The fluid variation shows relatively high values of SO_4, Ca and Mg, as seen in the field and in the cells, but also a decrease over time as the reactive minerals become depleted. The Ca and SO_4 values are furthermore limited by the saturation of gypsum in particular.

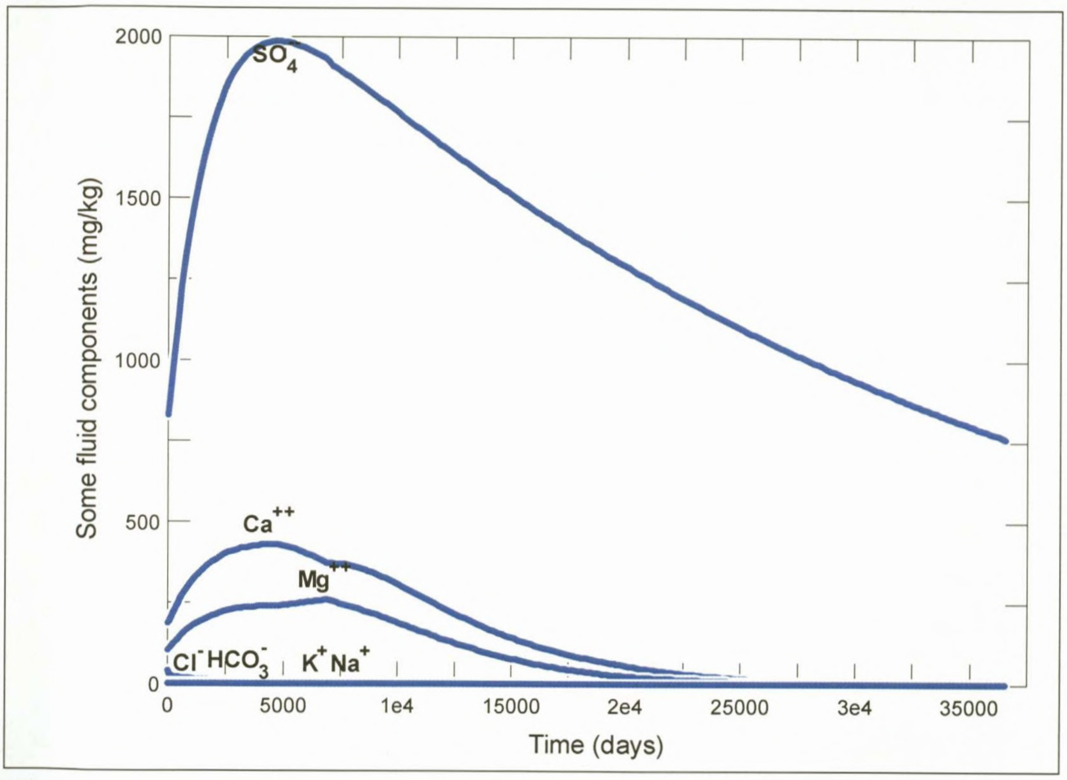


Figure 7-49: Concentrations of major ions over time.

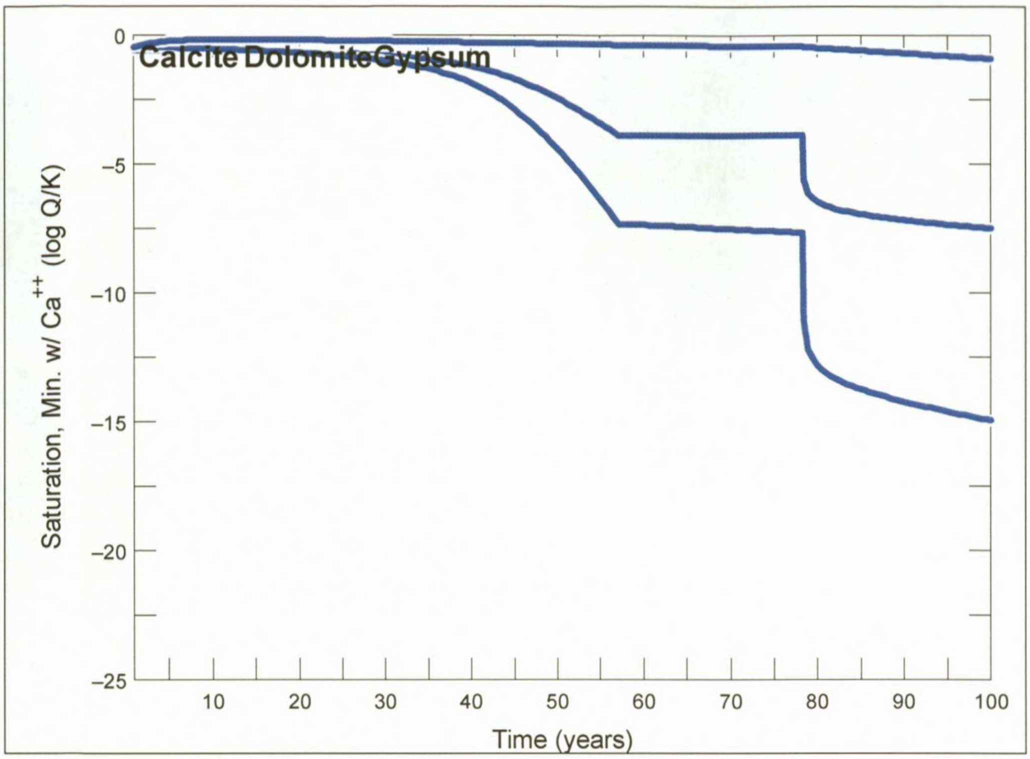


Figure 7-50: Associate mineral saturations.

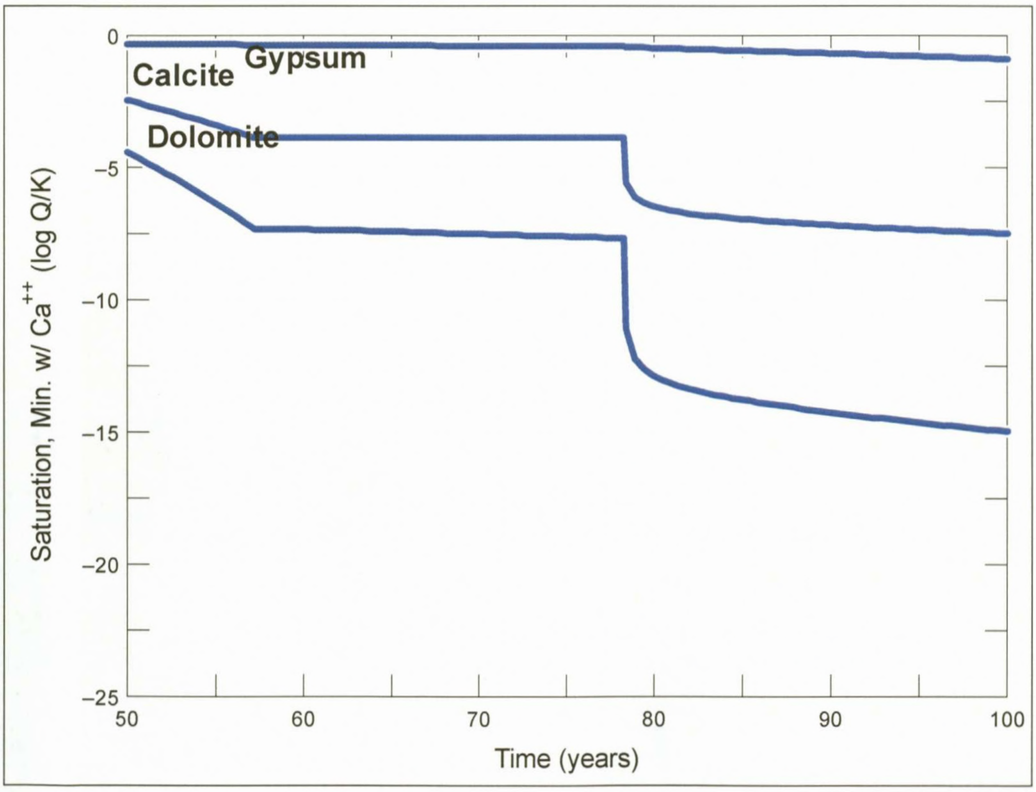


Figure 7-51: Latter part of reaction sequence mineral saturation.

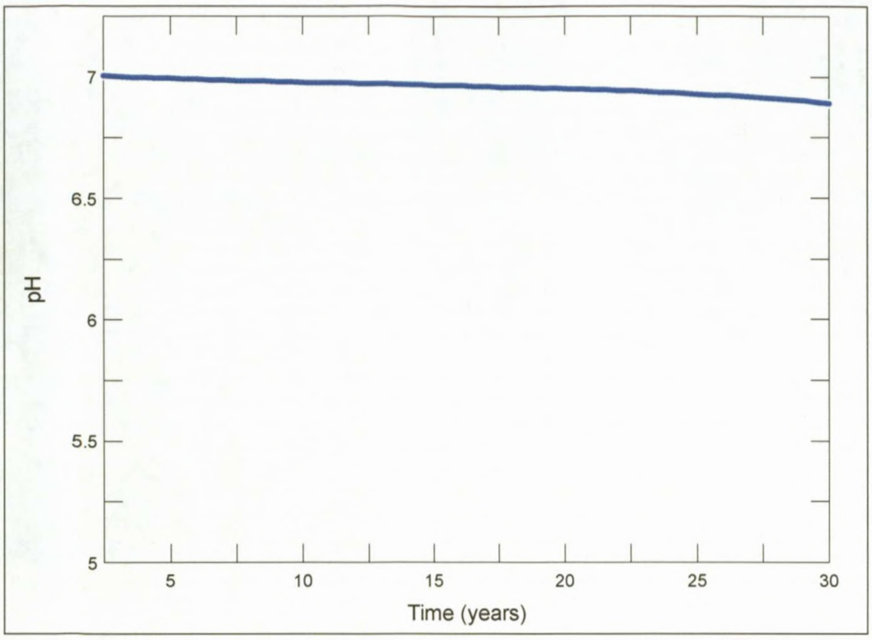


Figure 7-52: pH variation.

From the pH variation, it appears that acidification is unlikely. However, a consideration of the relative depletion of pyrite against the carbonates (Figure 7-53) suggests that acidification may occur. For this reason, the model was rerun as described in the following section.

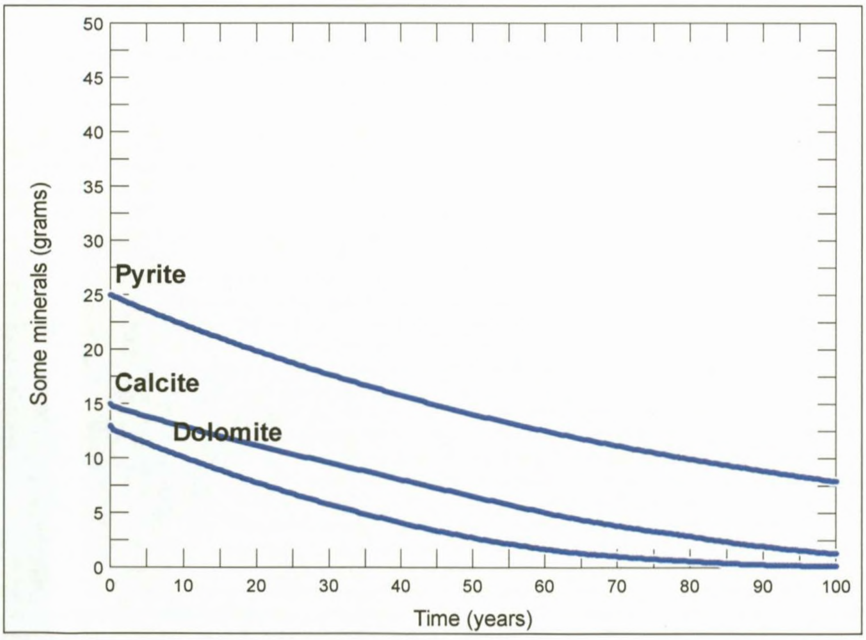


Figure 7-53: Decrease in reactive minerals over time.

7.4.2.2 Base case run for longer period

In the light of the observed pH response and depletion of the carbonates with relation to pyrite, it was decided to run the reaction for a longer period of time. It can be seen that, due to the elevated recharge from **clean** water irrigation, the concentrations subside with time.

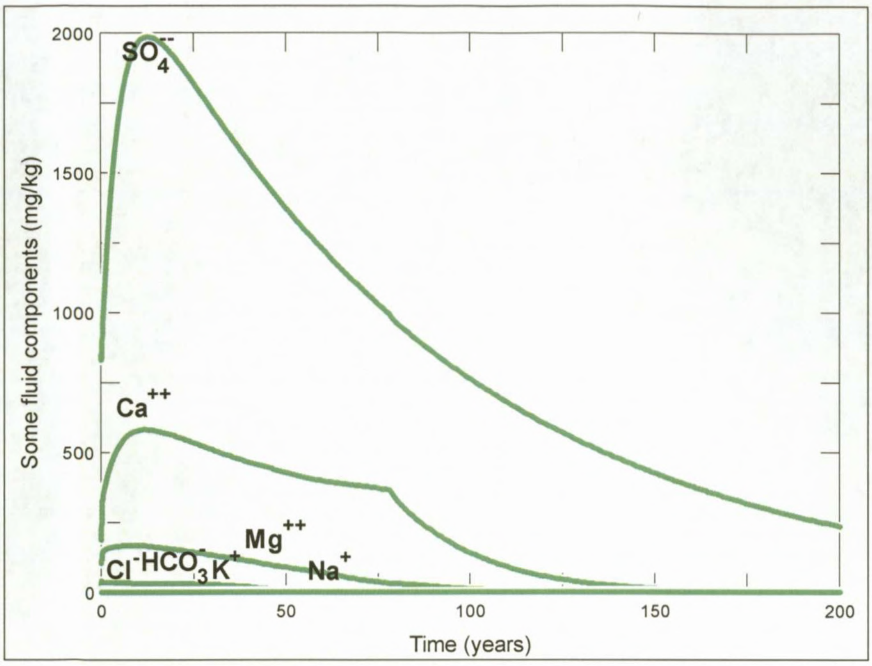


Figure 7-54: Concentrations of major ions over time.

The pH response is the most important, as it shows the dangers of arbitrarily defining a reaction period and then baking a decision on such a finding (Figure 7-55). This demonstrates that acidification would occur due to the persistence of pyrite over the carbonates, as shown in Figure 7-56.

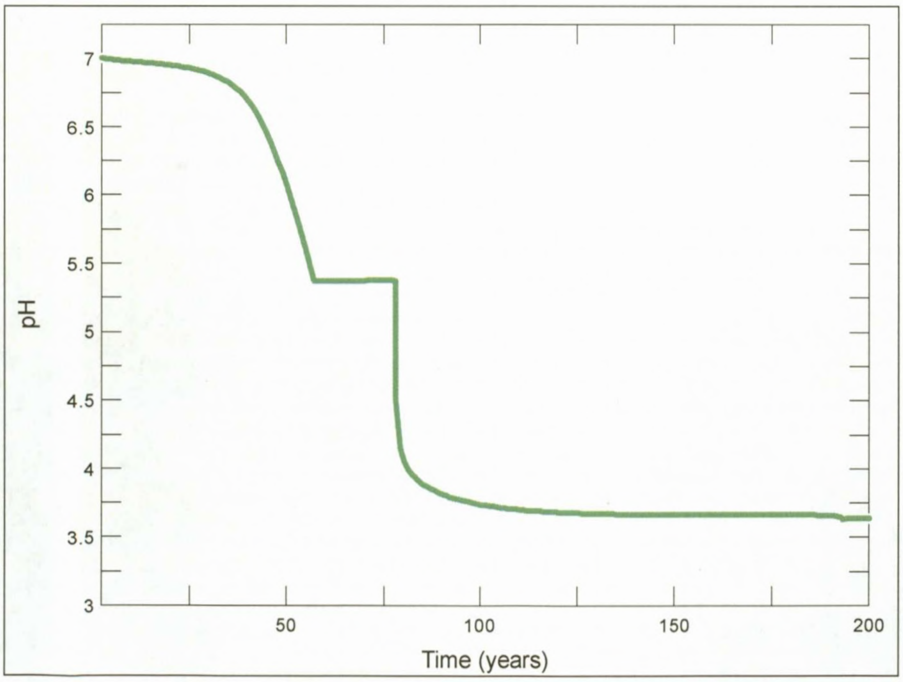


Figure 7-55: pH response showing reaction sequence effects over extended time.

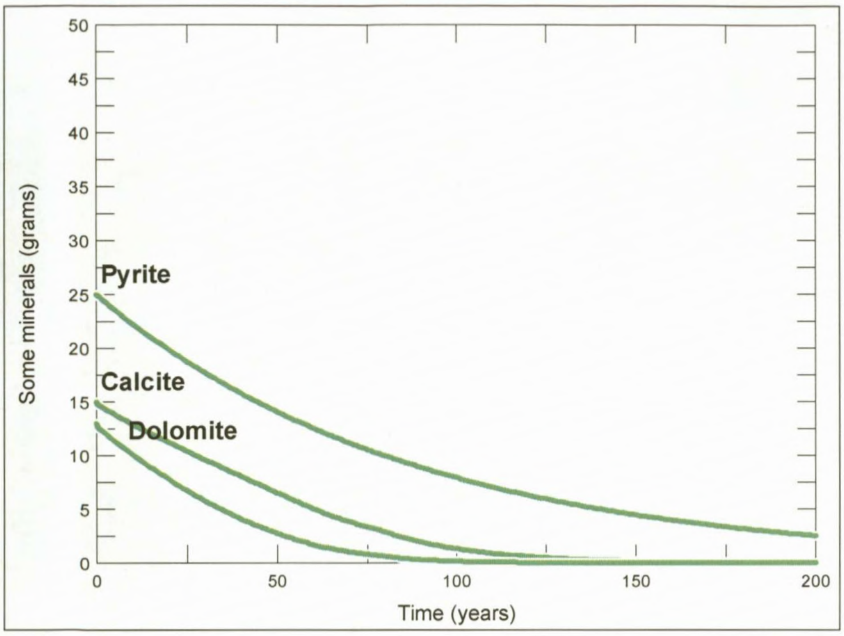


Figure 7-56: Decrease in reactive minerals over time.

7.4.2.3 Base case with recharge reduced

The base case assumes a certain amount of increased recharge. One of the key factors is to consider the effect of diminished recharge on the spoils chemistry. The effect of a 50% decrease in irrigation recharge is illustrated in the figures below (Figure 7-57 to Figure 7-59). As expected, the concentrations are greatly increased, but not doubled, due to the saturation effects previously discussed.

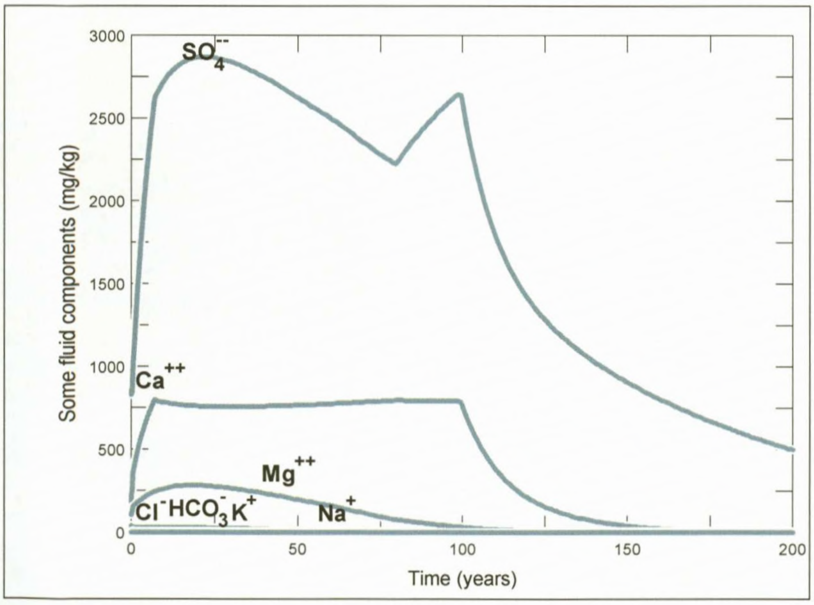


Figure 7-57: Concentrations of major ions over time with reduced recharge.

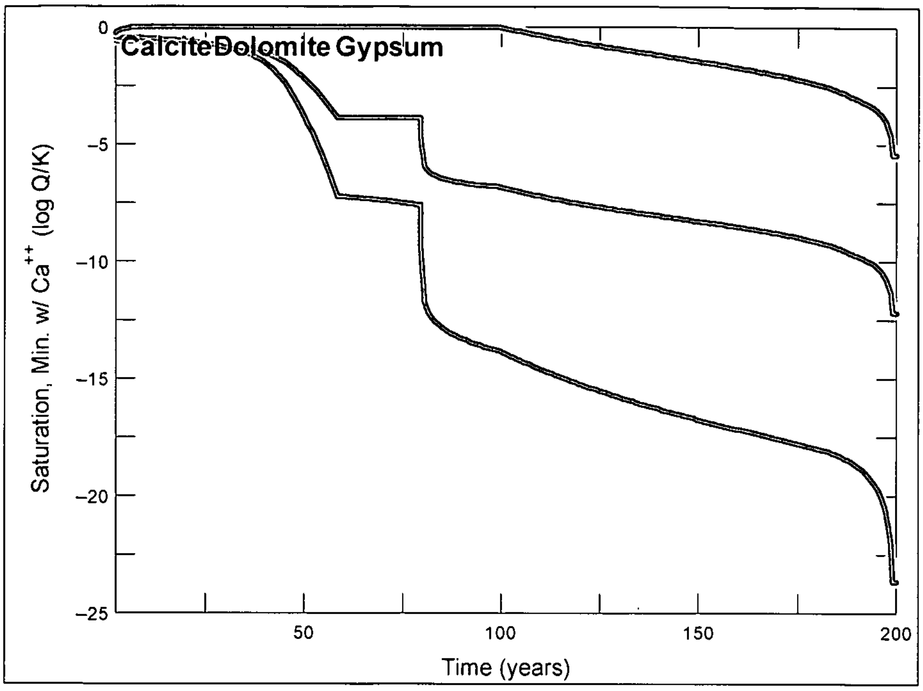


Figure 7-58: Associate mineral saturations with reduced recharge.

One of the key points to highlight is that the recharge reduction has very little effect on the pH profile. Only if the recharge contains a significant amount of alkalinity or acidity will this significantly alter the pH profile.

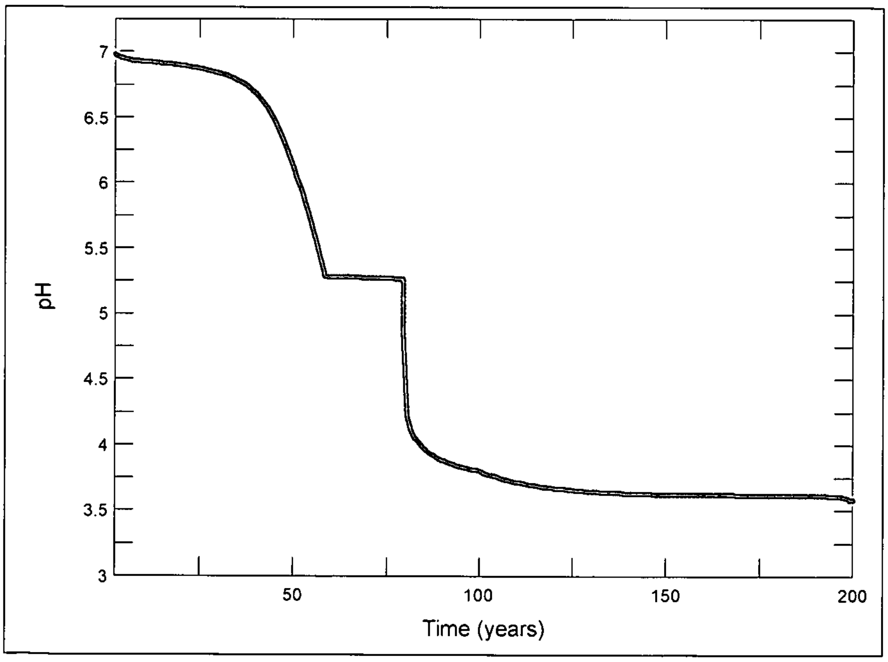


Figure 7-59: pH profile with reduced recharge.

7.4.2.4 Inundation resulting in order to lower pyrite rate

The effect of inundation on the spoils chemistry is also of importance. Here it is assumed that the initial system is started with the same conditions as previously but with oxygen excluded. It was shown that pyrite oxidation decreases due to the exclusion of oxygen and the decrease in activity of Thiobaccilus ferrooxidans when oxygen values are depleted.

The data in Figure 7-60 show that *T. ferrooxidans* activity ceases when O_2 is depleted. However, bacterial activity resumes even under extremely small increases in O_2 content, and reaches a maximum at approximately 0.01 mole or 1% of O_2 (Jaynes *et al.,* 1984).

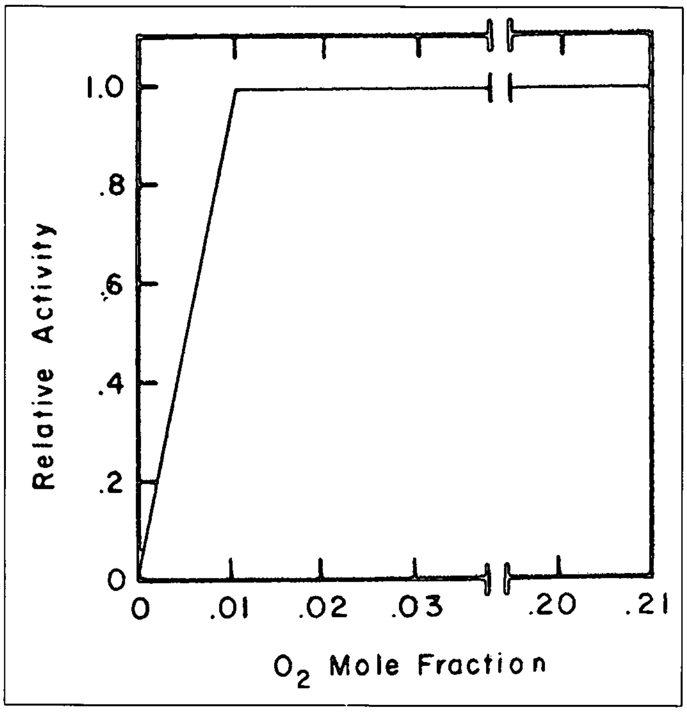


Figure 7-60: The influence of O_2 concentration on relative activity of T. ferrooxidans (Jaynes et al., 1984).

The effect of this response was simulated and the results indicate that, if the pyrite oxidation rate or activity is inhibited, the system will dilute (Figure 7-61). Pyrite oxidation and the resulting acidity, sulphate production, neutralisation and solubility effects are the principal drivers in the system. When the pyrite effects are reduced, the other minerals also react far less aggressively.

Equally important is the fact that, under these conditions, the pH will very quickly become neutral and then increase as the carbonates equilibrate with the available P_{co2} (Figure 7-62). The result is that the system reaches equilibrium with calcite and will remain neutral. The calcite and dolomite are also not depleted rapidly, since the system is not placed under stress by the added acidity under full pyrite oxidation kinetics (Figure 7-63).

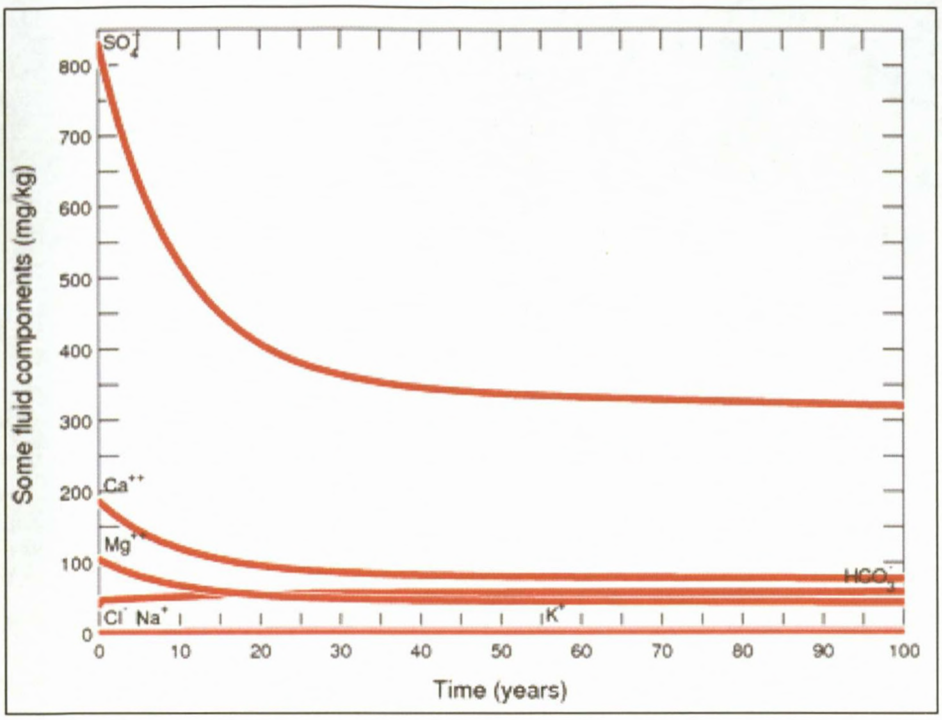


Figure 7-61: Decrease in concentrations at lower oxidation rate.

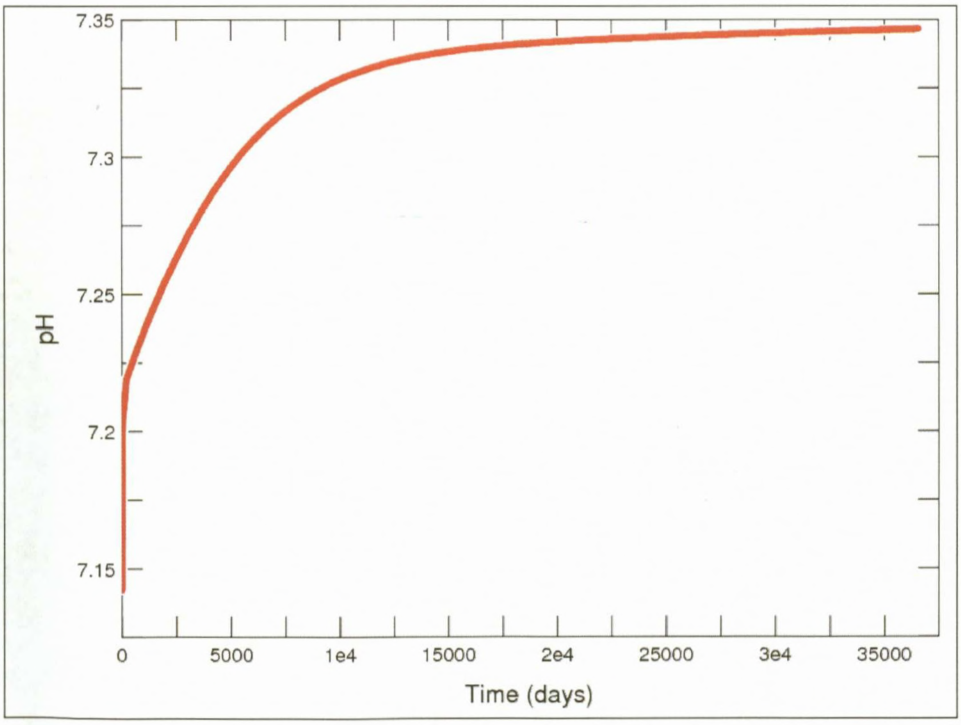


Figure 7-62: pH recovery if pyrite rate is decreased by an order.

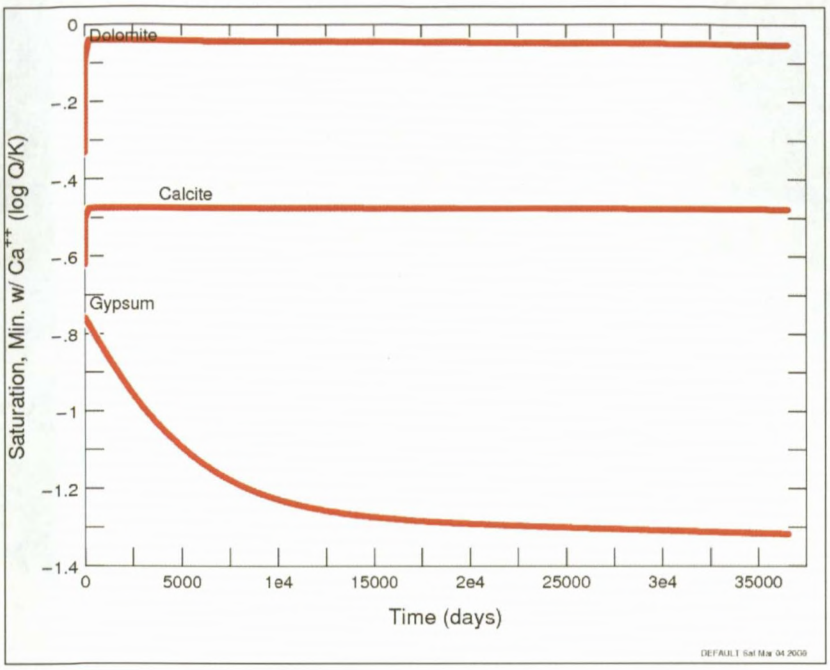


Figure 7-63: Mineral saturations at low pyrite oxidation rate (flooding conditions).

7.4.2.5 Base case with low NP simulation

As a variation of the base case, a situation was modelled where the pyrite greatly exceeds the Ca-containing carbonates. It is clear that the concentration of sulphate becomes significantly higher as does the resultant TDS, and that the pH-drop is rapid. This is shown on Figure 7-64 and Figure 7-65 respectively.

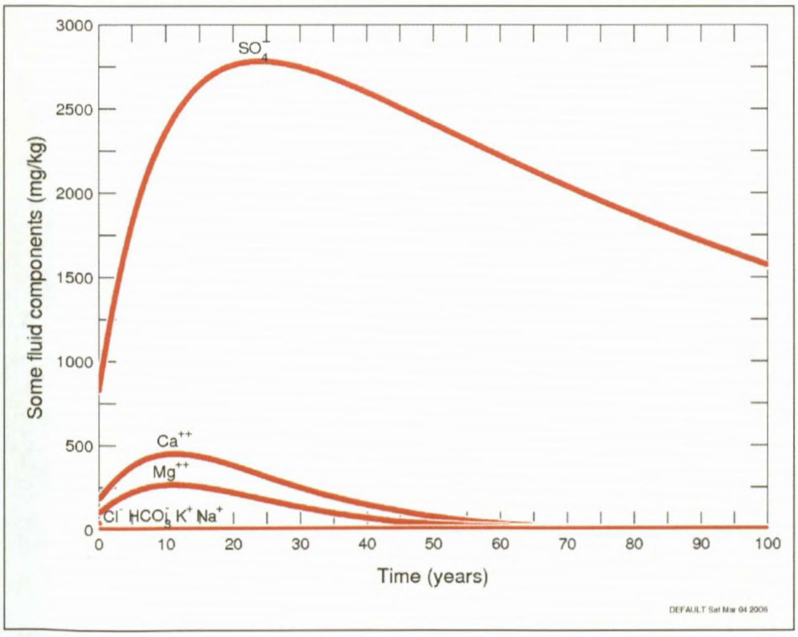


Figure 7-64: Aqueous concentration in low NP conditions showing an increase in sulphate and therefore in TDS.

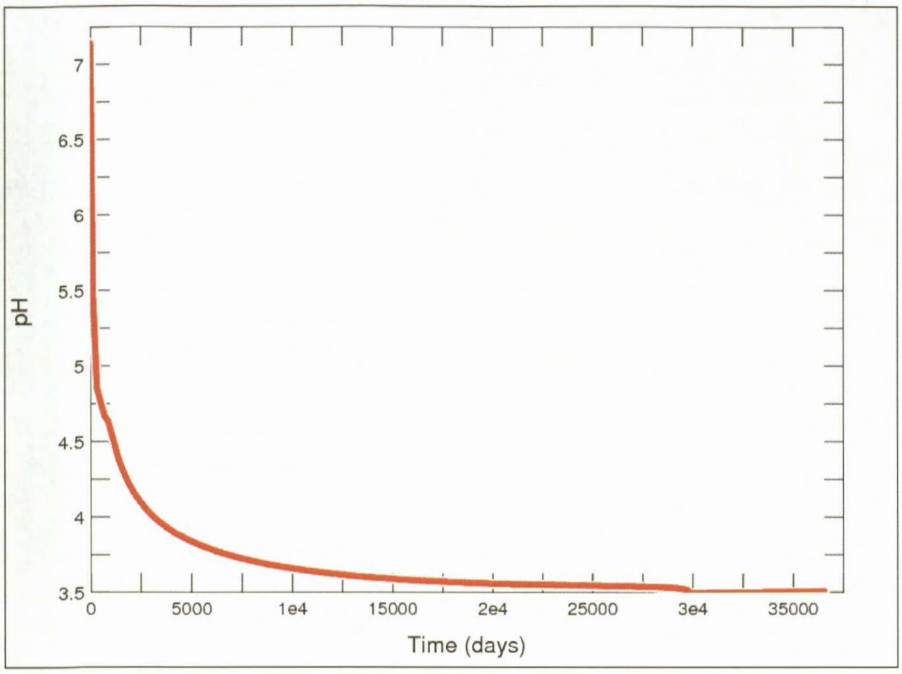


Figure 7-65: Rapid pH-drop.

Mineral saturation is of interest, as it shows the rapid undersaturation of dolomite and calcite as conditions become acidic. The gypsum remains relatively close to equilibrium for a long period of time, but due to the depletion in calcite and dolomite, this becomes undersaturated, as seen below.

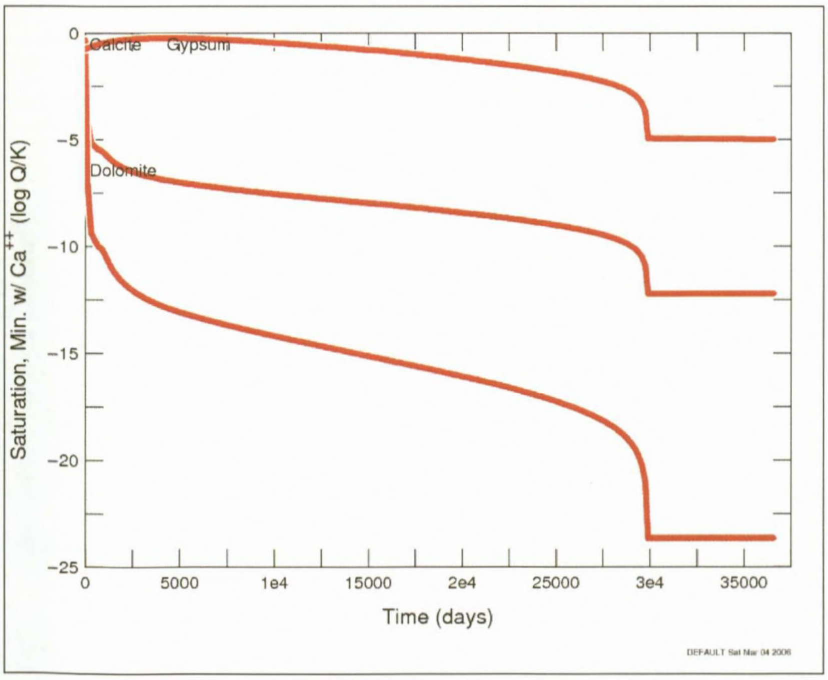


Figure 7-66: Mineral saturation showing depletion of carbonates associated with acidification.

7.4.2.6 Base case with high NP simulation

Alternatively, NP greatly exceeds the acid potential, as indicated by the pyrite content. This result in the most stable chemistry due to the fact that sulphate and calcium are limited by saturation, while calcite and dolomite are not rapidly depleted, giving a stable pH profile over time (see Figure 7-67 and Figure 7-68).

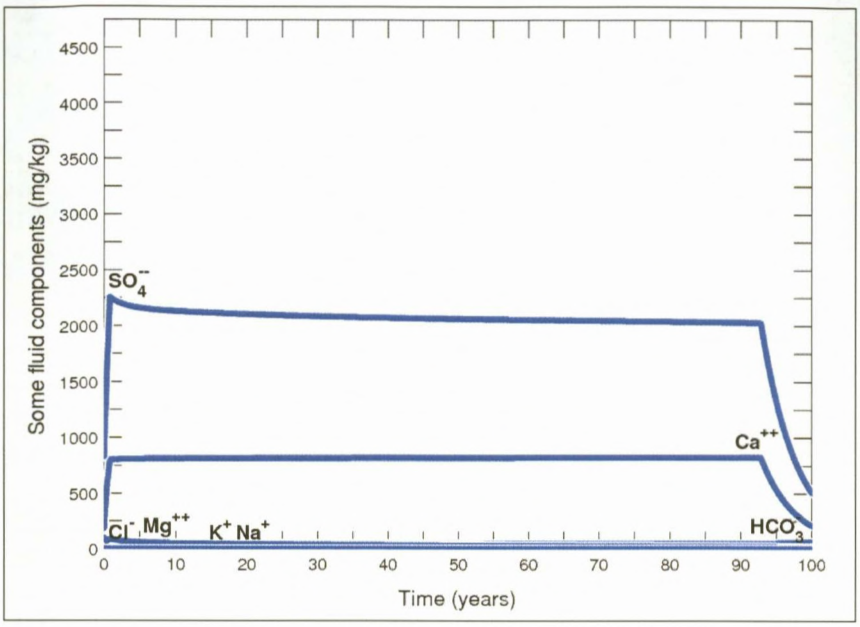


Figure 7-67: Concentrations of major ions over time with excess NP.

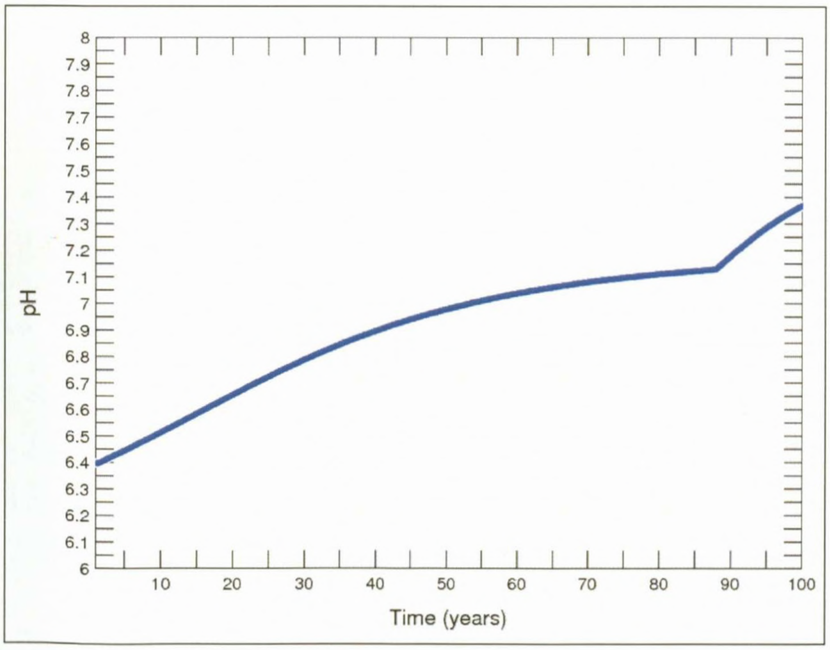


Figure 7-68: pH profile with excess NP.

The depletion of pyrite against calcite and dolomite is shown below. This behaviour explains the pH profile, as the NP is always in excess of AP with the result that the pH rises. The sulphate profile is also explained by this graph, as it indicates the continued production of sulphate in relation with the presence of pyrite. The concentration in the water is however controlled by gypsum solubility, which is at equilibrium until the pyrite is depleted, whereafter it consistently becomes increasingly undersaturated (Figure 7-70).

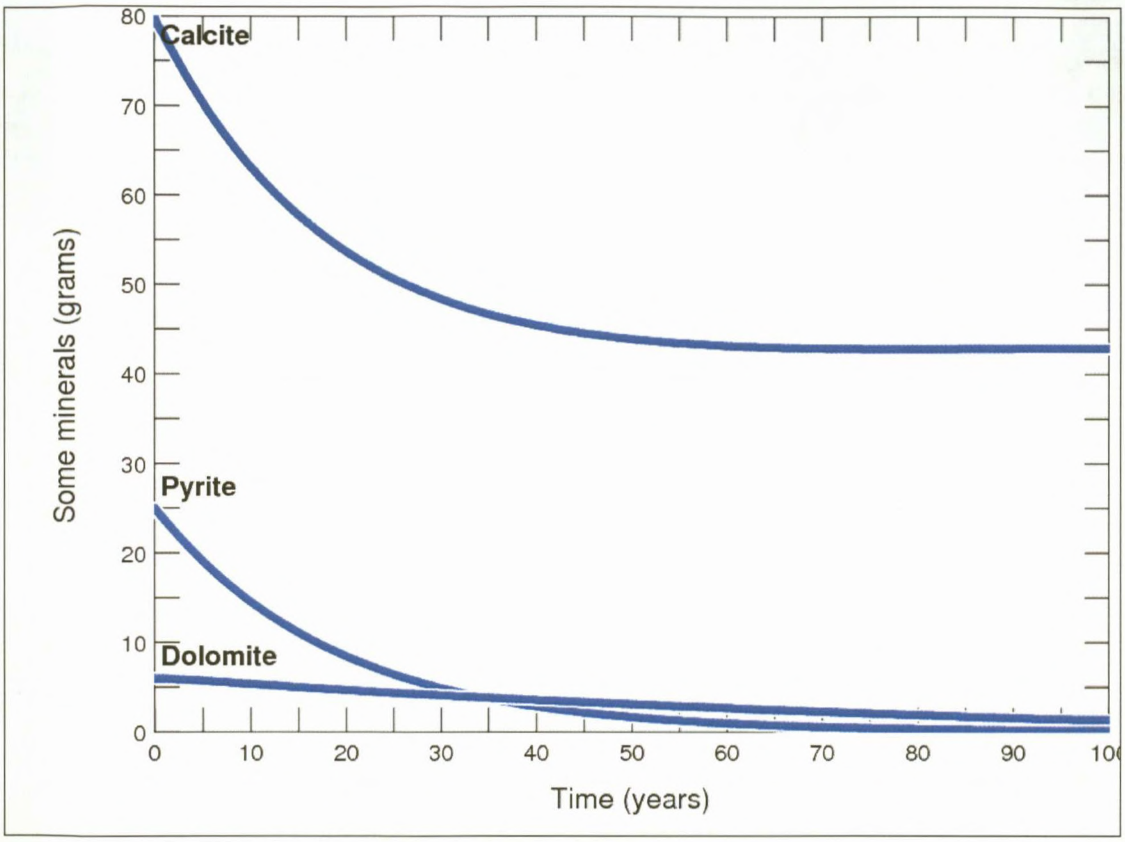


Figure 7-69: Calcite dolomite and pyrite depletion in high NP scenario.

The final depletion of pyrite and the consequent undersaturation of gypsum also results in an increase of dolomite saturation, as more Ca can now solubilise in the water (Figure 7-70).

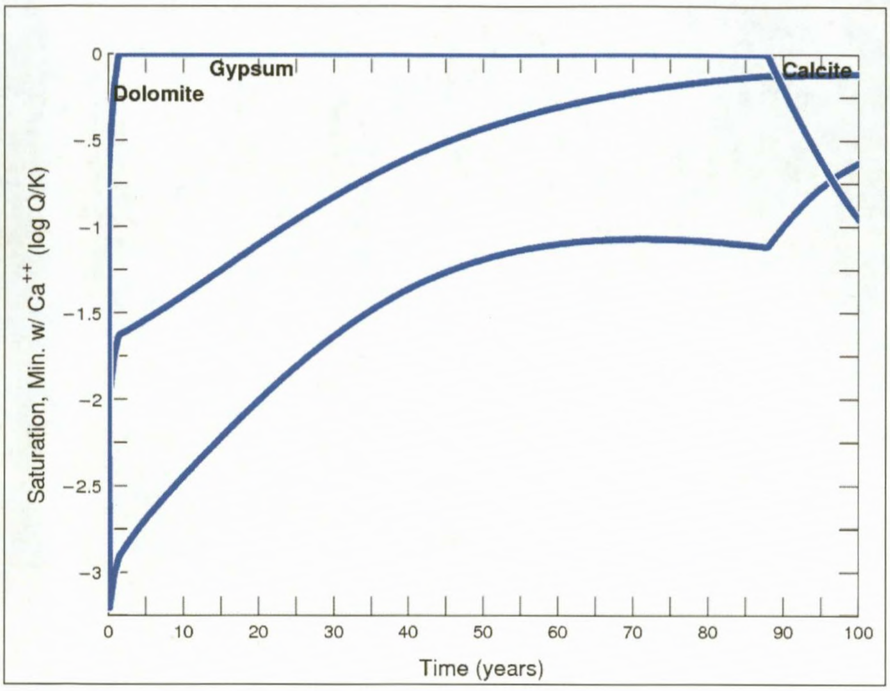


Figure 7-70: Mineral saturation over time for high NP scenario.

7.4.2.7 Flooded cells/columns

The variation of the flooded system is another scenario to consider similar to that of 7.4.2.4, as it is assumed to start with relatively unoxidised fresh spoils. The results show both low generation of salts and neutral pH profile.

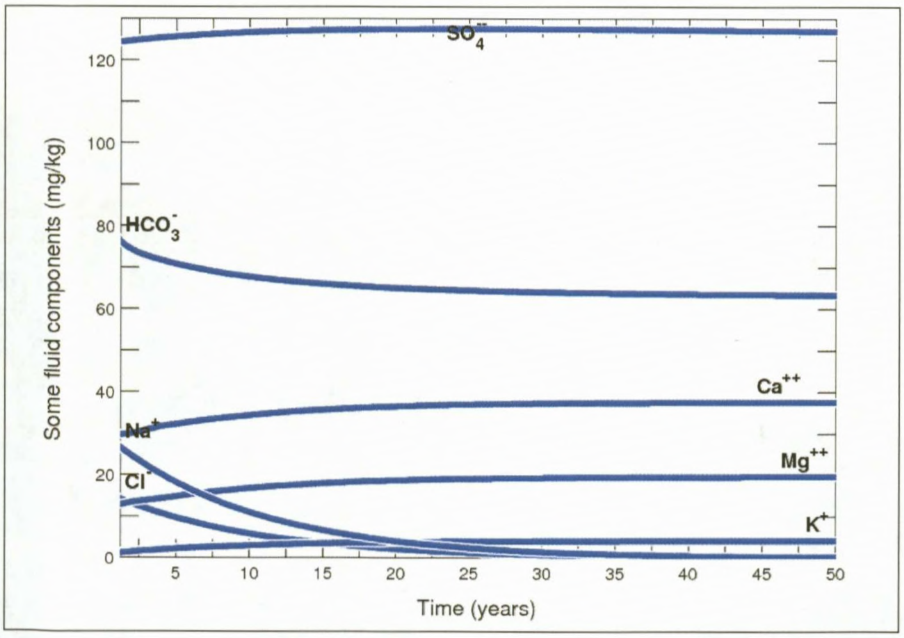


Figure 7-71: Concentration profile in fresh inundated spoils.

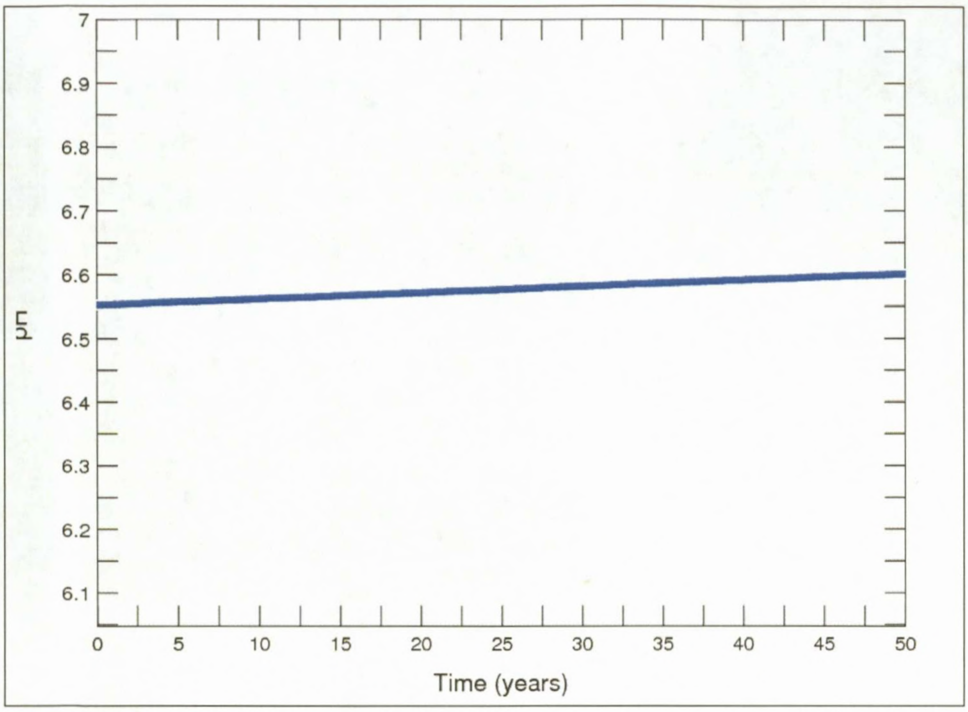


Figure 7-72: Neutral pH in fresh inundated spoils.

It is not surprising that the carbonates are in equilibrium and the gypsum is greatly below saturation levels.

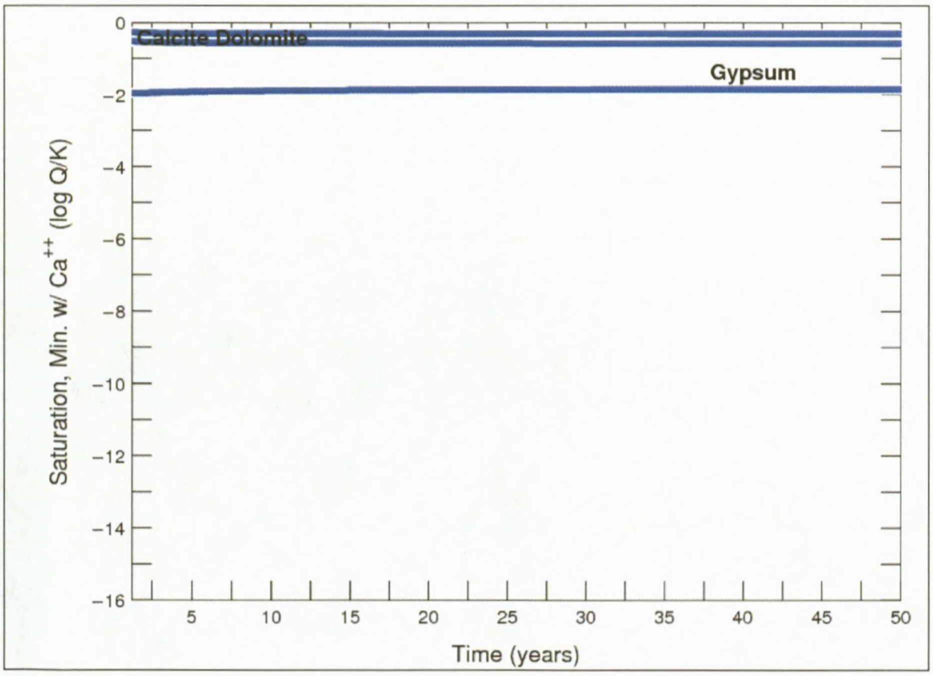


Figure 7-73: Mineral saturation where fresh spoils are inundated.

7.4.2.8 Geochemical modeling with Optimum Colliery water

The final three scenarios consider the result of leachate from irrigation. Three simulations were run with the following water qualities:

- The Optimum irrigation water (Table 7-4) evaporated by 85% (Table 7-5), as determined by PREEQC (this is in line with the expected ET at the pivot site). The simulation after evapotranspiration is illustrated in Figure 7-74.

*Table 7-4: Optimum irrigation water quality (**before evaporation**).*

pH	EC	Ca	Mg	Na	K	PAlk
	mS/m	mg/L	mg/L	mg/L	mg/L	mg/L
7.99	309	376	313	112	19.1	0
MAlk	**F**	**Cl**	**NO2(N)**	**Br**	**NO3(N)**	**SO4**
mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
185	0.62	34	<0.01	0.16	0.18	2290

*Table 7-5: Optimum irrigation water quality (**after evaporation**).*

pH	Ca	Mg	Na	K	Malk	Cl	SO4
7.78	426	835	234	21	26	146	5995

- The water that was sampled in the 2m column in the spoils at Optimum. (The original irrigation water quality is the same as in Table 7-4. This water has moved pass the root zone of the grass planted on top of the column and probably indicates the most accurate scenario. The high nitrate value is due to fertilizer application. The simulation after evapotranspiration is illustrated in Figure 7-75.

*Table 7-6: Optimum 2m column water quality (**after evapotranspiration**).*

pH	EC	Ca	Mg	Na	K	PAlk
	mS/m	mg/L	mg/L	mg/L	mg/L	mg/L
6.53	496	504	986	29.1	18.6	0
MAlk	**F**	**Cl**	**NO2(N)**	**Br**	**NO3(N)**	**SO4**
mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
31	0.2	43.39	<0.01	0.04	17.76	5423

- Water quality from Soil Water Balance program simulations, i.e. water that moved passed the root zone. The simulation after evapotranspiration is illustrated in Figure 7-79.

Table 7-7: Water quality simulated by SWB (water quality input before simulation by SWB).

pH	TDS	Ca	Mg	Na	K	HCO3	Cl	SO4
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
6.50	3336	480	265	47	0	580	38	1920

Table 7-8: Water quality simulated by SWB (water quality input after simulation by SWB).

Ca	SO4	Mg	Na	K	Cl	HCO3
mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
216	15853	38	4775	30	3861	347

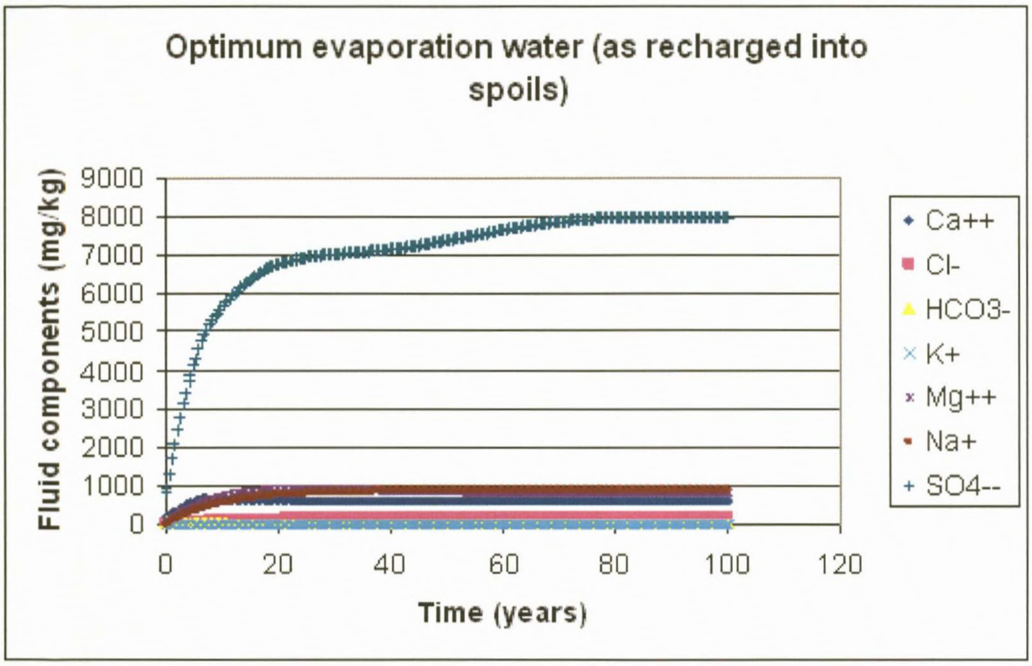


Figure 7-74: Concentrations of major ions over time with evaporated Optimum water.

From the simulations it is clear that the water quality measured in the spoils columns seems to be fairly accurate regarding movement past the root zone. The simulation for the Optimum 2m column water in Figure 7-75 and that of the simulated evaporated water in Figure 7-74 are very similar.

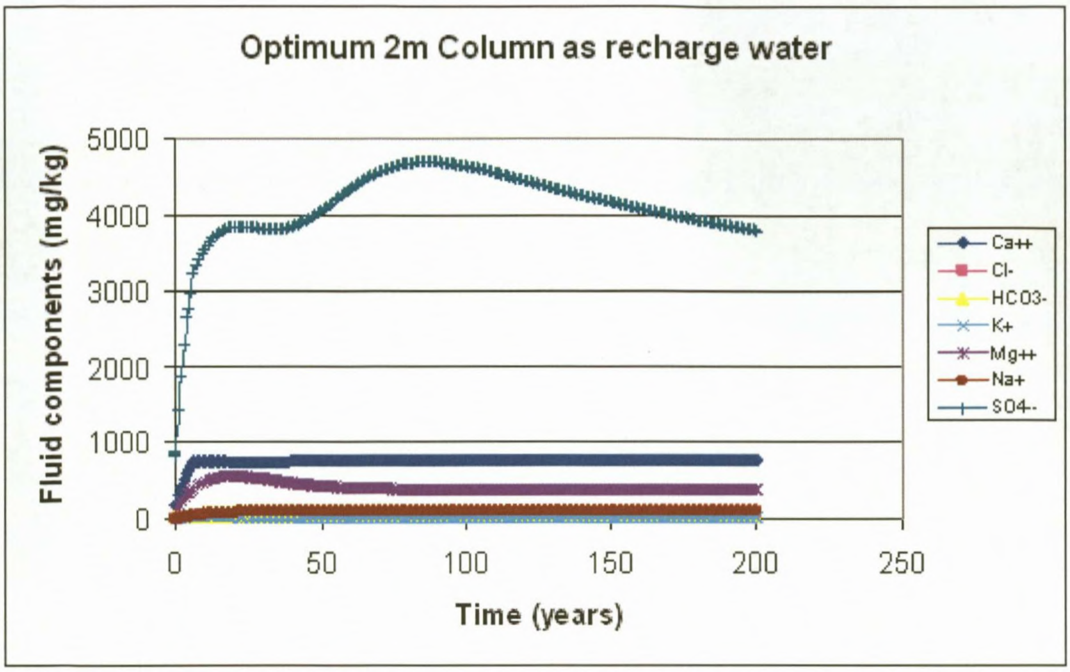


Figure 7-75: Concentrations of major ions over time with Optimum column water.

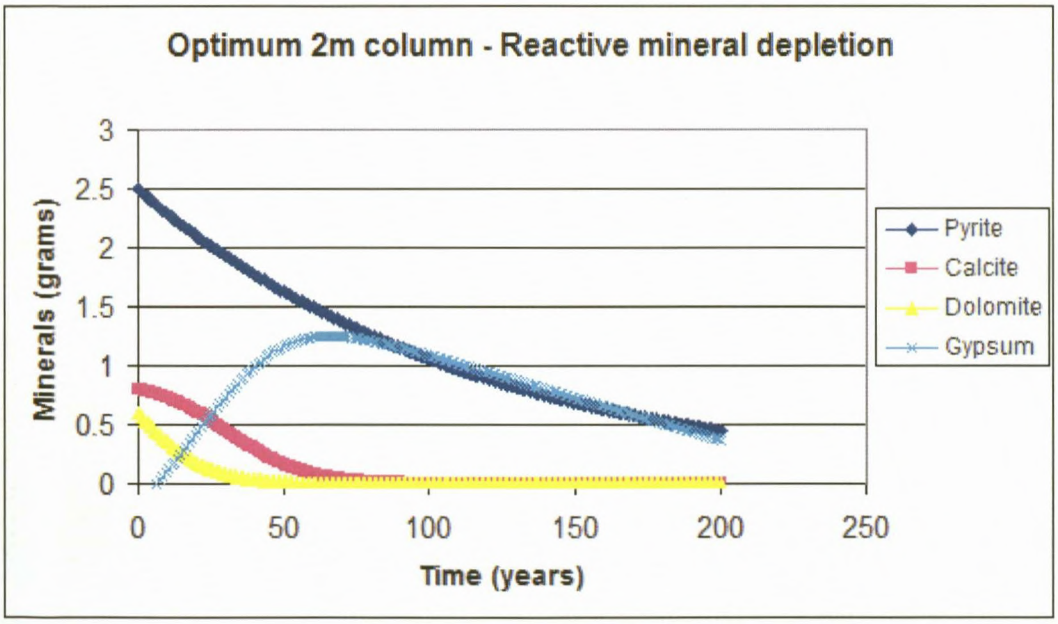


Figure 7-76: Decrease in reactive minerals over time.

The simulation of the Optimum column water indicates that the sulphate generation only starts to decrease after 90 years of irrigation (Figure 7-75). Figure 7-76 indicates that calcite and dolomite will be limited by the saturation of gypsum (Figure 7-78) and deplete within 50 years, togetherwith a decrease in pyrite and precipitation of gypsum. During this time the pH will drop (Figure 7-77). This demonstrates that acidification would occur due to the persistence of pyrite over the carbonates. After calcite and dolomite are depleted, gypsum will start acting as buffer.

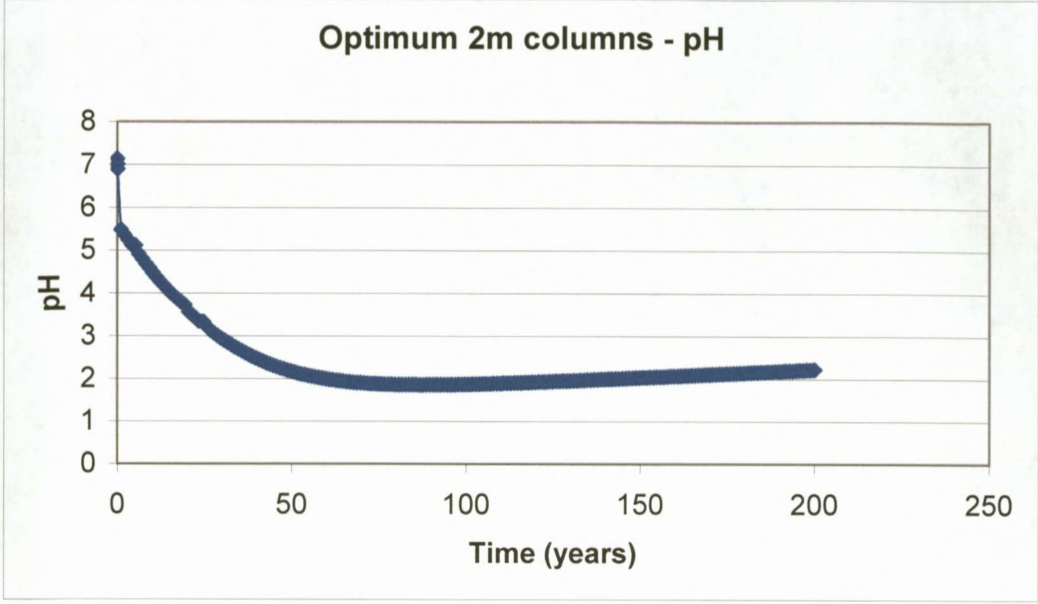


Figure 7-77: pH profile at Optimum over time.

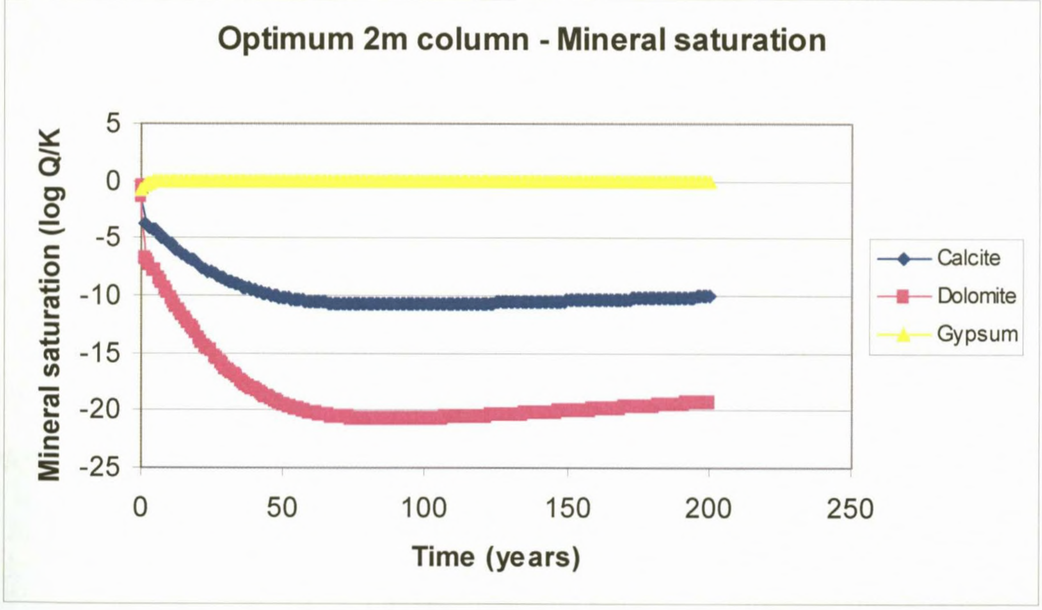


Figure 7-78: Mineral saturation of the Optimum 2m column water.

The values obtained from the Optimum simulations are much lower than those predicted based on Soil Water Balance model (SWB) simulated leachate in Figure 7-79. It therefore seems as if the SWB model predicts values that are too high, and the effect that this has on the spoils irrigation is that this will increase the concentration at which gypsum equilibrium occurs.

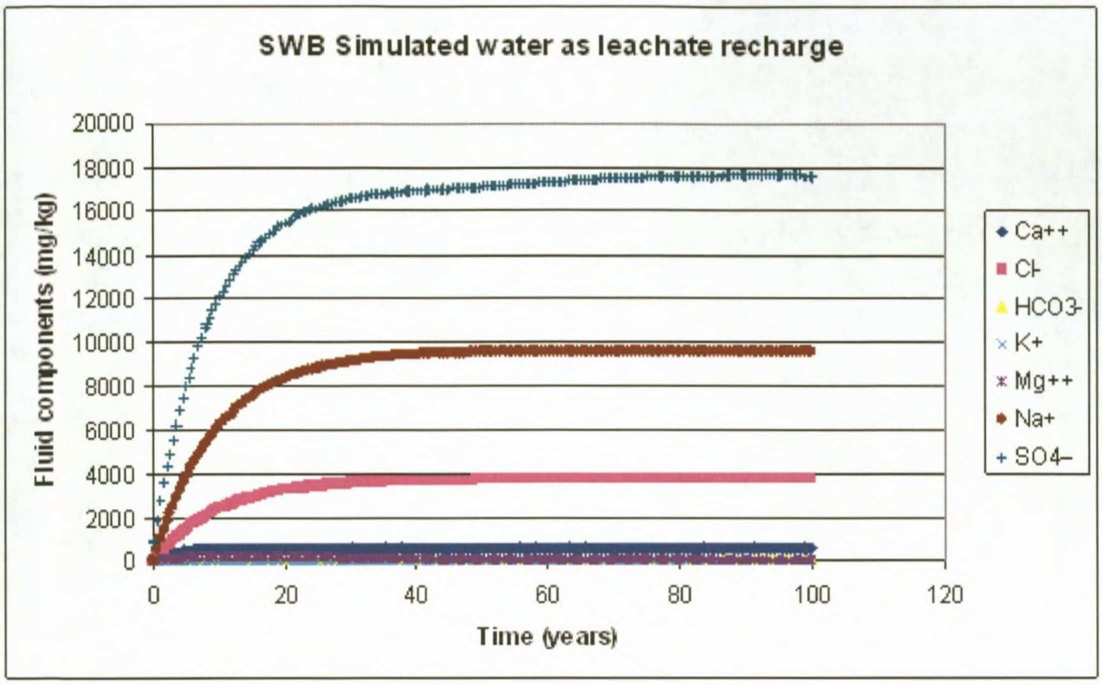


Figure 7-79: Concentrations of major ions over time with SWB simulated water.

Generally this indicates that mine water irrigation on spoils will lead to a further deterioration of spoils water quality, when compared to rainfall infiltration into the spoils.

7.5 Discussion of geochemical response

Laboratory and field studies, together with geochemical model testing, are carried out to determine the general behaviour of the spoils under various conditions. Each approach has its own particular advantages and drawbacks, but the cumulative understanding from the collective use of these techniques allows the construction of feasible conceptual reaction models and a derivation of expected outcomes from the different applications of mine water irrigation.

The tests and models indicate the great importance of the reactive nature of the spoils on which irrigation will occur. The potential for acid generation is a very important indicator of where to apply mine water irrigation, while it is also clear that in high sulphide areas, the irrigation will enhance reactions and therefore lead to a higher salt load generation.

The re-use of irrigation in certain systems has both advantages and disadvantages. The advantages of a "closed" or semi-closed loop means that the salt is not released into the environment. It is shown that secondary minerals solubility constraints will limit the possible upper values. It is therefore clear that the nature of the recirculating water is important.

Where the mine water used for irrigation is largely gypsyferous, the recirculation scenario is feasible under the correct conditions (e.g. impermeable floor rocks). Where this water contains many other elements, such as the sodium bicarbonate waters at Syferfontein, the solubility limits become far higher due to the increase in ionic strength of the percolating water. Under these conditions, concentrations will continue rising to very high levels. This continuous rise is confirmed not only by theoretical considerations and geochemical models, but also by observations from laboratory tests. The implication is that the nature of the spoils must be considered in terms of what the likely soluble concentrations of different elements will be.

Where mine water of relatively consistent quality is used, the changes in longer-term quality will be far less dramatic. The system reaches an equilibrium state and can continue in this state for long periods of time. The nature of the mine water is important in terms of the alkalinity, acidity and total ionic strength. The former two parameters will play a role in determining the depletion of the neutralisation capacity of the rock, which in turn will determine the relative reactivity and generated salts. Where mine water containing some alkalinity is used, this will decrease the salt loads in the long term, provided that the alkalinity is mostly associated with calcium-containing carbonates. Where this is not the case, the ionic strength effects of the co-existing dominant cation will result in the benefits of added alkalinity being offset and concentrations rising steadily in the longer term.

The complexity of the interactions makes it necessary to consider several factors simultaneously in terms of the feasibility and effects of mine water irrigation on spoils.

8 CONSOLIDATED MODELS OF MINE WATER IRRIGATION FOR VIRGIN SOIL IRRIGATION

8.1 Introduction

Irrigation with mine water is currently one of the most promising uses of excess mine water. However, there is continuing concern, especially from the regulatory authorities regarding the long-term impact that larger-scale implementation of this practice may have on water resource (specifically groundwater) quality and quantity. Other options for the use of the water e.g. the treatment of water for human consumption are being investigated. If this becomes a reality, irrigation will only be an option at collieries where there is excess water, thus reducing the area of irrigation drastically.

Opencast: About 75 000 ha of opencast will finally be rehabilitated in the Mpumalanga region. As the annual water use to irrigate 1 ha is 5 000 m^3, then the excess of 20000 ha could be irrigated for a single crop.

Underground: For shallow mines every 7-14 ha will provide enough water to irrigate one hectare. These values are also applicable to stooped areas. For deep underground bord-and-pillar areas 18 hectares will provide enough water through recharge to the underground workings for one hectare of irrigation.

Because the overall water quality trend in the deeper aquifer indicates that the water quality does not show significant deterioration over time the aim of the research was to determine the feasibility of irrigation with coalmine water, and what the effect will be on the groundwater. From all the work at the test sites and in the laboratory, detailed models of the water and salt migration at the different sites could be established.

8.2 Virgin soil model

Based on the earlier chapters, a general model for irrigation sites is as follows:

- Tensiometer data indicates that the soil throughout the profile is high in moisture content, with the exception of the top 0.5 - 1m. On average the moisture content is above 30%. The tensiometer data also indicates that the deeper layers dry out during winter.
- The clay rich layers play an important role in the moisture content, with a build-up of moisture above these layers. This indicates that clay does play a role in the vertical flux.

- The decrease in chloride values with depth in the profile (obtained from the porous cup data) indicates that preferential flow occurs at the irrigation sites together with the diffusive flow. Between 80% and 90% of the water needed for the dilution resulting in the chloride values at water table comes from lateral flow. (This calculated lateral flow corresponds with the calculated Darcy flux).

- At least 90% of the water that moves past the root zone reaches the water level. Due to lateral flow in the higher conductivity zones in the weathered saprolite zone, water moving past the root zone will have a lower concentration of salts.

- There is a definite relationship between the clay content and the vertical K-value. The vertical saturated K-value calculated is 10^{-4} m/d on average. This low value is the result of the swelling of the clays due to the moist conditions below the irrigation sites. The values obtained from these sites correspond with those obtained by other researchers. The unsaturated K-value derived from these findings indicates a value one order smaller than the saturated K, at the infered soil moisture contents measured from tensiometer data.

- Data from soil analysis with depth through the profile indicates that most of the salt is contained in the top 2 m of the profile. Chemical modelling of the soil water indicates saturation of the water with respect to gypsum above one meter, implying gypsum precipitation. Deeper down the soil water is unsaturated with regard to gypsum. Approximately 80% of the salts applied over the years of irrigation are retained. There is thus not a high degree of continuous leaching due to preferential flowpaths. Data from soil water analysis obtained from the porous cup sampling indicates that most of these salts occur in the soil water (about 60% of the total salts applied), and that the balance precipitates in the soil or gets adsorbed. This implies that over the short to medium term the irrigation with coal mine water does not influence the aquifers to a great degree. Dissolved salts leach to the aquifers at a very low rate and are diluted at such a fast rate because of lateral groundwater flux. As a result low concentrations are detected through borehole sampling.

- When irrigation ceases, it will take more than 15 years under optimal diffusive conditions to leach the salts out of the profile again. Due to the fact that preferential flow occurs, it can be more than 100 years. Of the sulphate captured in the soil, 25 % is adsorbed. This means that not all sulphate will be leached by excessive irrigation or rain.

- **Irrigation with gypsiferous water:**

Gypsum, more than any other single product on earth, uniquely helps soils to be more productive and fruitful (see Appendix C on Gypsum in soils). It also improves the soil structure and replaces harmful salts like sodium, which are detrimental to plant growth and development since they rupture and destroy plant cells. If gypsum is added, this will lead to a decrease in exchangeable sodium percentage (ESP). The calcium ions replace the sodium ions on the clay particles, 'stickiness' increases and sodicity decreases.

According to this research gypsum precipitates in the first meter in the soil profile. Salts are released very slowly into the groundwater, and the addition of water due to lateral flow dilutes it to such an extent that very little influence on the groundwater can be detected.

Recommendation: Irrigating with gypsiferous type water is an option over the short to medium term (10 years).

- Irrigation with sodium water:

However, the high sodium water at Syferfontein influences the ESP. High levels of sodium make the clay particles less 'sticky', so they do not adhere, or hold together, very well. Following rain in which the electrolyte concentration is relatively low, the combination of sodicity and raindrop action causes the clay particles to disperse instead of remaining in their original arrangement. The disruption of the soil structure, together with clay dispersion, greatly reduces the soil permeability since the larger pores are blocked.

Recommendation: Irrigating with sodium-type water is not an option over the medium to long term (> 10 years).

It is recommended that monitoring continue at the sites that are still in operation to study further trends.

8.3 Detailed site evaluation for virgin soil sites

In this section a detailed description and evaluation of each site will be dealt with. A reference to each section discussed is as follows:

- Water levels - section 3.3.4
- Groundwater monitoring - section 6.2

- Soil analysis - section 6.3
- Unsaturated soil sampling - section 6.4
- Gypsum precipitation - section 6.5
- Measuring moisture potential - section 6.6.1
- Salt balance - section 6.6.2
- Leaching of sulphate - section 6.6.3
- Identification of aquifer parameters - section 6.6.4
- Determination of the flow hydraulics - section 6.6.5
- Influence of clay on vertical conductivity - section 6.6.6

8.3.1 *Kleinkopje 1*

The soil at Pivot 1 varies with depth (Bainsvlei and Clovelly soils) and is underlain by sandstone and coal. The area below the pivot is undermined. The soil is on average 4m deep with a 4 - 6m weathered sandstone zone beneath itt. The soil texture at this site varies greatly with depth and there is a distinctive clay-rich layer at 2m (18.6%). Above this layer the clay content is <4% and below this layer the clay content is 9%.

The water levels, as expected at an irrigation scheme, are very shallow (approximately 2,8m). The time variation of the water levels indicates that they fluctuate in correspondence with the seasons. Typically, the water level drops during the mid- to late winter months, and then recovers again during mid- to late summer.

The total water that is applied to this site is 1500mm annually, of which 700mm is rain. The irrigation water applied is 800mm with a sulphate content of approximately 2200 mg/L. The gypsiferous type water results in an increase in the soil salinity, with most of this in the upper 0.7m of the profile. The data for the soil water monitoring from the porous cups shows a steady decrease in sulphate concentrations with depth (decreasing from 4700 mg/kg at 1m to 260 mg/kg at 3m - this is more than at the other sites. Irrigation at this site commenced a few years before the other sites, indicating movement down the soil profile, resulting in the larger concentrations of salts deeper down). Calcium decreases much more than the other cations, indicating gypsum precipitation in the upper drier soil. However, most of the salts in the moist layers 0.7 meter and deeper are retained in the soil water. Tensiometer data show a moisture content of 0.32 at 1m and 0.37 at 2m. The total mass of salts retained in one hectare of irrigated land is 56 ton, of which 47 tons is in the soil water (84 % of the total salts retained).

The decrease in the chloride values down the soil profile confirms preferential flow in the unsaturated and weathered zones. Under preferential flow or by-pass flow conditions some of the precipitated water (with relatively low chloride concentration) will flow directly along these preferred pathways to the water level. This bypass flow component, less affected by evapotranspiration, dilutes the soil water that is concentrated by transpiration, resulting in relatively low concentrations in the percolation zone with respect to the concentrations encountered in the root zone. Sharma and Hughes (1985) introduced a bimodal model including a bypass flow component. From a variation of this model it was calculated that the diffusive flux attributes 14% to the mixing process (of diluting the salts) and the lateral flux 86%. Of the total volume of water applied to the site, 9.4 % reaches the groundwater. This results in a build-up of salts in the profile above the water level, but there will also be an increase in salinity in the water below the pivot, as has been illustrated with the well constructed boreholes. This water will move through the weathered zone into the deeper fractured aquifer along vertical fractures, or laterally. Some may also daylight in streams or as springs.

Water balance:

- Total water applied /day (irrigation + rain) = 42 m^3/d
- Total volume of water per 1 ha that reached aquifer below irrigation pivot = Q_v+Q_{Bp} = 3.9 m^3/d
- Lateral flux along 1 ha = Qh = 0.25 m^3/d (estimated from Cl mass balance). Darcy estimate of lateral flux along 1 ha =T*i*L=3*.001*100 = 0.3m^3/d, which is in agreement with the Cl mass balance estimate.
- 35% of the water that moves past the root zone (after ET) reaches the water level. This is 9% of the total water applied daily (3.9 m^3/ha/d). This value is lower than at the other pivot site, probably because a large amount of the water drains down to the undermined area near to the test site.

Salt balance:

- Total salts applied (ton/ha) = 83 ton/ha
- Total salts retained in profile = 56 ton/ha. 67% of the total salts applied to Pivot 4 is retained in the soil
- Total retained salts in soil water = 47 ton/ha, which is 56% of total salts applied.

A summary of the detailed model at Kleinkopje 1 is illustrated in Figure 8-1.

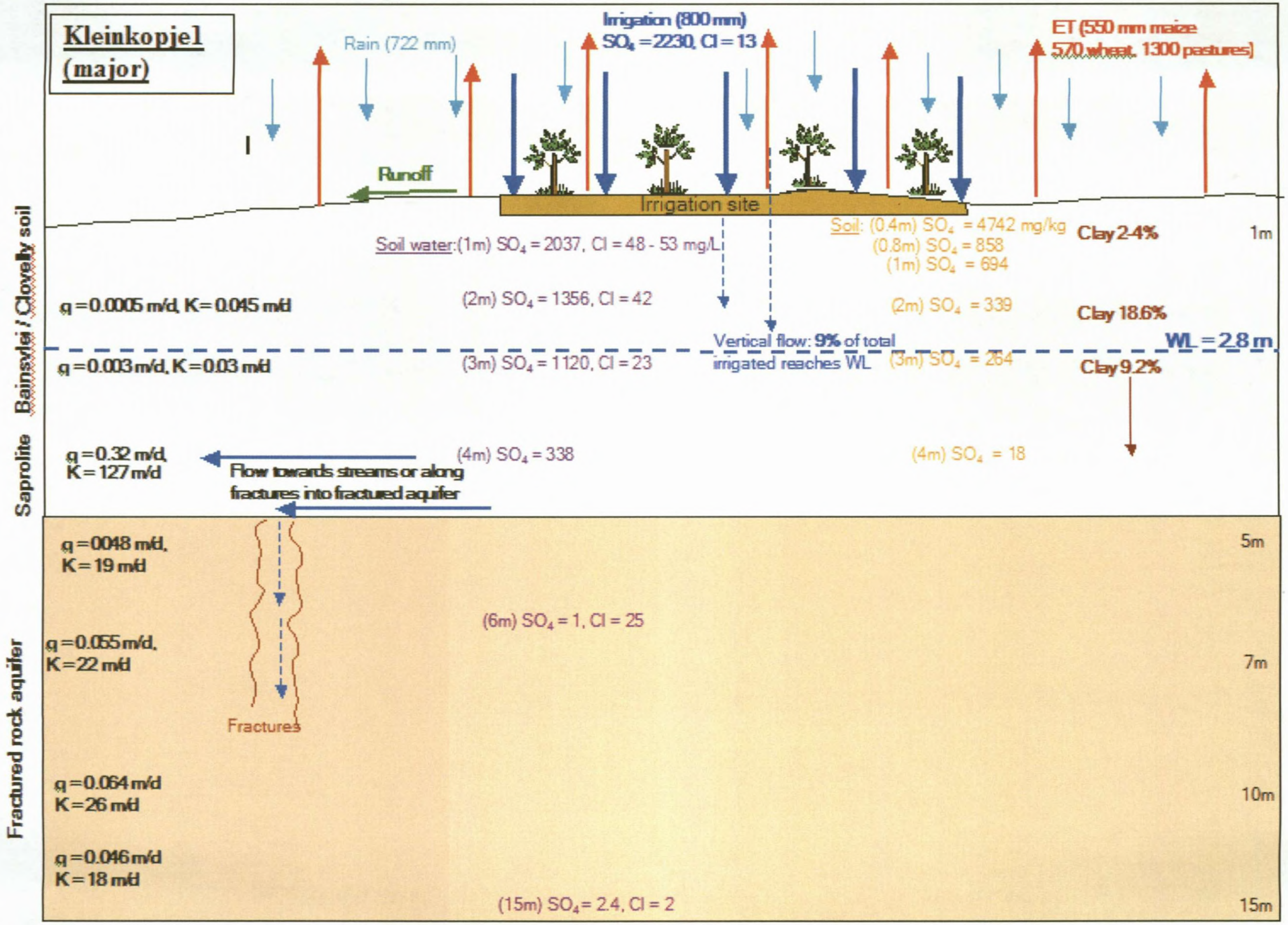


Figure 8-1: Detailed model of Kleinkopje 1.

8.3.2 *Kleinkopje 4*

The Hutton soil at Pivot 4 varies with depth and is underlain by sandstone. The soil is on average 6-7 m deep with a 4 - 6m weathered sandstone zone beneath it. The soil texture at this site varies greatly with depth and there is a distinctive increase of clay at 3m (27%). Above this layer, the clay content is 14 - 19% and 23% below it.

The water levels, as expected at an irrigation scheme, are shallow and vary between 3m and 4m. The water levels fluctuate in correspondence with the seasons. Typically, the water level drops during the mid- to late winter months, and then recovers again during mid- to late summer.

The total water applied to the site is 1500mm annually, of which 700mm is rain. The irrigation water amounts to 800mm, with an average sulphate content of 2200 mg/L. The gypsiferous type water results in an increase in the salt content in the soil, with 96% occurring in the upper 2m of the profile (48 ton/ha). The data for the soil water monitoring from the porous cups shows a sharp decrease in sulphate concentrations with depth (from 1600 mg/kg at 1m to 2 mg/kg at 3m. The sulphate concentration in the soil at 4m, just below the water level, is 59 mg/kg, which confirms that part of the salts reaches the water level, resulting in a build-up). XRD results indicate that calcium decreases far more than the other cations, indicating gypsum precipitation in the upper drier soil. Most of the salts is retained in the soil water. Tensiometer data showed a moisture content of 0.358 at 1m and 0.339 at 2m. The total mass of salts retained in one hectare of irrigated land is 48 tons (77% of total salts applied), of which 37 tons are in the soil water (60 % of the total salts retained). The clay layer at 3m causes ponding in the soil above this depth.

The decrease in chloride values down the soil profile confirms preferential flow in the unsaturated and weathered zones. From a variation of the Sharma and Hughes model it was calculated that the diffusive flux attributes 14% to the mixing process (of diluting the salts) and the lateral flux 86%. Of the total volume of water applied at the site, 24% reaches the groundwater. This results in a build-up of salts in the profile above the water level, but there will also be an increase in salinity in the water below the pivot, as has been illustrated with the well-constructed borehole adjacent to the pivot. This water will move through the weathered zone into the deeper fractured aquifer along vertical fractures, or laterally (pumping tests in the boreholes at this site indicates influx of water at 6m). Part of the water may also daylight in streams or as springs.

Water balance:

- Total water applied /day (irrigation + rain) = 42 m^3/d

- Total volume of water per 1 ha that reached aquifer below irrigation pivot = Q_v+Q_{Bp} = 10 m^3/d
- Lateral flux along 1 ha = Qh = 0.54 m^3/d (estimated from Cl mass balance). Darcy estimate of lateral flux along 1 ha =T*i*L=5*.001*100 = 0.5 m^3/d, which is in agreement with the Cl mass balance estimate!.
- 88 % of the water that moves past the root zone (after ET) reaches the water level. This is 24% of the total water applied daily (10 m^3/ha/d).

Salt balance:

- Total salts applied (ton/ha) = 62 ton/ha
- Total salts retained in profile = 48 ton/ha. 77% of the total salts applied at the pivot 4 have been retained in the soil.
- Total retained salts in soil water = 37 ton/ha, which is 56% of total salts applied.

A summary of the detailed model at Kleinkopje 4 is illustrated in Figure 8-2.

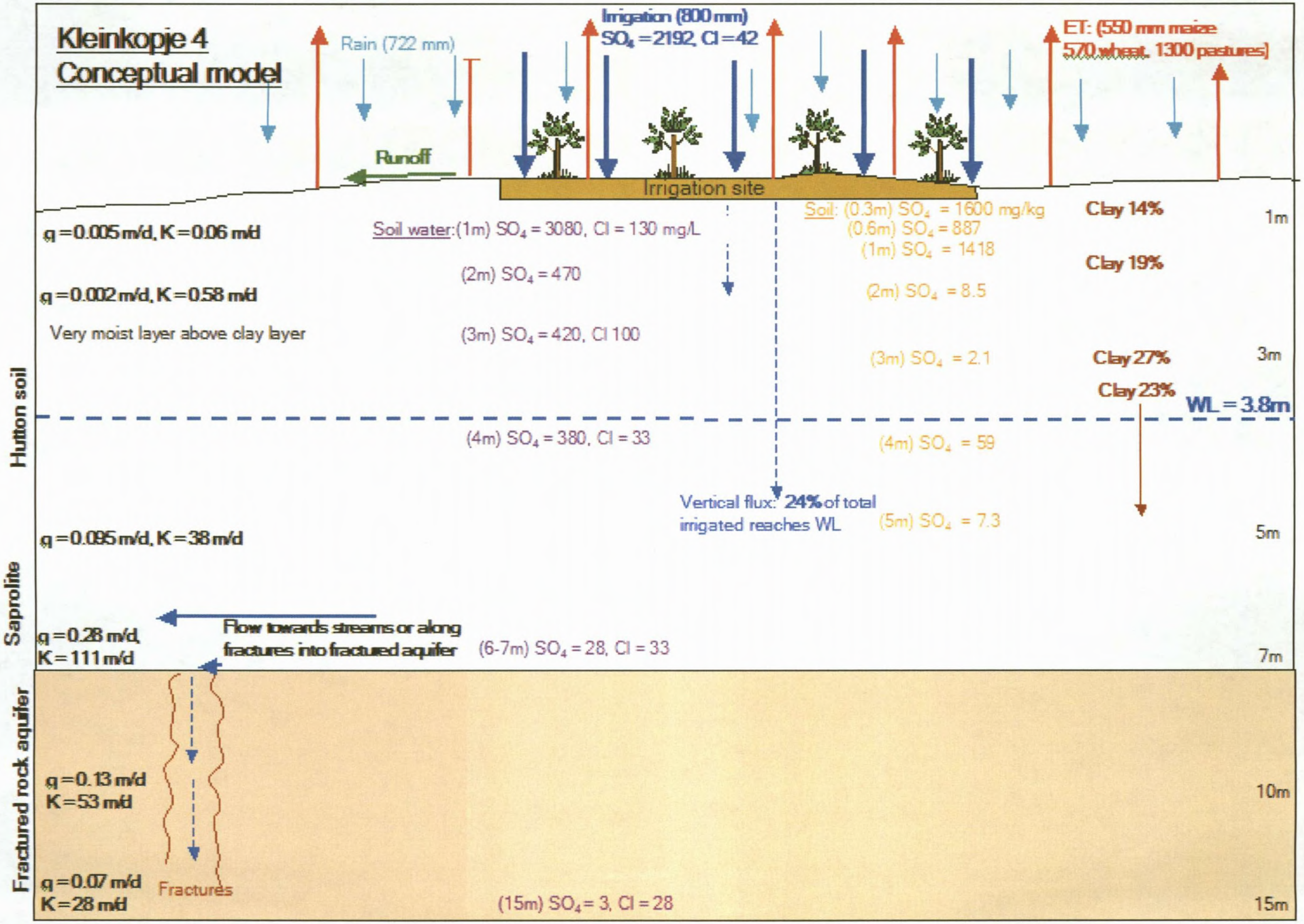


Figure 8-2: Detailed model of Kleinkopje 4.

8.3.3 *Syferfontein*

The geology at Syferfontein is relatively homogeneous with the weathered sediments up to 10m deep. The strata mainly consist of 2 - 6 m Arcadia soil, followed by weathered dolerite and shale to 10m. The shale is underlain by fresh sandstone with a white appearance. At the depth of 32-35 m the sandstone is underlain by shale. The Arcadia soil at Syferfontein varies with depth. The soil texture at this site varies greatly with depth, with a high clay content. The clay % at the top is 63%, decreasing to 31% at the water level of 4m. Below the water level it decreases to 26%.

The water levels, as expected at an irrigation scheme, are shallow and vary between 3 m and 5 m. The water levels fluctuate in correspondence with the seasons.

The total water applied to this site is 1500mm annually, of which 700mm is rain. The irrigation water amounts to 800mm with a sulphate content of 1370 mg/L. The sodium sulphate water results in an increase in the salt content of the soil, with 95% occuring in the upper 1m of the profile (41ton/ha). The data for the soil water monitoring from the porous cups shows a sharp decrease in sulphate concentrations with depth (decreasing from 6400 mg/kg at 1m to 17 mg/kg at 3m). Most of the salts are retained in the soil water. Tensiometer data showed a moisture content of 0.384 at 1m and 0.35 at 2m. The total mass of salts retained in one hectare of irrigated land is 42 ton (82% of total salts applied), of which 33 tons are in the soil water (64% of the total salts applied, or 78% of the salts retained).

The decrease in the chloride values down the soil profile confirms preferential flow in the unsaturated and weathered zones. From a variation of the Sharma and Hughes model it was calculated that the diffusive flux attributes 2% to the mixing process (of diluting the salts) and the lateral flux 98%. Of the total volume of water applied at the site, 26% reaches the groundwater. Most of the salts build-up in the profile above the water level, but there will also be an increase in salinity in the water below the pivot, as illustrated with the well-constructed deep borehole inside the pivot. (The sulphate value in the water is 150-175mg/L).

> Note: For a long period during the duration of the research project, the pivot was broken down. Due to flooding directly onto the irrigation site very near to the experimental site, the lateral flux values obtained may be exaggerated.

Water balance:

- Total water applied /day (irrigation + rain) = 42 m^3/d
- Total volume of water per 1 ha that reached aquifer below irrigation pivot = Q_v+Q_{Bp} = 11 m^3/d

- Lateral flux along 1 ha = Qh = 5 m^3/d (estimated from Cl mass balance). Darcy estimate of lateral flux along 1 ha =T*i*L=7*.005*100 = 3.5 m^3/d, which is in agreement with the Cl mass balance estimate.
- 94% of the water that moves past the root zone (after ET) reaches the water level. This is 26% of the total water applied daily (11 m^3/ha/d).

Salt balance:

- Total salts applied (ton/ha) = 51 ton/ha
- Total salts retained in profile = 42 ton/ha. 82% of the total salts applied at the pivot have been retained in the soil.
- Total retained salts in soil water = 33 ton/ha, which is 64% of total salts applied (or 78% of the salts retained).

A summary of the detailed model at Syferfontein is illustrated in Figure 8-3.

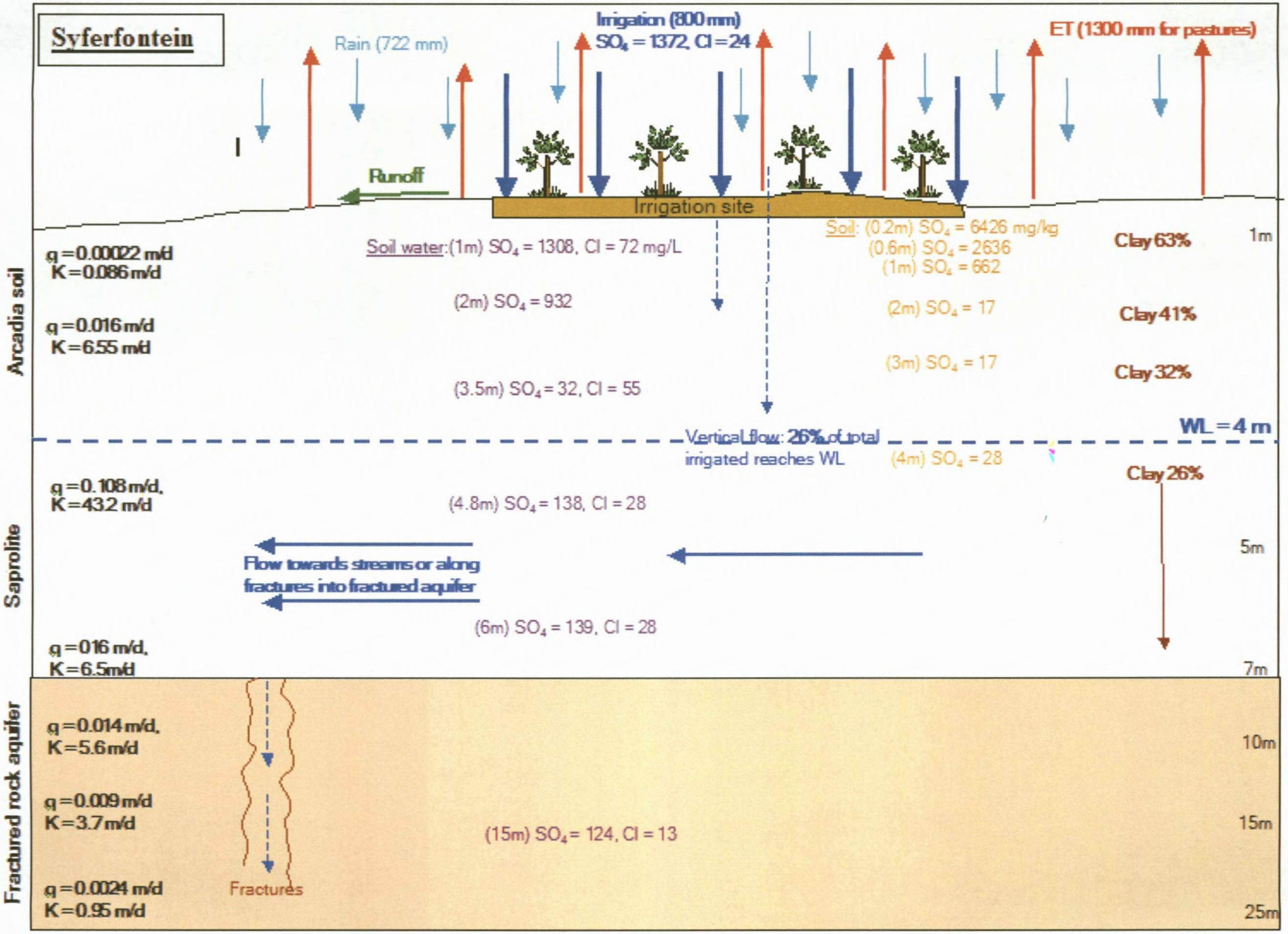


Figure 8-3: Detailed model of Syferfontein.

8.3.4 *New Vaal*

At New Vaal the profile is a very sandy soil with a clay layer of 24% above 3m. Above this layer the clay content is 4%, and 14% below it. Drilling at the site indicated that the sand is quite clayey deeper down, which will retard the vertical movement of water. The clay layer at 3m results in the retardation of the vertical movement of the water, and causes a build up and ponding on surface during periods of high irrigation.

The water levels at the irrigation site are deeper than at the other sites. They vary between 10 m and 12 m and shows a downward trend over time, which implies that the water drains away.

The total water that is applied to this site is 1500mm annually, of which 640 mm is rain. The irrigation water amounts to 800mm with a sulphate content of 450 mg/L. The sulphate-rich water results in an increase in the salt content of the soil. It is evenly distributed down the soil profile up to the water level, with some build-up above the clay layer at 3m. In the upper 1m very little salts are retained, with less than 200kg/ha in the soil. Only 36% of the salt are being retained in the soil water, indicating less moist conditions than at the other sites, which implies that the water moves down the soil profile relatively quickly. (The chloride in the aquifer indicates a recharge of more than 10% for the vicinity). The total mass of salts retained in one hectare of irrigated land is 18 tons (85% of total salts applied), of which 6.5 tons are in the soil water (30 % of the total salts retained).

In the upper layers an increase in chloride with depth occurs, which implies that no preferential flow occurs, or that the salts are being retained in the clayey layers. The decrease in the chloride values down the deeper soil profile confirms lateral flow in the unsaturated and weathered zones. From a variation of the Sharma and Hughes model it was calculated that the diffusive flux attributes 27% to the mixing process (of diluting the salts) and the lateral flux 73%. Of the total volume of water applied to the site, 25% reaches the groundwater. There is a slow increase in salinity in the water below the pivot, as illustrated with the borehole inside the pivot. (The sulphate value in the water is 93 mg/L).

Water balance:

- Total water applied /day (irrigation + rain) = 39 m^3/d
- Total volume of water per 1 ha that reached aquifer below irrigation pivot = Q_v+Q_{Bp} = 10 m^3/d
- Lateral flux along 1 ha = Qh = 0.26 m^3/d (estimated from Cl mass balance).
- All the water (100%) that moves past the root zone (after ET) reaches the water level.

Salt balance:

- Total salts applied (ton/ha) = 21 ton/ha
- Total salts retained in profile = 18 ton/ha. 85% of the total salts applied at the pivot have been retained in the soil.
- Total retained salts in soil water = 6.4 ton/ha, which is 30% of total salts applied.

A summary of the detailed model at New Vaal is illustrated in Figure 8-4.

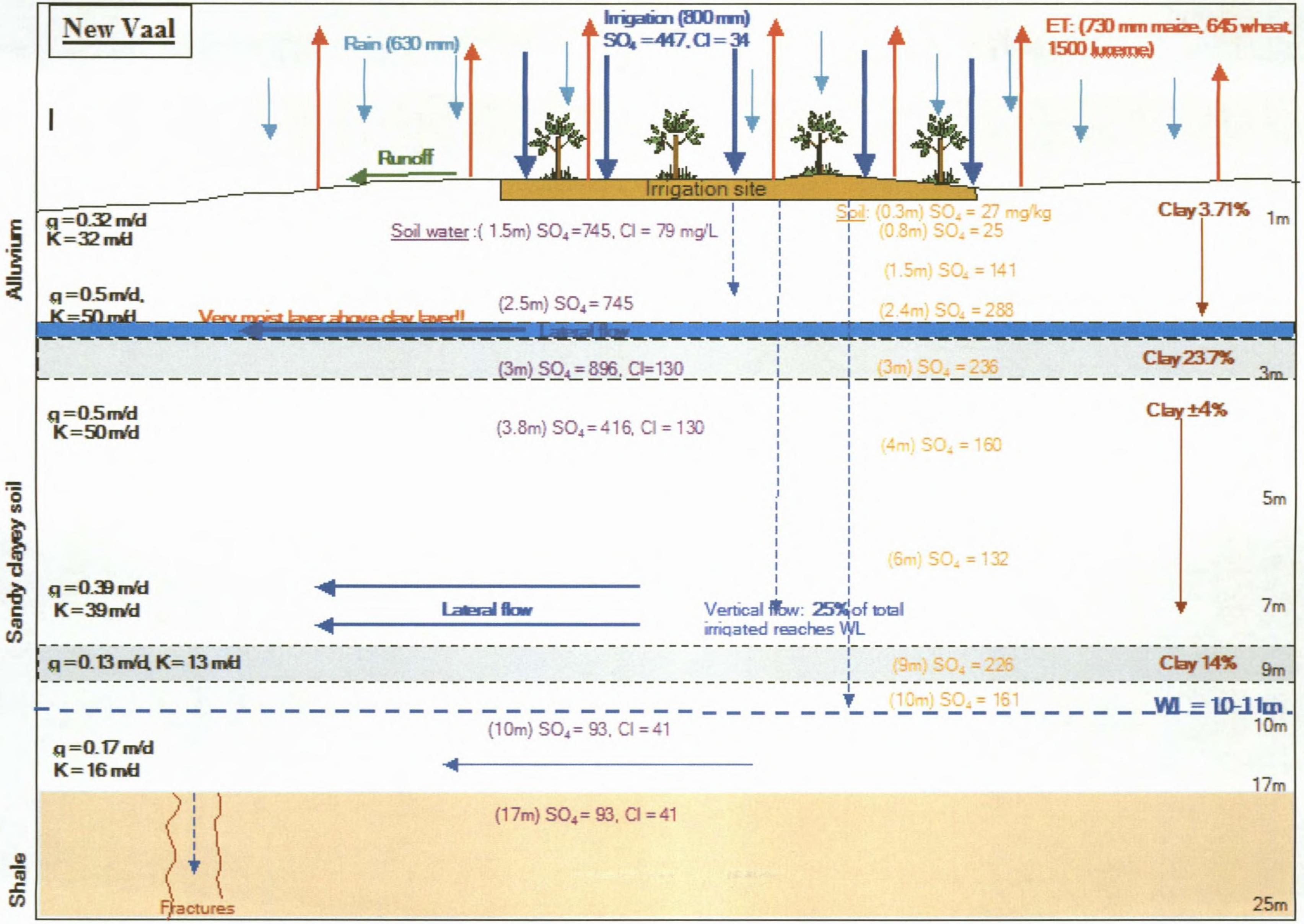


Figure 8-4: Deatailed model of New Vaal.

8.4 Summary of Results

In Table 8-1 a summary of all the experiments, the results as well as the implications for the research are portrayed.

Table 8-1: Summary of all the experiments.

Site	Description	Results	Implications
Kleinkopje 1 (Major) Kleinkopje 4 Syferfontein New Vaal	Borehole monitoring	1. The majority of the groundwater constituents at KK Pivot 1 and 4 and Syferfonrein have not shown increases over time. This indicates that these macro constituents are not reaching the groundwater. Very little, if any, pollution are detected in the groundwater. 2. PV5 within the New Vaal pivot area is showing signs of consistent water quality degradation, with increases in most of the constituents. The piesometers show high salt values in the water above the clay layer. 3. The water levels at all the sites are elevated.	1. It is clear at KK that there is currently a build up of salts in the soils above and within the clayey layers, and that a limited proportion of the associated salts move through into the groundwater. 2. The clay layers in the sands of NV are very important in the retardation of the movement of soil water and constituents down into the aquifer. Do we measure correctly? Is the leakage into the aquifer quick enough?
Kleinkopje 1 (Major) Kleinkopje 4 Syferfontein New Vaal	Pits and soil sampling	KK1: Sandy soil but shows a marked increase in clay content below the depth of 1m (18%). Calcium decreases with depth, while magnesium and sodium are affected by probably the clay layer just below one meter. Potassium also decreases with depth. KK4: The magnesium initially increases, and then decreases. This may be the result of sorption at the clay layer at 3m depth. Sodium and potassium level out at 3m, but do not decrease in value. Syfer: High sulphate concentrations in the upper one meter of soil. It can be concluded that all the cations move through the clayey Arcadia soils at the same degree, with sodium obviously at higher molar concentrations because of the composition of the irrigation water. The magnesium is a lot less in the water than calcium and potassium. NV: Calcium and magnesium concentrations increase drastically in the clay layer at 2.4m depth. Even the potassium, which has a far lower concentration in the water, increased in the clay layer. Chloride and sulphate follow the same pattern as all the major cations except sodium.	1. There are hydraulic and attenuation factors preventing the salts in the mine water used for irrigation from being mobilised down the soil profile and into the aquifer. The soil composition (especially the clay) and associated sorption and hydraulic properties may be informative. 2. The results point to several potentially important findings for the wider application of mine water irrigation. It would appear that where the soils are richer in clay content, there is a significant attenuation of salts in the shallower zones. The groundwater monitoring results indicate that this attenuation makes mine water irrigation a viable option in the short to medium term where gypsum rich waters are used. The clays play an important role in retaining the salts to the upper few layers of the profile. The comparison between the soil leaching and porous cup data supports this. 3. The clay layer in the sandy soil results in very little movement of salts pass the layer. This is conirmed by piesometer measurements. The clays results in ponding. Soil texture is important in soil moisture calculations.
Kleinkopje 1 (Major) Kleinkopje 4 Syferfontein	XRD	No gypsum could be detected in any of the samples, even those that consisted mostly of precipitate scraped from surface. It has been revealed that bassanite, the hydrous form, $CaSO4\ 0.5H2O$, or calcium sulfate hemihydrate, is present in most of the samples.	Heat built-up definitely occurs between the densely populated plants in the irrigation area, and probably dehydrates the gypsum enough to be transformed to bassanite in the upper soils (dehydration starts at 40°C). Gypsum is thus definitely present in the soils, may it be in a more dehydrated form of bassanite.
Kleinkopje 1 (Major) Kleinkopje 4 Syferfontein Optimum	XRF	KK: There are indications that gypsum precipitation should occur since Ca values are far higher in the shallow portions, while Mg values are more evenly distributed. Syfer:The sulphur values obtained from the XRF are of interest since they indicate a strong attenuation in the shallowest layers of the profile.	KK: This would suggest that the distribution is chemically controlled rather than by surface interactions since these two ions should have similar sorptive capacities. This is supported by the Na values, which have an even distribution with depth. More gypsum present in upper layers.
Kleinkopje 1 (Major) Kleinkopje 4 Syferfontein Optimum	Porous cups	KK1: It is clear that calcium decreases a lot more than the other cations in depth, indicating gypsum precipitation. Syfer: There is sorption and ion exchange between magnesium and potassium because potassium increased in depth and magnesium decreased. The reason why sodium does not exchange is because the sodium content of the irrigation water is already very high.The sodium sulphate water results in high sodium and sulphate content in the upper layers of soil, which decreases with depth. The conservative chloride anion moves through the different layers at the same degree, without any precipitation or adsorption.	The results of the soil tests suggest that the porous cup results are consistent with the trapped pore water, precipitates and adsorped ions at each of these levels. The fact that the data collected from the porous cups, the soil salinities and the groundwater quality indicate the same trends as the soil analysis is encouraging, in light of the continuing research. Decrease of salts in depth, most precipitates in upper layers - not enough leaching to dilute the salts. Will need high rainfall events (more than evaporation factor to leach the salts in soil water. Is lateral movement > vertical.
Kleinkopje 1 (Major) Kleinkopje 4 Syferfontein Optimum	Tensiometers	The tensiometers at the virgin soil as well as the spoils idicate a decrease in soil moisture content in depth during the "drier" winter months when the volume of water apllied are more controlled. The distinct clay layers in the soil results in ponding above these layers after large rainfall events.	Controlled irrigation (less than 20mm at a time) will result in the salts not moving down the soil profile in large quantities.In the case of irrigation with colliery water, the quality of the water is such that it will not leach the salts in the soil, but will result in the accumulation of more salts. Effective irrigation will result in salts accumulating in the upper soil layers with less effect on the groundwater. Leaching will only result after heavy rainfall events or after over irrigation.
Kleinkopje 1 (Major) Kleinkopje 4 Syferfontein Optimum	Point Dilution Tests	1. At all the pivots flow zones were determined in the saprolite zone. 2. Darcy velocities were calculated for all zones in the profile, varying greatly in the different zones. The flow zones indicated conductivity values as high as in excess of 100m/d in the main flow zones. 3. The clay layers have very small conductivity values.	The water follows the path of least resistance. This means that most of the water (from the vertical as well as the lateral component) flows away along these flow zones until it daylights or where it reaches a fracture, then moving downwards into the fractured rock aquifer. This is the reason why so little increase in salinity in the groundwater occurs.
Kleinkopje 1 (Major) Kleinkopje 4 Syferfontein Optimum	Falling head tests	The upper soil zones have very small concuctivity values, less than 1m/d and as small as E-2m/d.	This implicates that very liitle water movement occurs in these upper zones. Most of the flow is along preferred pathways.
Kleinkopje 1 (Major) Kleinkopje 4 Syferfontein Optimum	Pumping tests	Normal transmissivity values for Karoo aquifers were obtained in all the boreholes. These values ranges from 0.2 to $0.8m^2/d$, with most of them in the order of $0.2m^2/d$.	These values indicate that the deeper rocks are not as weathered as is the case with the shallower saprolite. Recharge into these aquifer will be a lot less than the lateral movement of water, implicating that very little pollutants will move down into these deeper parts of the aquifers.

Laboratory	Leaching columns -spoils	1. The EC and sulphate variations over time reveal a very interesting phenomenon, namely that, where clean water irrigation is employed, the values decrease over time. The reason for this lies in the fact that the spoils have been oxidised prior to the experiment. Since they represent the results of the *in-situ* spoils at Optimum, it can be expected that oxidation has occurred in these spoils over time and the secondary products from oxidation reactions and the subsequent neutralisation would be contained in the spoils. 2. The deionised cells become undersaturated as secondary products are flushed out, but where leachate is recirculated or mine water used, the values remain close to saturation. 3. As can be expected in these columns, the carbonates are not stressed in the reaction period and calcite and dolomite are at or above expected equilibrium.	1. The laboratory columns are useful as they provide a better understanding of the real rates at which the processes occur and thus provide a closer "real-time" analogue of the field situation, although the volumes of water added reflect a far longer time of irrigation than is usually the case in the field. The good comparison with the field situation is encouraging in this regard. 2. It does indicate that the initial salt loads in such a system would be very high, with stabilisation occurring in time.
Laboratory	Leaching columns - adsorption	1. There is a definite decrease in sulphate in both columns. The change in these values is not very significant, but may be due to some adsorption. 2. An average sulphate adsorption of 24.9% of the total sulphate extracted. The rest (water extracted part) is precipitation.	1. This means that not all sulphate will be leached by excessive irrigation or rain. It must be noted, however, that desorption can occur and that the 25% sorbed sulphate will not be irreversibly fixed in the soil profile. 2. The acidic conditions in the soil also enhance sulphate adsorption. 3. There is no direct correlation between the clay content of the soil and the adsorption values, but the increased values are definitely a function of the hydraulic properties of the soil.
Laboratory	Leaching columns - salt leaching	Most of the soils are leached in the first few years, but more than 6000mm will be needed to flush the soil.Calculated saturated K value is 0.4 m/d	Without taking evapotranspiration into account, it will take nearly 20 years to leach the salts. Check against John's figures for these values to calculate a time. Not all adsorped sulphates willl leach - some will never be retained (40% of 25% total sulphates will remain in soil)
Laboratory	Leaching drums	Calculations with PHREEQC indicate that all the leachate are saturated or over saturated with respect to gypsum. Moist soil results in the leachate being under saturated with respect to gypsum.The increase in Ca and SO4 can only occur up to a point, where the aqueous solubility of these ions becomes limited by the solubility of gypsum. The sulphate concentrations in the leachate were all in this range. When the soil is wet, soil water not saturated with respect to gypsum	In the case of irrigation with colliery water, the quality of the water is such that it will not leach the salts in the soil, but will result in the accumulation of more salts. The only way to leach the salts is with heavy rainfall events. This means that the maximum quantity of gypsum leached from the soil, is bound by the gypsum saturation of the water moving through the soil. Calculating the sulphate (1800-2000mg/L) and calcium (600-700mg/L) concentrations in the leachate indicates that, if 20 tons gypsum / ha precipitated in the upper layer of soil, at least 40 - 50 heavy rainfall events (75mm) will be needed to leach the precipitated salts from the soil. Soil type not very important -solubitlity in water more important, as well as movement through soil -eg. clay will leach at same tempo if clay dry out, resulting in cracks. Tilling of soil will also play a role in leaching, as well as soil water content..
Optimum - lab	Humidity cells	1. The sulphate response is of great interest and shows that, when the recycled water contains significant ions other than Ca and SO4, the sulphate can increase to very high values over time.	1. Geochemical composition of spoils is the most important characteristic. 2. Irrigation with water with elevated alkalinity will assist in preventing acidification. 3. Iriigation with gypsiferous water will result in the drainage quality being very similar to that expected without irrigation in the long term. 4. Irrigation without water which is high in non-gypsiferous constituents will result in enhanched solubility of minerals and therefor poorer drainage quality. 5. In systems where water will be recirculated, there will be a steady decline in quality.

9 OPERATION AND MONITORING GUIDELINES

One of the outcomes from this study is to define the conditions under which mine water irrigation can be implemented and the associated operational and monitoring guidelines that should be followed. The section that follows explains in detail the rationale used and the rules that have been established for mine water irrigation. These have been based on the findings from this study, the fundamental considerations of mine water irrigation, the regulatory environment and, as far as possible, the practical implementation of mine water irrigation as part of optimal mine water management.

9.1 Basic Data Input

It is important that the criteria for irrigation operation and monitoring take the fundamentals, the results from this research and the site specific conditions into account.

The rationale used to provide guidance on site selection, monitoring and operations is summarized by Figure 9-1.

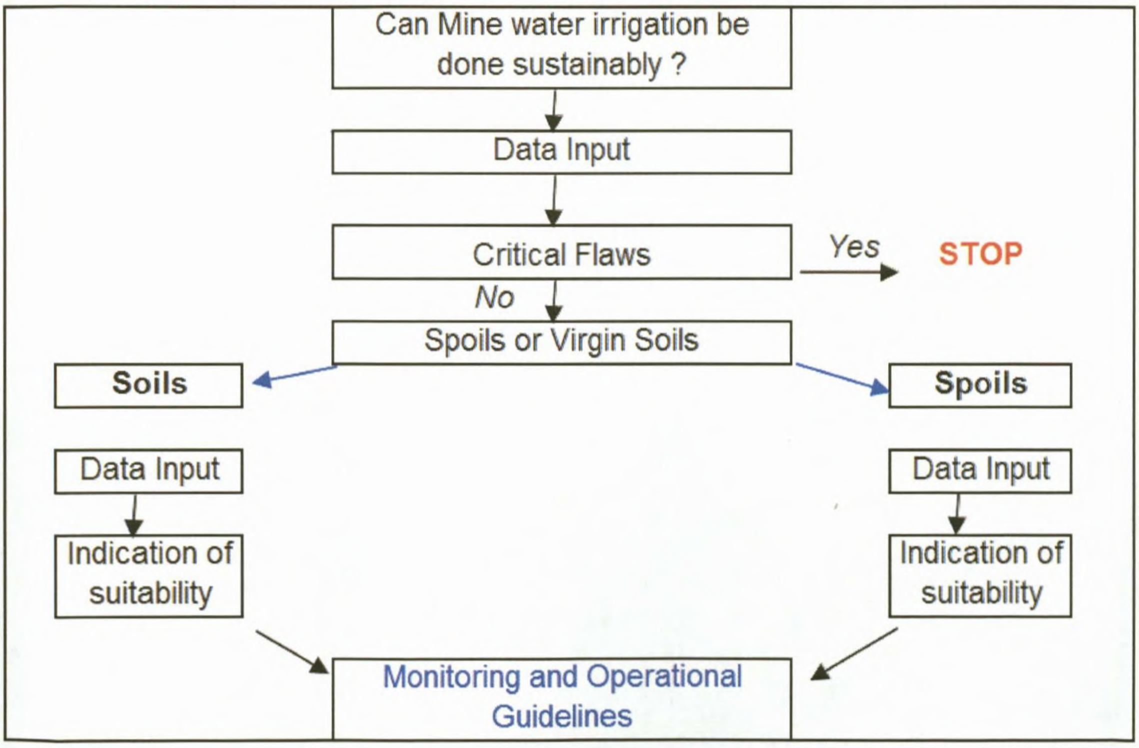


Figure 9-1: Rationale for defining site-specific criteria.

This figure indicates that there is basic data that needs to be provided before any kind of decision on the sustainability of mine water irrigation can be made. Several so-called critical flaws have also been identified by this research. The presence of these flaws will lead to an immediate recommendation that irrigation with mine water should not occur. If none of these flaws are present, the decision can be made whether mine water irrigation is to be done on virgin soils (green fields) or on rehabilitated mine spoils (brown fields). Criteria for each type of irrigation have been identified and included in this decision making process.

Figure 9-2 shows the type of information considered when defining the suitability of a particular site and the type of irrigation planned (duration, water quality, crop etc).

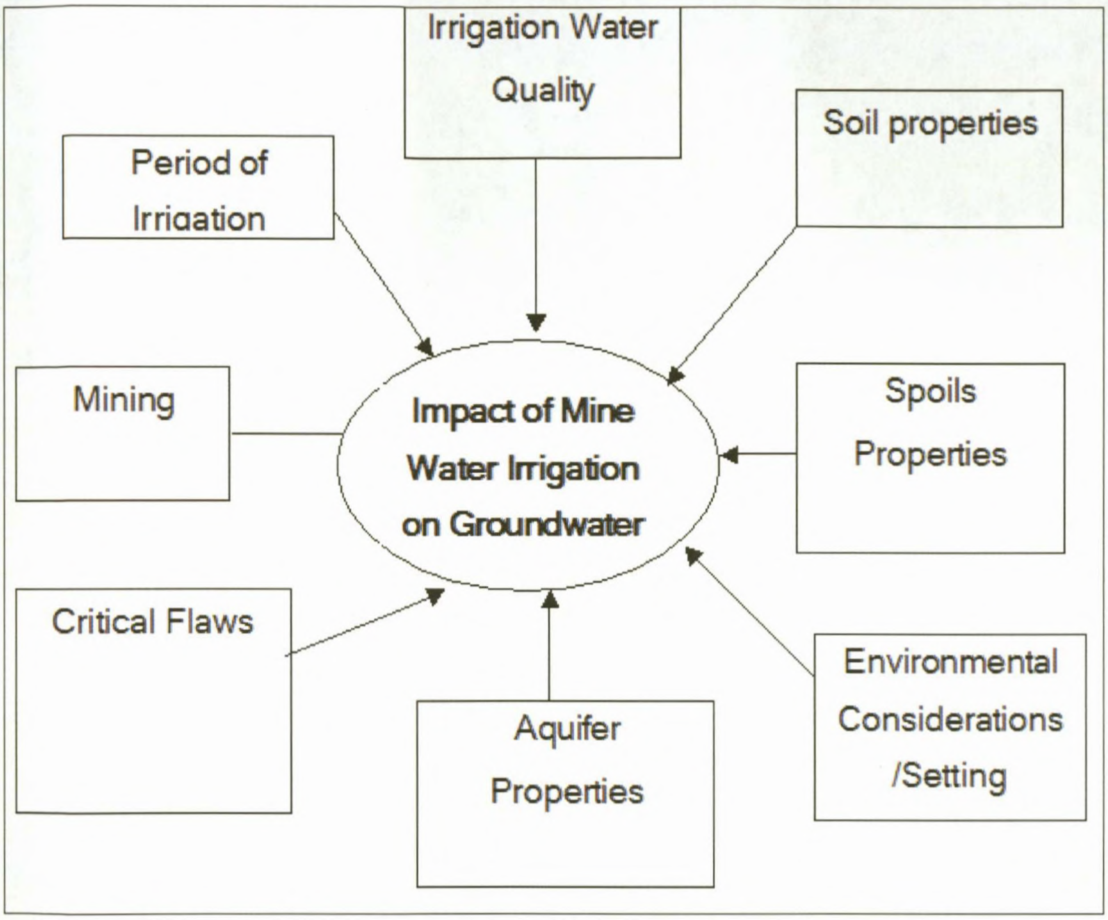


Figure 9-2: Data input required to determine impact and define criteria.

9.2 Selection criteria

The approach is to take information of different types and provide a screening tool.

- This approach is conservative and tiered.
- The screening combines a yes/no approach with the integration of (simplified) key fundamentals.
- An output of the assessment based on all the criteria is then evaluated.

These data inputs will be discussed in the following sections. *The most important question before irrigation can be introduced is if the land is suitable for irrigation.*

9.2.1 *Identifying land suitable for irrigation (le Roux, 2006)*

9.2.1.1 Background

Soil is often the only medium for dumping saline water. Using waste water for crop production under irrigation seems like a perfect solution as it can be financially beneficial as well. However, the soil is not always the perfect sink and the environment must be protected. Protection of the environment is often seen as a good reason to pollute the soil with degraded water, assuming that the soil is a perfect sink and/or the soil is not part of the environment. The extent to which the soil serves as a good sink varies. Soil can effectively remove environmental hazards without polluting the soil or the surrounding environment but usually either the soil or the groundwater is polluted.

Irrigation of soil with gypsum-rich water is an example where the soil may serve the goal well. If the composition of the irrigation water is favourable for precipitation of gypsum in the soil, the gypsum may be removed from the water effectively. After precipitation the impact of the salt on crops are drastically reduced. In the dissolved condition the severity of divalent salinity is very low compared to sodium chloride solutions.

9.2.1.2 Irrigation requirements of soils

The suitability of soils for irrigation primarily depends on four factors.

- Firstly the *final infiltration rate* of the soil must be high enough to prevent run off. The final infiltration rate is mainly determined by the soil texture, soil surface structure and slope.
- Secondly irrigation soil must have good *internal drainage*. The water must move through the root zone freely to avoid water logging. The factors controlling internal drainage are complicated but fortunately the soil morphology, as accommodated in the South African soil classification system, is a good indicator of internal drainage.
- Thirdly irrigation soil must have good *external drainage* as excess water, needed for leaching, must be able to move out of the system and either joins the groundwater or surface water in rivers and wetlands. The factors controlling the external drainage are even more complicated than internal drainage. Soil morphology, specific redox morphology, also serves as a good indicator of external drainage and therefore the soil types of the South African soil classification system are classified according to the degree of drainage. Limited drainage is aggravated by the position in the landscape or terrain morphological unit (TMU) and an example is illustrated in Figure 9-3.

- Fourthly the water *holding capacity* (WHC) of a soil must be large enough to hold water for one irrigation cycle, usually one weak. This limitation can be reduced by systems that can irrigate more often. Mechanical irrigation like drip and micro irrigation must be avoided as they are probably unsuitable for use with saline water as the leaching factor can not be upheld with them.

The principles applied in developing these soil suitability ratings were modified to fit the requirements of the area and quality of the irrigation water. Several factors contribute to the decision to make the drainage requirements stricter. The rainfall of the area is high, increasing the risk of water logging. The criteria for soil depth are therefore more strict than usual. Saline water combined with water logging increases the risk of salinisation and puts more emphasis on soil depth.

The WHC is mainly determined by the depth and texture of the soil. The texture of the well-drained soils of this area is in the optimum range and hold 120 mm of plant-available water per meter of soil. Soils shallower than 500 mm cannot hold enough water to supply the peak water use in late summer with ET reaching 10 mm per day in a mature crop stand. This limitation can be addressed to some extent with more frequent irrigation cycles if the system permits. Shallow soils are also sensitive to water logging and accelerated salinisation.

The degree of management required for successful production of cash crops under irrigation increases significantly with increased clay content. In clay soils the final infiltration rate is lower, distribution of water is uneven and workability is poor. The increased aggregation caused by gypsum in saline waters may improve this parameter to the extent that the negative effect of high clay content is negligible. Except for differentiating between soil types in terms of drainage, soil depth and the terrain morphological unit (TMU) are also taken into account (Figure 9-3). Drainage can be improved by artificial drainage but at a cost roughly equal to the cost of an irrigation system. Fertility is not considered as a factor in the suitability of soils for irrigation as fertilisation and/or liming and/or adding gypsum can usually address it. Salinity is not considered either as the salinity and impact on crop production must be monitored continuously.

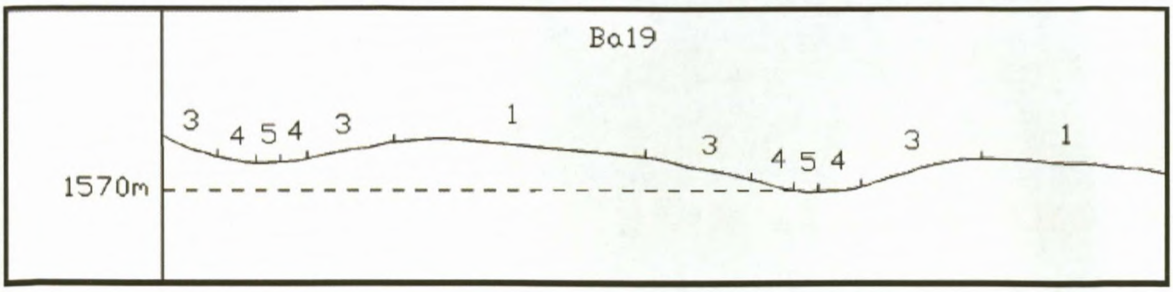


Figure 9-3: Terrain morphological units for soil Ba 19 as an example

9.2.1.3 Soils of the area

The distribution of the soils of South Africa is mapped as land types (Figure 9-4). The soil data in a land type is presented as the typical pattern of soil distribution in the landscape - from the crest, midslope and footslope to the valley bottom. The distribution of soils in the twenty-two land types that cover the area is presented in the land type inventories. The same soils occur in most of the landscapes of all twenty-two land types. The distribution of the soils in the land types is rearranged for ease of evaluation.

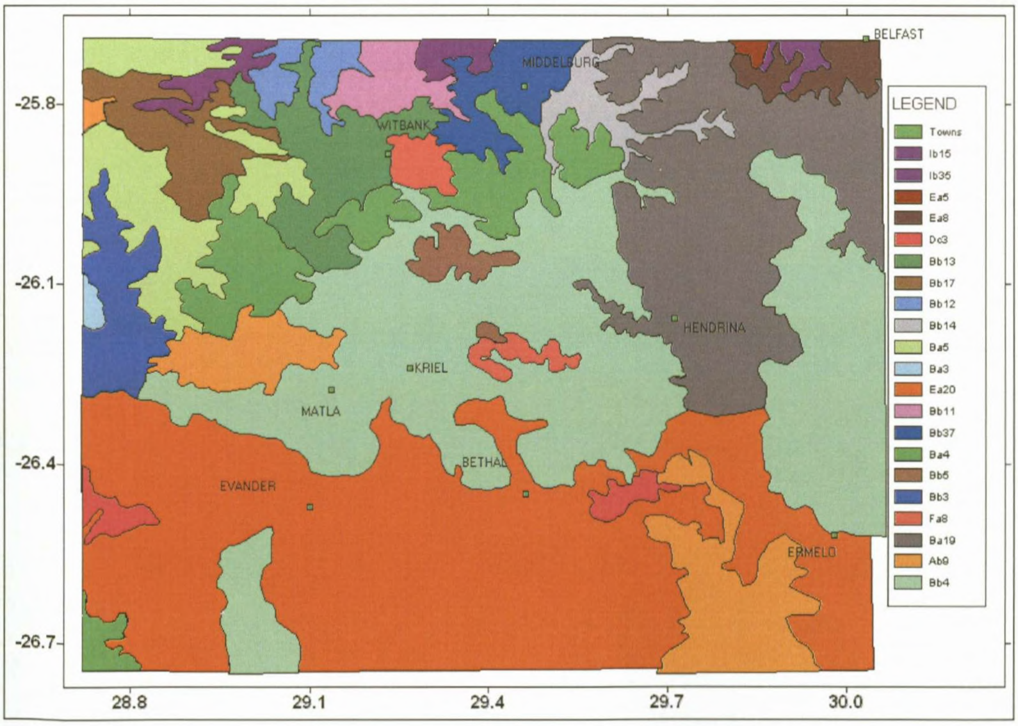


Figure 9-4: Soil types in study area

Soil suitability rating

The soil types present in these land types are divided in three groups according to natural drainage namely the well drained, moderately drained and poorly drained.

- The group of ***well-drained*** soils are soils of the Hutton (Hu), Clovelly (Cv), Oakleaf (Oa), Arcadia (Ar), Valsrivier (Va), Swartland (Sw), Bonheim (Bo) and Dundee (Du) forms. Exceptions to this rule is that all series (subdivisions of the forms in the 1997 edition) of the Oakleaf, Valsrivier, Swartland, Bonheim and Dundee forms with signs of wetness and all families (subdivisions of the forms in the 1991 edition) of the Swartland, Bonheim and Dundee forms of the South African soil classification system should be considered as moderately drained. Soils of the Dundee form have layered subsoil deposits and therefore its suitability varies over short distances. Its suitability should be evaluated by intensive soil survey. The criteria used in the land type survey make it impossible to evaluate the depth of soils of the Swartland and Valsrivier forms. Although few of these soils occur in the land types they are not taken into account for their contribution to land suitable for irrigation making the figures slightly conservative.
- The *moderately drained* soils are all the series (1977) and families (1991) of the Bainsvlei (Bv), Avalon (Av) and Glencoe (Gc) forms of the South African soil classification system.
- *Poorly drained* soils are all series (1977) and families (1991) of soils of the Westleigh (We), Longlands (Lo), Wasbank (Wa), Estcourt (Es), Kroonstad (Kd), Katspruit (Ka), Rensburg (Rg) and Willowbrook (Wo) forms of the South African soil classification system.

The soils are classified in four suitability classes namely very suitable (S1), suitable (S2), barely suitable (S3) and not suitable (N). The suitability classes are defined as:

- S1 - Very suitable soils are the soils which are easy to manage under normal irrigation practices and do not restrict crop production for optimal yields. They have a low risk of water logging and salinisation but soluble salts that do not precipitate under these conditions in the soil will leach through the soil and contaminate the ground water.
- S2 - Suitable soils are soils that require improved irrigation management systems. These include mechanical systems of irrigation, artificial drainage and/or a high level of irrigation expertise for example advanced irrigation scheduling.
- S3 - Soils barely suitable should be avoided if possible. Multiple irrigation problems may occur. The risk of reduced crop yields, water logging and salinisation is a short-term hazard.
- N - Soils not suitable for irrigation are soils and land where the cash crops generally produced in that area cannot be produced economically even with the best irrigation practice and most profitable crop generally grown.

Table 9-1: Soil suitability rating guide for well-drained soils.

Soil factor	Soil rating guide				Limitation
	S1	S2	S3	N	
Depth (mm)	>1200	1200-800	500-800	<800	WHC
Texture (clay %)	<35	35-55	>55		Management
TMU	1+3	4		5	Drainage

Table 9-2: Soil suitability rating guide for moderately drained soils.

Soil factor	Soil rating guide				Limitation
		S2	S3	N	
Depth (mm)		>1200	>800	<800	WHC
Texture (clay %)		<55	>55		Management
TMU		3	1+4	5	Drainage

The following soils and land types are not suitable for irrigation for several reasons namely rock, Mispah (Ms), Glenrosa (Gs), Mayo (My), Cartref (Cf) and stream beds.

9.2.2 *Procedures for selecting land for irrigation*

1. Select a land type with a high percentage of land suitable for irrigation.
2. Select a terrain morphological unit in the landscape containing the highest percentage of land suitable for irrigation. Take into consideration that the percentage may be high and the area covered quite low.
3. Take slope into account. Different irrigation methods accommodates slope differently.
4. Do a detail soil survey.
5. Select the best land for irrigation.
6. Select crops resistant to salinisation.

In Table 9-3 the percentage of suitable land in the Mpumalanga coalfields for the different land types as well as the actual size in hectares are portrayed for the different suitability ratings.

Table 9-3: Distribution of soils suitable for irrigation in different land types of the area.

Distribution of soils suitable for irrigation in different land types of the area.

		Percentage (%)				Area (ha)			Total	
	TMU	S1	S2	S3		S1	S2	S3	(%)	(ha)
Ab9	1	65	X	5		8779	X	675		
	3	55	5	15		13619	1238	3714		
	4	X	40	30		X	1801	1350		
	5	X	X	X		X	X	X	69	31176
Ba19	1	30	10	20		8084	2694	5388		
	3	25	5	10		6736	1347	8083		
	4	10	10	25		1010	1010	2526		
	5	20	X	X		674	X	X	55	36880
Ba3	1	5	X	X		464	X	X		
	3	30	X	X		8349	X	X		
	4	40	X	X		2783	X	X		
	5	20	X	X		464	X	X	26	12062
Ba37	1	35	10	10		14368	4105	4105		
	3	30	10	5		6717	2239	1120		
	4	5	20	20		373	1493	1493		
	5	X	X	X		X	X	X	98	73239
Ba5	1	X	60	X		X	9320	X		
	3	X	65	X		X	30290	X		
	4	X	45	X		X	5242	X		
	5	X	X	X		X	X	X	58	44852
Bb3	1	40	X	35		17873	X	15639		
	3	25	X	35		17555	X	24576		
	4	X	10	10		X	638	638		
	5	X	X	X		X	X	X	60	76919
Bb4	1	15	X	50		10562	X	35209		
	3	10	X	70		14083	X	98583		
	4	X	X	10		X	X	4108		

	5	X	X	X		X	X	X	64	148462
Bb11	1	45	X	15		6374	X	2125		
	3	40	X	15		4249	X	1593		
	4	X	25	10		X	2479	992		
	5	X	X	X		X	X	X	50	17812
Bb12	1	45	X	15		10444	X	3481		
	3	40	X	15		6962	X	2611		
	4	X	25	10		X	4062	1625		
	5	X	X	X		X	X	X	50	29185
Bb13	1	50	15	X		8063	2419	X		
	3	40	35	X		7256	6349	X		
	4	X	30	X		X	1209	X		
	5	X	X	X		X	X	X	50	25296
Bb14	1	X	X	X						
	3	20	X	X		X	X	X		
	4	X	X	X		1988	X	X		
	5	X	X	X		X	X	X		
Bb16	1	10	X	30		X	X	X	6	1988
	3	X	X	25		1840	X	5520		
	4	X	X	X		X	X	4140		
	5	X	X	X		X	X	X		
Dc3	1	X	X	X		X	X	X	31	11500
	3	X	X	X		X	X	X		
	4	X	X	10		X	X	X		
	5	X	X	33		X	X	98		
Ea5	1	X	20	X		X	X	98	3	196
	3	30	10	X		X	2790	X		
	4	X	X	90		8372	2790	X		
	5	X	X	40		X	X	10045		
Ea8	1	X	X	X		X	X	1116	30	16741
	3	X	X	X		X	X	X		

	4	X	X	10		X	X	X		
	5	X	X	30		X	X	114		
Ea20	1	X	X	X		X	X	85	4	199
	3	X	X	X		X	X	X		
	4	X	10	X		X	X	X		
	5	X	X	X		X	1746	X		
						X	X	X	1	1746

Land types Ib15, Ib24, Ib35 and Fa8 do not have land suitable for irrigation.

9.2.3 *Site specific and more general data.*

The first criteria required when evaluating each site considered for irrigation is if it is virgin *soil or spoils.*

9.2.3.1 Virgin soils:

The baseline information that will decide if land will be feasible and suitable for irrigation is the following:

1. Name of the colliery and the name of the irrigation site.
2. Irrigation area size (ha)
3. Water quality

pH	EC	Ca	Mg	Na	K	PAlk	MAlk	Cl	SO4

4. Landtype
5. Geology and structures: If a dyke (barrier or preferred pathway) is present, a warning should occur. The impact on receptors should be investigated.
6. Water level at the site
7. Depth of soil
8. Annual rainfall
9. Irrigation volumes
10. Crop type
11. Distance to closest community - is the site up gradient or down gradient
12. Community dependence on groundwater
13. Is pivot site in area of land instability?
14. Is there an underlying dolomitic aquifer?
15. Is area undermined? Type of mining: Bord and pillar or high extraction
16. Aquifer classification must be provided

17. Environmental data: - River systems and base flow
- Distance to closest receptor
- WQO: user specified or SANS 241:2005 - (TDS, EC, SO4)
- Sensitive site: Will a wetland, nature reserve, Ramsar site or springs be influenced

18. Current Monitoring systems: - Number of boreholes
- Distance from site
- How many down gradient
- Monitoring frequency
- Current groundwater quality

9.2.3.1.1 Critical Flaw list:

A set of critical flaws for mine water irrigation has been established. These flaws are situation-related to the location, water quality and receiving environment. If any of these criteria occur on site, mine water irrigation should only be allowed after the Department of Water Affairs and Forestry (DWAF) water use permitting system has been followed.

The critical flaws have been defined as follows:

1. No irrigation is allowed with **potable water** (defined as TDS < 900 or EC< 150) for basic human needs (BHN).
2. **Aquifer classification:** If the irrigation is planned on a shallow sole source aquifer, it is *critical flaw.*
3. **Area of irrigation**: If the area is greater than 150 ha, DWAF water use permitting guidelines rather than the criteria used in this document must be followed since no current research has been done on such a scale. The success of current irrigation is also due to the relatively small scale of application.
4. **Water quality**: The irrigation water must be suitable for crop production. If the irrigation water pH < 5, or if (Ca+SO4+HCO3) in meq is < 60% of the total ionic composition (unless EC < 200 mS/m), or if the irrigated water is less than one and a half times that of the background EC, then irrigation cannot be allowed. Also if the SAR > 15, then this is a *critical flaw* and irrigation should not be allowed.
5. **Land type**: If the assessment for soil suitability is N, this is considered to be a critical flaw. If there is a clay layer with a clay % more than 10% greater than the average from that soil type and this occurs less than1m below the root zone, this is a *critical flaw.*
6. **Water level**: If the groundwater level < 1.5 m, *critical flaw.*
7. **Depth of soil**: Less than 0.5 m soils, *critical flaw.*
8. **Community dependence on groundwater**: If community dependence on groundwater > 80%, it is a critical flaw unless community > 2km away or up gradient of the proposed irrigation or irrigation is planned for a very short period of time.

9. **Land stability**: If pivot site is in an area of land instability, sinkholes or if there is an underlying dolomitic aquifer, this would constitute a *critical flaw.*
10. **Environmental**: If there is a wetland, nature reserve, Ramsar site or a site similar down gradient within 2 km, this is *critical flaw.*

Critical flaws should highlight potential situations where mine water irrigation is likely to cause long-term problems. However, with detailed determination of the on-site conditions, and potential monitoring and mitigation, irrigation in such areas may still be possible.

9.2.3.2 Opencast spoils

At opencast sites, there are two main issues to consider. One important factor is the rehabilitated soils on top, and the other the spoils underneath.

Rehabilitated soils:

- Depth of soil (value in mm)
- Type of soil: The same criteria as for virgin soil in area (this can be carried over from virgin soil input), or site-specific soil properties (% clay, loam and sand) must be considered.

Spoils:

- Is it free draining
- Potential for acidity (Assume that it is Potentially Acid Generating (PAG) unless other data exists). Based on available data, either Potentially Acid Generating, Non-Acid Generating or Uncertain spoils will be used. Site specific ABA data can be included.
- Proportion of spoils unit to be irrigated (either percentage, or enter total spoils area draining to decant point and area of mine water irrigation)
- Water use (will decant water be re-used for irrigation)
- Is any decant released to the environment, currently or in the future?
- What % of spoils is flooded at the decant elevation (% value)
- To what degree can gasses enter the spoils

9.2.3.2.1 Rules/Calculations

- Criteria for ABA:

If NNP = NP-AP <0 the sample has the potential to generate acid.

If NNP = NP-AP >0 the sample has the potential to neutralise acid produced.

More specifically, any sample with NNP<20 is potentially acid-generating (PAG), > 40 NAG and in between is uncertain.

1. Samples with less than 0.3% sulphide-S are regarded as having insufficient oxidisable sulphide-S to sustain acid generation.

2. Neutralising Potential Ratio (NPR) of >4: 1 are considered to have enough neutralising capability (NAG)
3. NPR ratios below 1: 1 with sulphide-S above 0.3%, are potentially acid generating.

- If applicant indicates decant water will never be released, any irrigation is allowed but a warning is given that irrigation will accelerate acidification and water quality deterioration rates.
- For all assessments where spoils are PAG:
    - Irrigation on < 10% of spoils is allowable,
    - 10-30% is allowed with a warning that irrigation is only a short term measure and
    - Anything > 30% disallowed.
    - An exception to this occurs if the % spoils flooded at decant elevation is >80%.
    - For marginal spoils this value is >70%

- If the spoils are uncertain then one must consider the likely leachate quality as obtained from PHREEQC:
    - If significant alkalinity exists and the TDS of the leachate is <7000mg/l or leached Ca:Na ratio (in equivalents) >2 then a marginal spoils can be considered NAG.
    - In all other cases a marginal spoils becomes PAG.

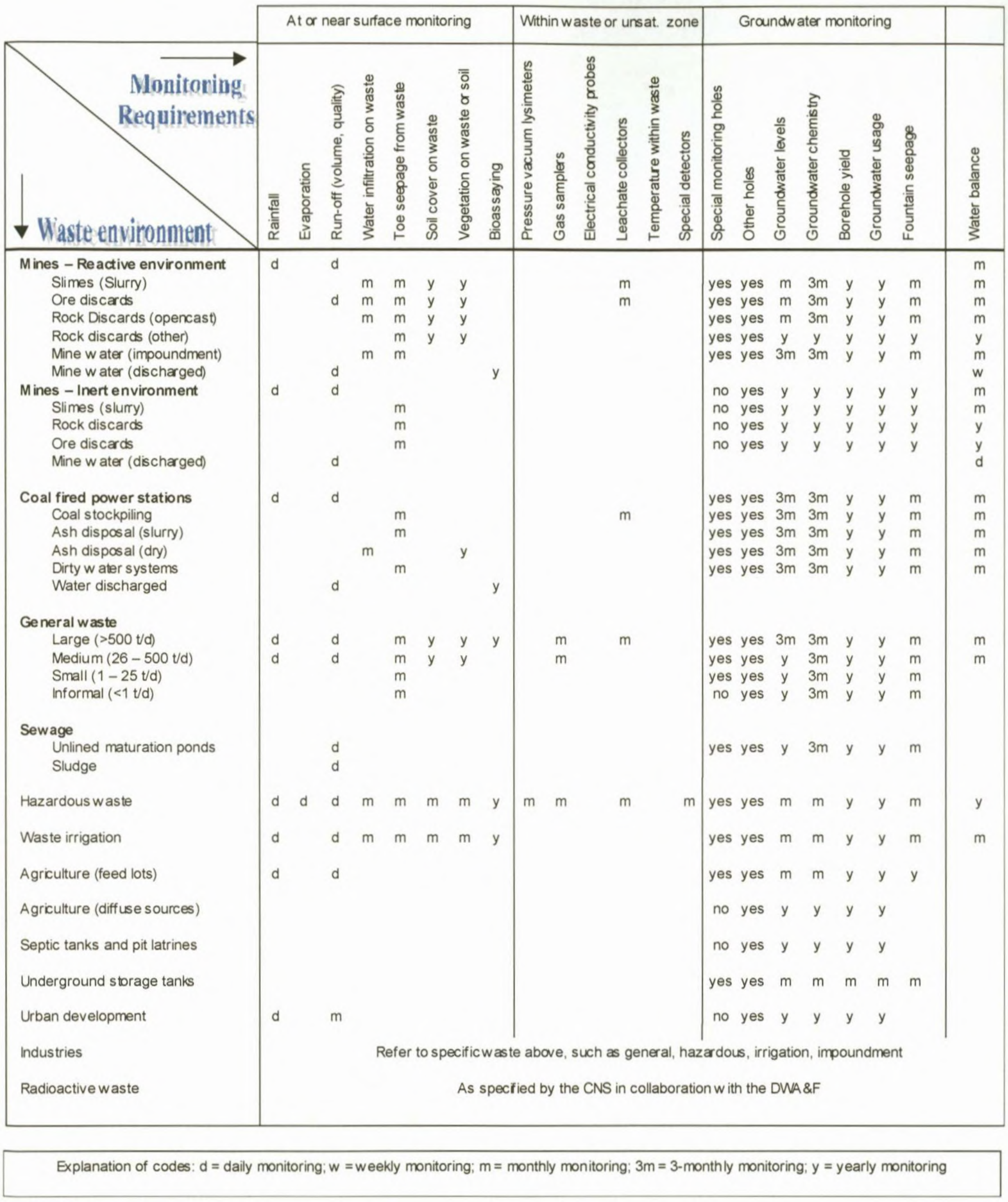
- If user indicates water is recirculated then the same rules as above apply except that:
    - Irrigation is limited to a 5 year period if irrigation <10.01% of spoils and
    - Irrigation is limited to two years if irrigated area between 10 and 30% of spoils area contributes to decant. This is only a short term method to decrease water volume at colliery.

9.3 Monitoring Guidelines

If the potential site fulfills all the criteria set out in the previous sections, **appropriate monitoring must be put in place**.

Since the suggested monitoring must meet DWAF requirements, the most appropriate manner in which to deal with such irrigation is to apply the DWAF Minimum Requirements for Monitoring at Waste Disposal facilities. Table 9-4 provides an overview of suggested minimum required monitoring at different types of waste facility.

Table 9-4: Minimum monitoring requirements at various types of waste management facilities (DWAF, 2005).



Monitoring Requirements → / ↓ Waste environment	At or near surface monitoring								Within waste or unsat. zone						Groundwater monitoring							
	Rainfall	Evaporation	Run-off (volume, quality)	Water infiltration on waste	Toe seepage from waste	Soil cover on waste	Vegetation on waste or soil	Bioassaying	Pressure vacuum lysimeters	Gas samplers	Electrical conductivity probes	Leachate collectors	Temperature within waste	Special detectors	Special monitoring holes	Other holes	Groundwater levels	Groundwater chemistry	Borehole yield	Groundwater usage	Fountain seepage	Water balance
Mines – Reactive environment	d		d																			m
Slimes (Slurry)				m	m	y	y					m			yes	yes	m	3m	y	y	m	m
Ore discards			d	m	m	y	y					m			yes	yes	m	3m	y	y	m	m
Rock Discards (opencast)				m	m	y	y								yes	yes	m	3m	y	y	m	m
Rock discards (other)					m	y	y								yes	yes	y	y	y	y	y	y
Mine w ater (impoundment)				m	m										yes	yes	3m	3m	y	y	m	m
Mine w ater (discharged)			d					y														w
Mines – Inert environment	d		d												no	yes	y	y	y	y	y	m
Slimes (slurry)					m										no	yes	y	y	y	y	y	m
Rock discards					m										no	yes	y	y	y	y	y	y
Ore discards					m										no	yes	y	y	y	y	y	y
Mine w ater (discharged)			d																			d
Coal fired power stations	d		d												yes	yes	3m	3m	y	y	m	m
Coal stockpiling					m							m			yes	yes	3m	3m	y	y	m	m
Ash disposal (slurry)					m										yes	yes	3m	3m	y	y	m	m
Ash disposal (dry)				m			y								yes	yes	3m	3m	y	y	m	m
Dirty w ater systems					m										yes	yes	3m	3m	y	y	m	m
Water discharged			d					y														
General waste																						
Large (>500 t/d)	d		d		m	y	y	y		m		m			yes	yes	3m	3m	y	y	m	m
Medium (26 – 500 t/d)	d		d		m	y	y			m					yes	yes	y	3m	y	y	m	m
Small (1 – 25 t/d)					m										yes	yes	y	3m	y	y	m	
Informal (<1 t/d)					m										no	yes	y	3m	y	y	m	
Sewage																						
Unlined maturation ponds			d												yes	yes	y	3m	y	y	m	
Sludge			d																			
Hazardous waste	d	d	d	m	m	m	m	y	m	m		m		m	yes	yes	m	m	y	y	m	y
Waste irrigation	d		d	m	m	m	m	y							yes	yes	m	m	y	y	m	m
Agriculture (feed lots)	d		d												yes	yes	m	m	y	y	y	
Agriculture (diffuse sources)															no	yes	y	y	y	y		
Septic tanks and pit latrines															no	yes	y	y	y	y		
Underground storage tanks															yes	yes	m	m	m	m	m	
Urban development	d		m												no	yes	y	y	y	y		
Industries	Refer to specific waste above, such as general, hazardous, irrigation, impoundment																					
Radioactive waste	As specified by the CNS in collaboration with the DWA&F																					

Explanation of codes: d = daily monitoring; w = weekly monitoring; m = monthly monitoring; 3m = 3-monthly monitoring; y = yearly monitoring

DWAF (2005) states that monitoring networks at waste management facilities must allow monitoring of the system on a representative basis, and that the key to successful monitoring is the linking of point information into larger systems, referred to as monitoring networks. As such it is recommended that these DWAQF guidance documents should provide the **minimum monitoring requirements** at mine water irrigation sites and that the monitoring *"should extend beyond pollution plumes to allow for the delineation of plumes and investigations into the pollution migration rate."*

DWAF guidance for different types of environment is provided below:

Environment	No. Holes	Distance From Waste	Monitoring Frequency
Mines - Reactive Environment			Samples from boreholes every 6 months. Sample monthly from streams above and below mine. If pollution from mine occurs, install recorders in streams above and below mine. Measure daily flow, EC and pH. Sample farmers' boreholes 1-5 km radius, initially and when problems are expected.
Slimes (Slurry)	1-3	50-250 m downstream	
Ore discards	2-5	50-500 m downstream and above	
Rock discards (opencast)	1/250 ha	into water accumulations	
Rock discards (other)	1-3	50-200 m downstream	
Mine water (impoundment)	2-6	50-1000 m downstream	
Farmers' boreholes		within 1-5 km from mine workings	
Mines - Inert Environment			
Slimes (Slurry)	0-1		Monthly samples from streams above and below mine If pollution from mine occurs, install recorders in streams above and below mine. Measure daily flow, EC and pH. Samples farmers' boreholes 1-2 km radius initially and when problems are expected.
Ore discards	0-1		
Rock discards (opencast)	0-1		
Rock discards (other)	0-1		
Mine water (impoundment)	0-1		
Farmers' boreholes		within 1-2 km from mine workings	
Coal Fired Power Stations			Samples from boreholes every 6 months. Monthly from streams above and below power station. If pollution occurs in streams, install recorders in streams above and below power station. Measure daily flow, EC and pH. Sample farmers' boreholes 1-5 km radius, initially and when problems arise.
Coal stockpiling	2-3	50-500 m downstream	
Ash disposal (wet)	2-3	50-500 m downstream	
Ash disposal (dry)	2-3	50-500 m downstream	
Dirty water systems	2-3	50-500 m downstream	
Private boreholes		within 1-5 km from power station	
General Waste			
Large (>500 t/d)	3-6	20-200 m surrounding	Samples from boreholes every 6 months or as specified in permit. Sample water-supply boreholes 1-5 km radius initially and when problems are expected. Sample surface water as specified in permit. Sample monthly for leachate, if any.
Medium (150 - 500 t/d)	2-3	20-200 m 1 up- and 1 downstrear	
Small (25 - 149 t/d)	2	20-200 m 1 up- and 1 downstream	
Communal (<25 t/d)	1	20 m downstream	
Private boreholes		within 1 km from waste	
Sewage			
Unlined maturation ponds	1	20-50 m downstream	Samples from boreholes every 6 months. Samples monthly from streams above and below sewage works
Sludge	1	20-50 m downstream	
Hazardous waste	5-10	10-200 m surrounding	Site-specific constituents at frequencies recommended by impact study
Waste Irrigation	3-6	50-500 m 1 up- and 1 downstrean	Samples from boreholes every 6 months. Monthly samples from streams above and below.
Agriculture - feed lots	2-3	50-200 m 1 up- and 1 downstrearr	Samples from boreholes every 6 months. Monthly samples from stream above and below.
Agriculture - diffuse sources	0		Samples from existing water-supply boreholes when problems are expected.
Septic tanks and pit latrines	0		Samples from existing water-supply boreholes when problems are expected.
Urban development	0		Monthly EC in streams above and below development

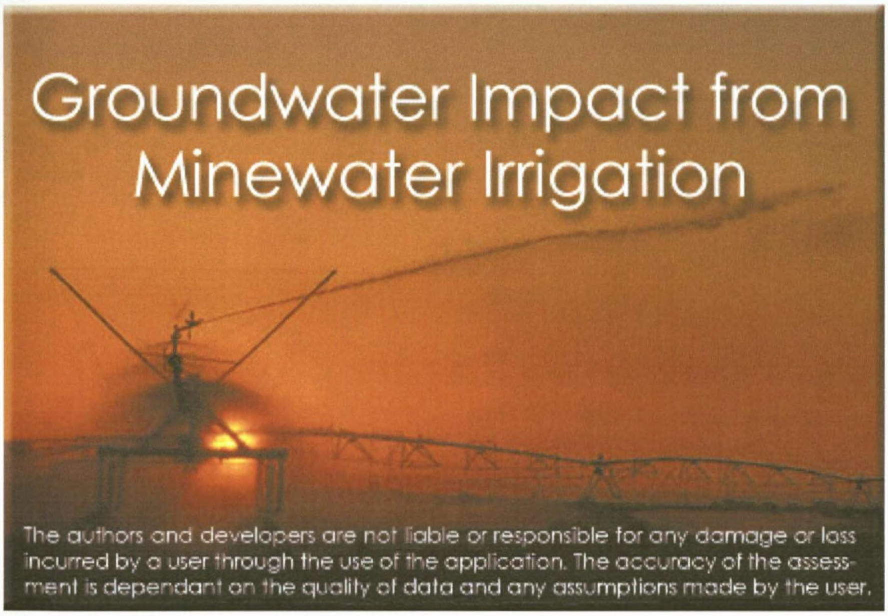
Based on this guidance it is recommended that mine water irrigation be dealt with in the same manner as "Waste Irrigation" or General Waste, where the monitoring suggested should be similar to that of a small to medium waste site. *The DWAF guidelines are the absolute minimum requirement that should be adhered to. To properly understand the interactions on the site, a more extensive monitoing program is recommended.*

Based on the observations from the research and the DWAF Minimum Monitoring Requirements, it is suggested that for each pivot where mine water irrigation is undertaken, the following groundwater monitoring is recommended:

- Before installation of monitoring boreholes a detailed conceptual model of the expected site geohydrology should be constructed so that appropriate monitoring is put in place.
- As the system is installed, detailed measurements and observations of the geology, aquifer characteristics (using techniques such as slug or pump testing etc) and should be done, and the conceptual model verified. This data will also allow a more accurate determination of the expected impact of the irrigation activities.
- At each pivot site at least one upgradient and two down-gradient boreholes should be installed, together with a borehole pair near the centre of the pivot itself.
- The boreholes on the outside of the irrigation must be constructed in a manner which is consistent with DWAF's Minimum Requirements document.
- The borehole pair within the pivot should be installed as follows:
    - 1 Shallow borehole that is drilled down to the top of the hard rock underlying the irrigation area, to below the weathered zone. This borehole should have a very short length of solid casing followed by slotted casing or a borehole screen to the bottom of the borehole. If the material is not competent, it is recommended that a slotted piezometer be installed with a gravel pack to ensure that the shallow groundwater can be accurately characterized.
    - In close proximity a deeper borehole should be drilled into the Karoo formation. This borehole should be cased off with solid casing to below the weathered zone.
    - At these boreholes proper sanitary seals and/or other preventative measures should be put in place to prevent the irrigation water from flowing directly into the boreholes.
- The following parameters should be measured in each borehole:
    - Water levels on a monthly basis
    - Groundwater sampling for the macro-constituents at *least 6 monthly*, and *before and after each crop* is planted and harvested. The analytical constituents should include pH, EC, Ca, Mg, Na, K, SO_4, HCO_3, Cl, NO_3 and PO_4.
- Data should be compiled into a database and handled as prescribed in DWAF's Minimum Requirements (2005).

9.4 GIMI- A user-friendly decision support application for mine water irrigation

In an attempt to standardise decision-making regarding mine water irrigation, the criteria, data, rules and fundamentals discussed in the preceding sections have been combined in a user-friendly tool, called GIMI (Groundwater Impacts from Minewater Irrigation). GIMI is a screening tool to help users make informed decisions about mine water irrigation. GIMI consist of a GIS system which contains all the base maps as shape files and an assessment interface where scenarios are built using a CAD interface. **(An "Install" for GIMI is on the attached DVD).**



The authors and developers are not liable or responsible for any damage or loss incurred by a user through the use of the application. The accuracy of the assessment is dependant on the quality of data and any assumptions made by the user.

The aims of this tool can be summarised as follows:

- User-friendly tool to integrate considerations/understanding
- Should take most important lessons into account
- Simplifies complex interactions
- Gives guidance on:
  - Applicability
  - Monitoring
  - Data requirements

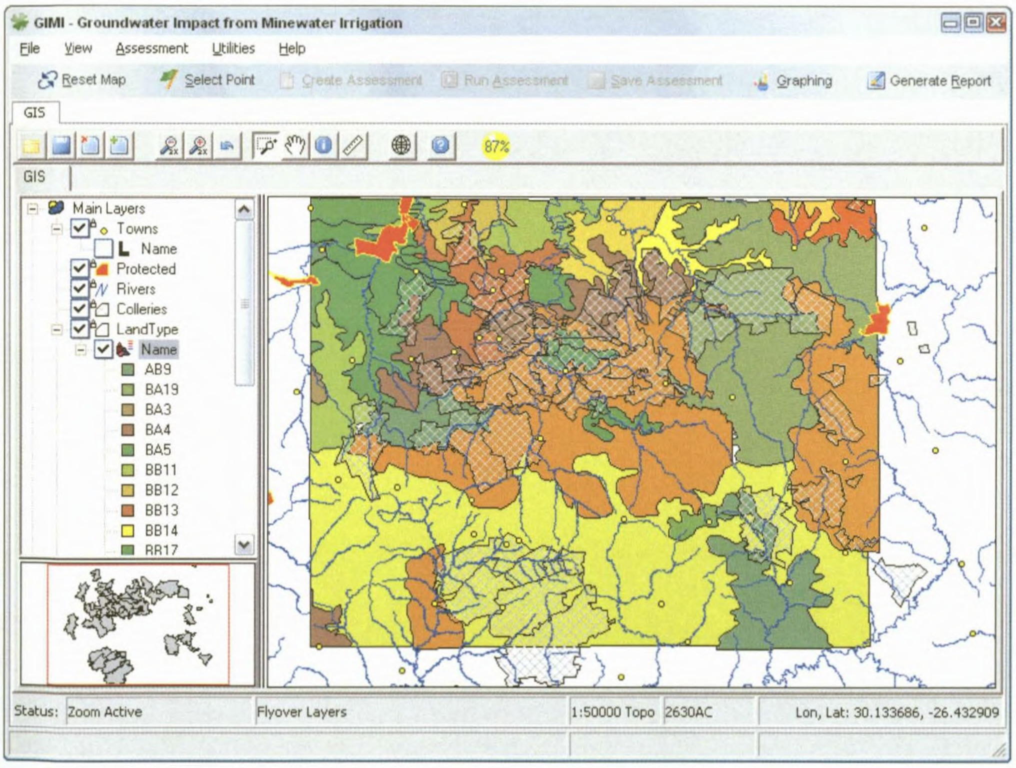
The approach followed was to:

- Take information of different types into account

- Provide a screening tool
- Employ a conservative methodology to ensure protection of the water resources
- Combine yes/no approach with integration of (simplified) key fundamentals
- Series of input screens with guidance
- Output of assessment

9.4.1 *Overview of GIMI operation*

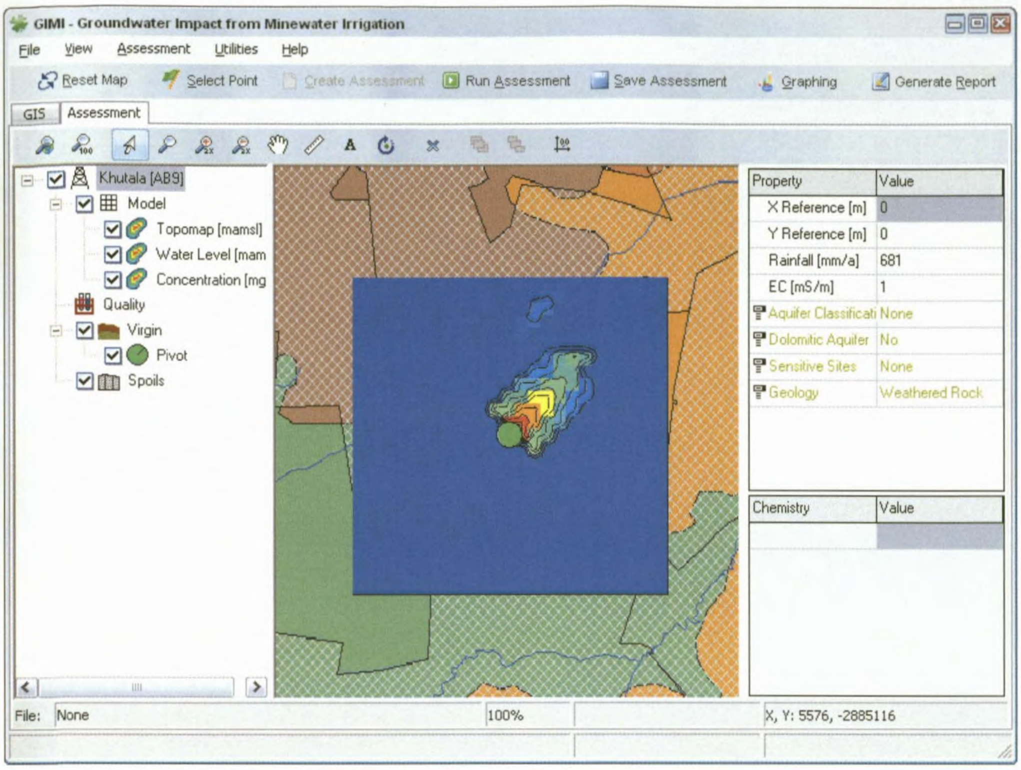
The working of the tool is very much in line with that discussed above. Initially users will provide information on the area, type of irrigation, water quality and similar values. Examples of the input screens are provided below:



Status: Zoom Active | Flyover Layers | 1:50000 Topo | 2630AC | Lon, Lat: 30.133686, -26.432909

Figure 9-5: GIMI input screen with clickable soils map to link to soil properties.

The clickable soil map will link the detailed soil information directly to the area of irrigation.



Property	Value
X Reference [m]	0
Y Reference [m]	0
Rainfall [mm/a]	681
EC [mS/m]	1
Aquifer Classificati	None
Dolomitic Aquifer	No
Sensitive Sites	None
Geology	Weathered Rock

Chemistry	Value

File: None

100%

X, Y: 5576, -2885116

Figure 9-6: Example of input screen from GIMI.

9.4.2 *Additional features in GIMI*

In terms of irrigation water quality, GIMI has a few features in which will greatly assist users in determining the eventual impacts. The water quality input can either be done manually or can be linked to a WISH database or Excel sheet. This water quality will be scrutinized for relative ionic contribution (see "critical flaws"), SAR indices and EC/TDS ratios for comparison to aquifer water. Additionally a link has been built to the PHREEQC geochemical model. This will enable correct determination of the concentration and equilibration of the water as volumes are reduced. This ensures that waters remain in ionic balance, and equilibrium with gypsum, calcite and dolomite. The mass of precipitated minerals can also be determined in this manner. The Chemical model used in GIMI is PHREEQC version 1.5 PHREEQC is a computer program written in the C programming language that is designed to perform a wide variety of low-temperature aqueous geochemical calculations. PHREEQC is based on an ion-association aqueous model and has capabilities for (1) speciation and saturation-index calculations; (2) batch-reaction and one-dimensional (1D) transport calculations involving reversible reactions, which include aqueous, mineral, gas, solid-solution, surface-complexation, and ion-exchange equilibria, and irreversible reactions, which include specified mole transfers of reactants, kinetically controlled reactions, mixing of solutions, and temperature changes; and (3) inverse modeling, which finds sets of mineral and gas mole transfers that account for differences in composition between waters, within specified compositional uncertainty limits.

Results of the chemical model are displayed for each Pivot object in the object editor.

The impact on receptors will be determined by using the concentration and load as determined by the PHREEQC and the water balance equations, and the Domenico (1987) approach. The time span of irrigation, the distance to the receptor and the water quality objective (where none- is present the SA drinking water standards for EC/TDS are used as default) at this receptor will be used to assess applicability.

Figure 9-7: Water Quality and Environmental Data in GIMI.

The Domenico analytical model is based on the advection-dispersion partial-differential equation for organic contaminant transport processes in groundwater as described below (Domenico and Robbins 1985):

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial x}$$

Where,

C - contaminant concentration in groundwater (mg/L),
t - time (day),

v - groundwater seepage velocity (ft/day),
x, y, z - coordinates to the three dimensions (ft),
D_x, D_y, D_z - dispersion coefficients for the x, y, z dimensions (ft_2/day),respectively.

To solve equation (1) analytically, under conditions of the steady-state source and finite continuous source dimension with one-dimensional groundwater velocity, three-dimensional dispersion, and a first order degradation rate constant, the analytical solution can be expressed as (Domenico 1987):

$$\frac{C_x}{C_0} = \exp\left\{\frac{x}{2\alpha_x}\left[1-\left(1+\frac{4\lambda\alpha_x}{\upsilon}\right)^{\frac{1}{2}}\right]\right\} erf\left[\frac{Y}{4(\alpha_y x)^{\frac{1}{2}}}\right] erf\left[\frac{Z}{4(\alpha_z x)^{\frac{1}{2}}}\right]$$

Where:

C_x - contaminant concentration in a downgradient well along the plume centerline
at a distance *x* (mg/L),
C_0 - contaminant concentration in the source well (mg/L),
x - centerline distance between the downgradient well and source well (ft),
$\langle_x$, $\langle_y$, and $\langle_z$ - longitudinal, transverse, and vertical dispersivity (ft), respectively,
$D_x = \langle_x \cdot \{$, $D_y = \langle_y \cdot \{$, $D_z = \langle_z \cdot \{$,
⌊ - degradation rate constant (1/day),
⌊=0.693/$t_{1/2}$ (where $t_{1/2}$ is the degradation half-life of the compound).
{ - groundwater velocity (ft/day),
Y - source width (ft),
Z - source depth (ft),
erf - error function,
exp - exponential function.

The Domenico Analytical Model assumes:

(1) The finite source dimension,

(2) The steady state source,

(3) Homogeneous aquifer properties,

(4) One dimensional groundwater flow,

(5) First order degradation rate,

(6) Contaminant concentration estimated at the centerline of the plume,

(7) Molecular diffusion based on concentration gradient is neglected,

(8) No retardation (e.g., sorption) in transport process.

Understanding model assumptions is crucial to simulate transport process for a specific contaminant in groundwater.

9.4.3 *Guidelines for operating GIMI*

The GIS interface has its own help file and can be accessed through the button shown in the screen shot in Figure 9-5.Under Content in the Help file there is a menu with:

- Introduction
- Frequently asked questions
- Utilities
- Models
- Quick start guide

The following section provides a step-by-step guideline to operate GIMI:

Step 1 - Select the point of interest using the button.

Step 2 - Zoom to required extent of the assessment by placing the GIS in zoom mode through the use of the button. Hold down the left mouse button and drag a rectangle to the bottom right that will represent the zoom area.

Step 3 - Click on Create Assessment using the button. The number of available topography points in the selected area will be displayed. Click OK to continue.

The default model grid will be displayed on the assessment area, ready to start building the assessment:

9.4.3.1 Assessment Toolbar

The assessment toolbar is where the navigation and placement features are accessed from. The list below provides a summary of the toolbar buttons:

Zoom to full extent of the area

Set the zoom factor to 100%

Selection mode to select object and move them around in the CAD interface

Zoom mode (dragging a rectangle from top left to bottom right)

Zoom in 2x from the selected point

Zoom out 2x from the selected point

Pan mode

Place a ruler object on the mine area

A Place a text object on the mine area

Rotate selected object

✕ Delete selected object

Move selected object to the front

Move selected object to the back

Use reference (Set reference by holding down Ctrl & Alt and click point)

9.4.3.2 Assessment Objects

The objects are selected from the object menu. The menu is invoked through a right click on the object tree as shown below:

The connecting rules for objects are enforced through the menu system. Thus objects in the menu are disabled for a particular tree node if the objects are not allowed to connect to the node in question.

A summary of all object types:

Mine or area object which from the parent of all objects in the object tree

Model object that represents the transport model

Contour map object (topography, water levels and concentration)

Quality object representing the mine water quality

Virgin soils

Spoils object

● Pivot object, which is placed on the virgin soils or spoils

Crop object, which is connected to pivot objects

Acid based accounting object connected to the spoils

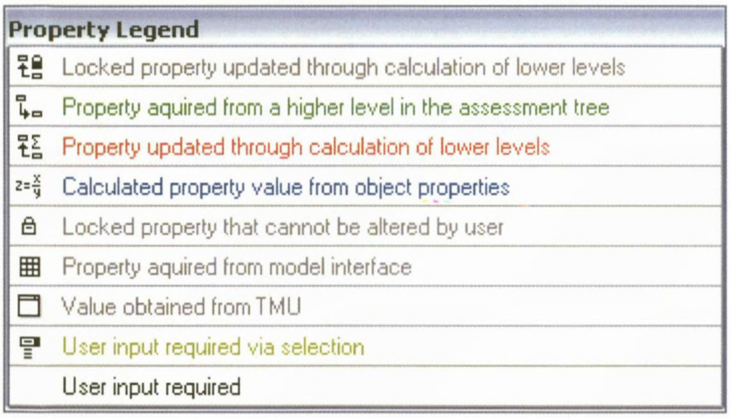
• Borehole object, which is placed on the area (mine) and acts as a receptor

Population object, which is placed on the area (mine) and acts as a receptor

Receptor object, which is placed on the area (mine)

9.4.3.3 Object Properties

Each object consists of properties. Some properties is user supplied and some are calculated from the system. The screen below is the legend describing the various property types:

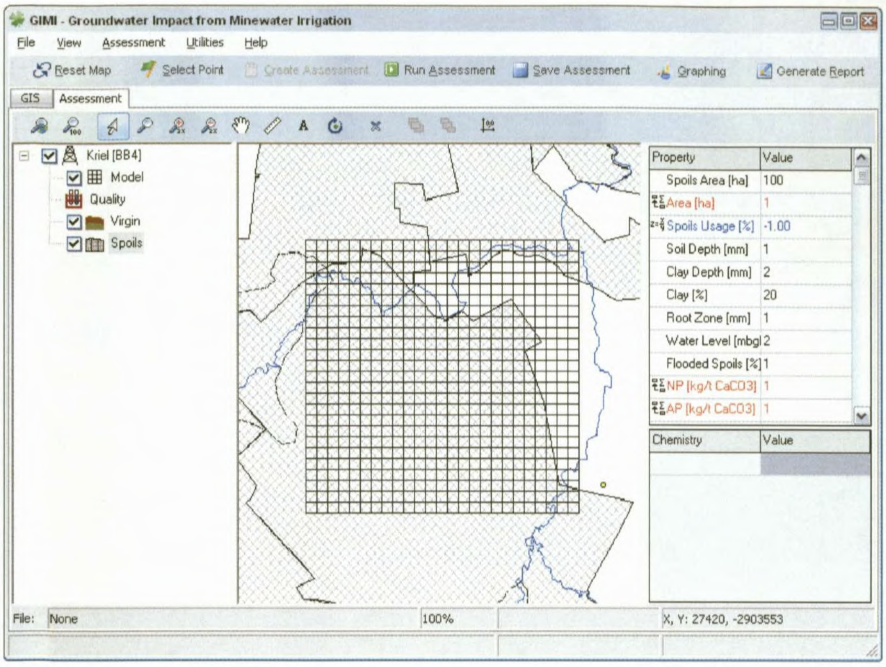


Property Legend
Locked property updated through calculation of lower levels
Property aquired from a higher level in the assessment tree
Property updated through calculation of lower levels
Calculated property value from object properties
Locked property that cannot be altered by user
Property aquired from model interface
Value obtained from TMU
User input required via selection
User input required

9.4.3.4 Assessment Interface

The assessment interface consists of 3 main components:

1. The object tree view on left hand side of the screen
2. The modeling area in the center of the screen
3. The object property editor on the right hand side of the screen



Property	Value
Spoils Area [ha]	100
Area [ha]	1
Spoils Usage [%]	-1.00
Soil Depth [mm]	1
Clay Depth [mm]	2
Clay [%]	20
Root Zone [mm]	1
Water Level [mbgl	2
Flooded Spoils [%]	1
NP [kg/t CaCO3]	1
AP [kg/t CaCO3]	1

Chemistry	Value

Object Tree

The object tree represents the assessment and all objects used is visible in the tree view. By clicking on each tree node the object properties will update on the right hand side of the screen in the property editor. The objects with a check mark next to them can be switched on and off simply by clicking on the check mark. All nodes in the tree can be renamed and this is important if multiple receptors, pivots and crops are used to distinguish between them in the report. Click on the node text to highlight it and click on it again to put it in edit mode.

Modeling Area

The modeling area is a CAD interface with a grid placed on top of it which represents the transport model used in GIMI. The assessment toolbar is used to navigate and place objects in the assessment interface. Visual objects are displayed on the assessment area as the user places them. Note not all objects in the object tree is visual objects and may only exist in the tree.

Property Editor

The property editor is the place where the objects gets populated with information. Some properties are user input and some are calculated. Each property is color coded and has an icon next to it depicting the property type.

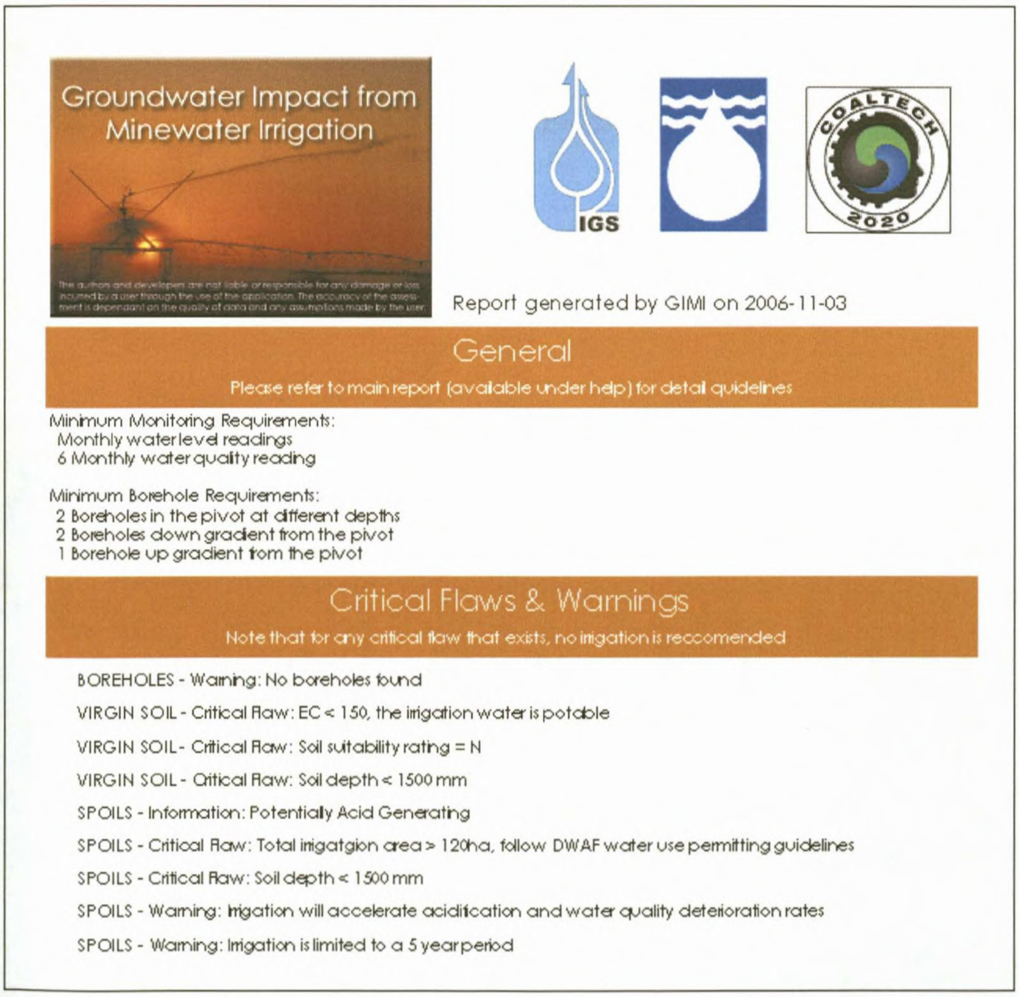
9.4.3.5 Analysing an Assessment

Once the assessment has been built through the available objects and the user is confident that all data requirements have been addressed the assessment can be run through the use of the button. Once the assessment has run the user will notice the various contour maps that are generated and that various object properties have been updated after the model run. If the user changes any of the object properties the assessment must be re-run to update relevant object properties.

After an assessment is run the user has the option of saving the assessment for future use through the use of the button.

Graphing of the pivot parameters can be done through the graphing tool as shown below:

A report of the assessment highlighting critical flaws and warnings can be generated through the use of the button (Figure 9-8). The report can be saved in the custom report format to be opened through the report generator or can be saved to PDF format for distribution.



Groundwater Impact from Minewater Irrigation

The authors and developers are not liable or responsible for any damage or loss incurred by a user through the use of the application. The accuracy of the assessment is dependant on the quality of data and any assumptions made by the user.

IGS

COALTECH 2020

Report generated by GIMI on 2006-11-03

General

Please refer to main report (available under help) for detail guidelines

Minimum Monitoring Requirements:
Monthly waterlevel readings
6 Monthly water quality reading

Minimum Borehole Requirements:
2 Boreholes in the pivot at different depths
2 Boreholes down gradient from the pivot
1 Borehole up gradient from the pivot

Critical Flaws & Warnings

Note that for any critical flaw that exists, no irrigation is reccomended

BOREHOLES - Warning: No boreholes found

VIRGIN SOIL - Critical Flaw: EC < 150, the irrigation water is potable

VIRGIN SOIL - Critical Flaw: Soil suitability rating = N

VIRGIN SOIL - Critical Flaw: Soil depth < 1500 mm

SPOILS - Information: Potentially Acid Generating

SPOILS - Critical Flaw: Total irrigatgion area > 120ha, follow DWAF water use permitting guidelines

SPOILS - Critical Flaw: Soil depth < 1500 mm

SPOILS - Warning: Irrigation will accelerate acidification and water quality deterioration rates

SPOILS - Warning: Irrigation is limited to a 5 year period

Figure 9-8: Report of the assessment.

10 CONCLUSIONS AND RECOMMENDATIONS

This thesis has investigated the impact of irrigation with coal mine water on groundwater resources. Various field and laboratory experiments were done to determine the impact and feasibility of irrigation in the short to medium term. Based on the findings from this study, the results were used to set up guidelines and to develop the GIMI tool. This tool should assist in the practical implementation of mine water irrigation as part of optimal mine water management.

10.1 Availability of irrigation water:

Opencast collieries: Approximately 75 000 ha of opencast will eventually be rehabilitated in the Mpumalanga region. If it is assumed that the recharge to the rehabilitated opencasts will be in the order of 20% of MAP, and that the annual irrigation water for 1 ha is 5 000 m^3, then in excess of 20000 ha could be irrigated for a single crop.

Underground collieries: Approximately 19500 m^3 of water will be in storage when filled for every hectare mined. Calculated according the average rainfall, shallow mines with a recharge of 5-10% of MAP will annually have an amount of 350 - 700 m^3 /ha available annually for irrigation. This means that every 7-14 ha will provide enough water to irrigate one hectare. For deep underground bord-and-pillar areas with a recharge of 4%, 18 hectares will provide enough water for one hectare of irrigation.

However, not all of this water will be available for irrigation. Three desalination plants are envisaged for the Mpumalanga coal fields to provide water to the local authorities. Less than 20% will thus be available for other water uses, of which irrigation is only one.

10.2 Water levels and water quality

1. The water levels at all the pivots have varied very little over time.

2. The irrigation water has, as yet, shown a minimal impact on the groundwater. Some exceptions occur, but none of the boreholes outside the pivot areas show any meaningful change in water quality from leaching from the irrigated area. This implies a very slow movement of the constituents in the irrigation water, and that these are attenuated by different mechanisms between the surface and the aquifers, often in the clay layers. The

amount leaching through the soil is small enough to be easily diluted by the regional groundwater flow. It thus appears that the soil type and morphology plays a very important role in the vertical movement of the irrigation water constituents. However, in the sandy aquifer at New Vaal the analyses show that there is a steady and consistent rise in the electrical conductivity in the groundwater underlying the pivot. This indicates that the irrigation water is slowly leaching through the more clayey sand layers and is influencing the groundwater quality directly below the irrigation area.

10.3 Soil and Soil Water Analysis

The *soil analysis* indicated that most of the salts are captured in the upper one or two meters of the soil profile. The salts move along the profile in the soil water. The data indicates that the clay layers, which play a major role in the vertical flux of the water, therefore also have an influence on the salt distribution through the soil profiles.

According to the *soil water* quality the water is saturated with gypsum in the first meter or two, indicating gypsum precipitation. The calcium decreases much more than the other cations, indicating the gypsum precipitation.

XRF/XRD analysis indicated that gypsum precipitation occur since Ca values are far higher in the shallow portions, while Mg values are more evenly distributed. This suggests that the distribution is chemically controlled rather than by surface interactions since these two ions should have similar sorptive capacities. This is supported by the Na values, which are evenly distributed with depth. Research has revealed that bassanite ($CaSO_4$ $0.5H_2O$, or calcium sulphate hemihydrate) is present in most of the samples.

Sulphate adsorption: Leaching column experiments indicated sulphate precipitation as well as adsorption. This means that not all sulphate will be leached by excessive irrigation or rain. It must be noted, however, that desorption can occur and that the sorbed sulphate will not be irreversibly fixed in the soil profile.

Soil moisture: Even at sites with shallow water levels there is a visible decrease in soil moisture during winter when effective irrigation is being practiced. This will result in salts retained in the upper layers of the soil, as indicated by the soil analyses and the soil water analyses. The clay layers are important in the downward movement of the soil water. This will also have an effect on the salts being attenuated in the soil layers above the saprolite zone. The profile above 1m is less moist than at 1m. Therefore the conditions above one meter will be much more favourable for gypsum precipitation.

Salt balance: One of the critical issues in successful irrigation with the coalmine waters is how much of the salts are retained in the soil profile over the medium term. Geochemical modeling has indicated that the soil water in the top one meter is saturated with gypsum, and precipitation should occur. In the deeper moist layers the water is still undersaturated with regard to gypsum. The salt balance calculations revealed that 80% of the sulphate applied during irrigation since 1999 (2001 at other sites) has been retained in the soil profile (also as gypsum), most of it in the upper two meters. On average, between 75% and 80% of the sulphate retained are in the pore water (more than 60% of the total sulphate applied) and the rest precipitates or is sorbed. Hydraulic, adsorption and attenuation factors prevent the salts in irrigation mine water from being directly and rapidly mobilised down the deeper soil profile and into the aquifer. New Vaal is the exception where a large amount of the salts is retained in the clayey soils deeper down the profile. Most of the salts in the clayey soil of Syferfontein are retained in the upper 0.6 m. At Kleinkopje 4 the salts have migrated a little deeper, with most remaining at 1-2 m in the moist area above the clayey layer.

Leaching: The conditions in the soil will be drier under normal cultivating conditions (after irrigation has ceased), and recharge will maximum be 5-6%. It will thus take a very long time to leach the sulphate from the soil (probably more than a hundred years).

10.4 Hydraulic behaviour in the unsaturated zone

- The chloride values at all the different irrigation sites showed a decrease in chloride values with depth, implicating bimodal flow.
- Twenty five percent of the total volume of water applied through irrigation reaches the water level.
- There is a correlation between clay content of the soil and the diffusive component of the bimodal flow. Due to the moist conditions at irrigation sites, swelling of the clay results in a very low vertical conductivity value of 10^{-4} m/d.
- Due to lateral flow in the weathered saprolite zone, dilution occurs (lateral flow contributes approximately 85% towards the dilution process). Water will move along the weathered zone, and part of the salinity will move deeper down into the fractured aquifer, some will daylight or seep into adjacent strata. This means that the release of salinity into the groundwater is a very slow process, which makes irrigation a viable option over the short to medium term.

10.4.1 *Kleinkopje 1*

In the short to medium term there is a build-up of salts in the soil profile, with most of it (83%) retained in the soil water. A portion of these salts moves through to the groundwater, which will limit long-term sustainability of irrigation from an environmental perspective.

Note: The salinity concentrations at this site are a conservative estimate, because the test site is situated close to a borehole that drains into the mine, thus leaching some of the salts that build-up in the upper profile, down the mine during high rainfall or irrigation events.

10.4.2 *Kleinkopje 4*

In the short to medium term there is a build-up of salts in the soil profile, with 77% of it in the soil water. A portion of these salts moves through to the groundwater, which impact negatively on a long-term irrigation project. However, the build-up is slow due to dilution because of the lateral movement of water, which in the short to medium term will not impact negatively on the aquifer.

However, gypsum improves the soil structure, especially in clayey soils, and replaces salts like sodium (See Appendix C for an explanation). This make the irrigation option with gypsiferous type water even more viable.

10.4.3 *Syferfontein*

In the short to medium term there is a build-up of salts in the soil profile especially in the upper 1m, with little movement down the profile. A portion of these salts does move through to the groundwater (as can be seen from the water quality in the well-constructed borehole), which impact negatively on a long-term irrigation project. Although the swelling clay (smectite) of well developed Arcadias at Syferfontein can restrict water movement to micro pore flow, it shrinks when dry. This can cause large cracks in the upper soil profile (Soil Classification Working Group, 1991) which allows for large volumes of water to enter the soil at the start of a rainfall event. This is a reason for the higher than expected percentage water that moves through this very clayey soil profile.

Due to the high sodium content of the water at this very clayey site, the feasibility of irrigation is questionable. The disruption of the soil structure, together with clay dispersion, greatly reduces the soil permeability since the larger pores are blocked (See Appendix C).

10.4.4 *New Vaal*

In the short to medium term there is a slow but definite build-up of salts in the groundwater. Most of the salts are retained in the shallow clayey layer and the deeper clayey soils because of the movement of the water through the profile. The salts that move through to the groundwater will impact negatively on a long-term irrigation project. However, the build-up is slow due to dilution.

10.5 Detailed site evaluation for opencast (spoils) sites

- Models indicate the great importance of the reactive nature of the spoils on which irrigation will occur. The potential for acid generation should be a very important consideration of where to apply mine water irrigation, while it is also clear that in high sulphide areas, the irrigation will enhance reactions and therefore lead to higher salt loads.
- The re-use of irrigation in certain systems has both advantages and disadvantages. The advantages of a "closed" or semi-closed loop means that the salt is not released into the environment. It has also been shown that secondary minerals solubility constraints will limit the possible upper values. It is therefore clear that the nature of the recirculating water is important. Where mine water used for irrigation is largely gypsyferous, the recirculation scenario is feasible under the correct conditions (e.g. impermeable floor rocks). Where this water contains many other elements such as sodium chloride, the solubility limits become far higher due to the increase in the ionic strength of the percolating water. Under these conditions, concentrations will continue rising to very high levels. This continuous rise is confirmed not only by theoretical considerations and geochemical models, but also by observations from laboratory tests. The implication is that the nature of the spoils, and the irrigation water quality, must be considered in terms of what the likely soluble concentrations of different elements will be.
- Where mine water of relatively consistent quality is used, the changes in longer-term quality will be far less dramatic. The system reaches an equilibrium state and can continue in this state for long periods of time.

Recommendation:

The complexity of the interactions makes it necessary to consider several factors simultaneously in terms of the feasibility and effects of mine water irrigation on spoils. One of the important factors seems to be the time of year (during winter when it does not rain) and the management of the irrigation schedule (not to over-irrigate and wet the spoils too much). Field tests have indicated that during winter the spoils dry out in depth in the profile, which will result in an increase of acid generation. Overall the modeling, laboratory tests and field tests indicate that mine water irrigation on spoils will lead to a further deterioration of spoils water quality, when compared to rainfall infiltration into the spoils. Where mine water of relatively consistent quality is used, the changes in longer-term quality will be far less dramatic. It is suggested that irrigation with water containing enough buffering potential be used for irrigation on spoils.

10.6 Overall Recommendation

Irrigation with mine water must be implemented such that the environmental impacts are minimized. Based on the slow expected salinity build-up observed at the different sites, it is recommended that irrigation be done on an alternating basis (i.e. alternating between two pivots over time), if site criteria selection has been adhered too (See Chapter 9), and that mine water irrigation should not be done for periods exceeding 10 years in any particular area. A non-negotiable prerequisite is that appropriate monitoring must be put in place at such a site. These boreholes must be constructed in such a way that they monitor all the different flow zones and aquifers at these sites.

It is imperitave that the guidelines outlined in Chapter 9, being adhered too. The guidelines provided should lead to sustainable mine water irrigation.

It is unknown how long this accumulation of salts in the upper layers can continue before leaching into the underlying aquifers, but in the short to medium term, the evidence from groundwater monitoring shows that irrigation with mine water does not hold significant threats for the regional groundwater quality.

To determine the impact of the viability of irrigation with coal mine water in the long term, it is suggested that monitoring continues at the various test sites. Monitoring should be done as described in Chapter 9.3.

Due to the relatively short period of research, there are still uncertainties regarding the long-term sustainability of irrigation, which may be answered if monitoring at these sites continues. This wil address the following issues:

- The amount of gypsum that can precipitate in the soil, and for how long this will this sustainable.
- The effect of the gypsum build-up on the structure of the soil?
- How much of the applied salts can precipitate into the upper layers of the profile.

- How much of the salts will leach out, and at what rate. If irrigation ceases at some of the sites (as is the case at New Vaal), this should be investigated. This will also indicate how the salts will affect the groundwaterover the long term.

This study has shown that it is possible to irrigate with coal mine water in such a manner that the impacts on groundwater resources is minimal. Therefore it is imperitave that the regulatory agencies and water managers consider the potential socio-economic benefits when evaluating coal mine water irrigation.

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Summary

Key words: Virgin soils, spoils, gypsiferous water, irrigation, precipitation, diffusive and bimodal flow, leaching, monitoring.

Huge volumes of mine water, impacted on by acid mine drainage, are presently produced as a result of mining activities. These waters are mostly neutralised either as a result of seepage through neutralising geological strata, or artificially by the addition of lime. Mine drainage is, therefore, often saturated with gypsum. Gypsiferous mine water can thus be regarded either as one of the greatest problems associated with mining, or as a potential asset. Large amounts of waste water could be made available to the farming community, and utilised for the irrigation of highly productive soils in the coalfields. Concentrating the gypsiferous soil solution through evapotranspiration, thereby precipitating gypsum in the soil profile, will reduce environmental pollution, as these salts are removed from the water system. However, the regulatory authorities have raised some concerns regarding the possible impact of larger-scale irrigation on water resources. This research attempts to provide meaningful answers.

Five different irrigation sites were selected for research. Monitoring indicates that very little salinity applied on surface during irrigation reaches the water table. Soil analysis indicates that most of the salts are captured in the upper one or two meters of the soil profile. The data indicate that the clay layers, which play a major role in the vertical flux of the water, also have an influence on the salt distribution through the soil profiles. The porous cups data suggest that the majority of the salts is currently contained within the uppermost portions of the soil profile, showing a steady decrease in sulphate concentrations with depth. Geochemical modelling indicates that soil water in the uppermost meter is saturated with gypsum, and precipitation occurs.

Virgin soils:

The chloride values at all the different irrigation sites showed a decrease value with depth, indicating bimodal flow. The saline water moving through the soil profile contributes approximately 15% or less to the mixing process of the water. Lateral flow in the highly conductive F zones on the contact of the weathered zone with the solid rock, results in salinity dilution. Twenty-five percent of the total irrigation water volume reaches the water level. There is a direct correlation between the clay content of the soil and the diffusive

component of the bimodal flow. Due to the moist conditions at irrigation sites, swelling of the clay results in the very low vertical conductivity value of 10^{-4} m/d.

The average estimated moisture content with depth is:

Depth	1000mm	2000mm	3000mm	4000mm
Kleinkopje 1	0.32	0.373	0.34	0.34
Kleinkopje 4	0.358	0.339	0.34	0.28
Syferfontein	0.384	0.35	0.274	0.262

The salt balance revealed that 80% of the sulphate applied during irrigation is retained in the soil profile, most of which occurs in the upper two meters. 80% of this retained sulphate occurs in the soil water. After irrigation ceases, it can take more than 100 years to leach the sulphate from the soil profile, due to bimodal flow and low recharge.

Conclusion: In the short to medium term, irrigation is feasible on virgin soils, as most of the salinity is captured, and little is released in the groundwater.

Spoils:

The tests and models indicate the great importance of the reactive nature of the spoils on which irrigation will occur. Where mine water of relatively consistent quality is used, the changes in longer-term quality will be far less dramatic.

Based on the slow salinity build-up at the different sites, it is recommended that irrigation be alternated (i.e. between two pivots over time) if site criteria selection has been adhered to, and that mine-water irrigation should not be done for periods exceeding 10 years in any particular area. A non-negotiable prerequisite is that appropriate monitoring must be in place.

Opsomming

Groot volumes water, geimpakteer deur suurvorming, word huidiglik geproduseer as gevolg van mynbou aktiwiteite. Hierdie water word meestal geneutraliseer as gevolg van vloei deur geologiese strata wat neutralisering aanhelp, of deur die toevoeging van kalk. Water afkomstig van mynbou is dus dikwels versadig met gips. Hierdie gipsryke water kan beskou word as een van mynbou se grootste probleme, of as 'n potensiële bate. Groot hoeveelhede afval water kan tot die beskikking van die landbou gemeenskap gestel word vir gebruik in besproeiing op die hoë-potensiaal gronde van die steenkoolveld. Deur die gipsryke water te konsentreer deur evapotranspirasie, kan gips in die grond gepresipiteer word. Dit sal die omgewingsbesoedeling verminder deurdat soute verwyder word uit die waterstelsel. Die betrokke owerheid is egter besorg oor die impak wat grootskaalse besproeiing kan hê op die grondwater reserves. Hiedie navorsingsprojek poog om sulke vrae te beantwoord.

Vyf verskillende besproeiings persele is geselekteer vir die projek. Monitering van die persele oor tyd toon dat baie min van die soute wat deur die water op die grond toegedien word, die water tafel bereik. Grond analises toon dat meeste van die soute in die boonste twee meter van die grond profiel vasgevang is. Die klei lae speel 'n groot rol in die vertikale beweging van die water. Analises toon ook dat dit 'n invloed het op die sout verspreiding deur die grond profiel. Poreuse koppie data het hierdie bevinding bevestig, en aangetoon dat daar 'n afname van sulfaat konsentrasie met diepte is. Geochemiese modelering toon dat die grondvog in die boonste meter van die profiel versadig is met gips, en dat presipitasie plaasvind.

Onversteurde grond:

Die chloried konsentrasie by al die verskillende persele wys 'n afname in konsentrasie met diepte. Dit dui op voorkeur vloei. Die soutryke water wat afbeweeg in die profiel dra ongeveer 15% of minder by tot die vermenging van die water om die laer chloriedwaardes te verkry. Die hoë geleidingsones op die kontak tussen die verweerde sone en die soliede rots veroorsaak die laterale vloei van water wat bydra tot die verdunning van die soutkonsentrasie. Vyf-en-twintig persent van die toegediende besproeiingswater bereik die water tafel. Daar is 'n direkte verband tussen die klei inhoud van die grond en die diffusie komponent van die bimodale vloei. As gevolg van die natter toestande op

besproeiingspersele, veroorsaak die swelling van die klei dat die vertikale konduktiwiteitswaarde baie laag is, nl. 10^{-4} m/d.

Die gemiddelde vog inhoud met diepte is:

Depth	1000mm	2000mm	3000mm	4000mm
Kleinkopje 1	0.32	0.373	0.34	0.34
Kleinkopje 4	0.358	0.339	0.34	0.28
Syferfontein	0.384	0.35	0.274	0.262

Die soutbalans wys dat 80% van die sulfaat wat op die perseel toegedien is, in die grond vasgevang is. Die meeste hiervan is in die eerste twee meter van die profiel. Nadat besproeiing gestaak is, sal dit meer as 100 jaar neem om die sulfaat uit die grondprofiel te loog, omdat bimodale vloei en lae reën aanvulling loging sal vertraag.

Gevolgtrekking: In die kort tot medium termyn, is besproeiing met die gipsryke water haalbaar. Die meeste van die sout is vasgevang, en baie min loog deur na die water tafel.

Versteurde grond:

Die proewe en modelle wys dat die reaktiewe aard van die versteurde grond waarop besproeiing plaasvind, baie belangrik is. Die verandering in langtermyn water kwaliteit sal baie minder wees as water van redelik konstante kwaliteit gebruik word vir besproeiing.

Gebasser op die stadige opbou van soute in die grondprofiel, word wisseling van besproeiing tussen twee persele voorgestel as alle reëls vir die kies van geskikte persele nagekom is. Besproeiing moet nie langer as tien jaar per perseel geskied nie. 'n Ononderhandelbare voorwaarde vir besproeiing is dat geskikte monitering in plek moet wees.