

# **Development of guidelines for the management of groundwater in and around rehabilitated coal discard facilities**

by

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## DECLARATION

I, Duheine Myburgh, hereby declare that this dissertation, submitted for the degree Masters in the Faculty of Natural and Agricultural Sciences, Department of Institute for Groundwater Studies, University of the Free State, Bloemfontein, South Africa, is my own work and has not been submitted to any other institution of higher education. I further declare that all sources cited or quoted are indicated and acknowledged by means of a list of references.



Signature

2017/05/24

Date

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I would like to dedicate this study to my late Mother, Anne-Marie Myburgh who always believed in me, supported and motivated me to achieve my goals. I would not have had the perseverance if not for you.

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## LIST OF ACRONYMS AND ABBREVIATIONS

LOM	Life of Mine
ARD	Acid Rock Drainage
ABA	Acid Base Accounting
ARD	Acid Rock Drainage
AP	Acid Potential
BPG	Best Practice Guideline
$\text{Ca}(\text{OH})_2$	Calcium Hydroxide
CaO	Calcium Oxide
CO	Carbon Monoxide
$\text{CO}_2$	Carbon Dioxide
CSM	Conceptual Site Model
DMR	Department of Mineral Resources
DWS	Department of Water and Sanitation
EA	Environmental Assessment
EIA	Environmental Impact Assessment
EMPr	Environmental Management Plan report
GDP	Gross Domestic Product
LOM	Life of Mine
mamsl	metres above mean sea level
MAP	Mean annual precipitation
MAR	Mean Annual Recharge

MPRDA	Mineral and Petroleum Resources Development Act, 2002
Mt.	Million tons
NEMA	National Environmental Management Act, 1998
NOx	Oxides of Nitrogen
PCD	Pollution Control Dam
PRB	Permeable Reactive Barrier
Rbn	Rand (billion)
Reg. 704	Regulation 704
SA	South Africa
SAP	Sulphide Acid Potential
SOx	Oxides of Sulphur
TAP	Total Acid Potential
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
Waste Act	National Environmental Management: Waste Act, 59 of 2008
WCA	World Coal Association
WMA	Water Management Area
XRD	X-Ray Diffraction

## CHAPTER 1: INTRODUCTION

Since the late 1800's coal mining has been active in the Mpumalanga Province. And has exerted numerous costs and hazards onto the biophysical environment since inception. Coal mining is seen as a destructive process as it excavates what is valuable beneath the surface of the earth and then produces heaps of waste material and rock through the crushing and washing processes. Waste separated prior to beneficiation is referred to as spoil or waste rock and is normally placed on surface on waste rock dumps or put back into the mining voids as part of the rehabilitation process. Waste separated by beneficiation is referred to as discard material and is placed on surface or in voids in heaps or engineered facilities. During the Life of Mine (LOM) discard dump rehabilitation should be done to ensure safety of the facility and to prevent pollution and harm to the environment.

The effect of discard facilities generally sustain numerous generations as it endures the full degree of the life of mine which consists of project phase, operational, decommissioning and closure phases. Acid Rock Drainage (ARD), water reclamation, treatment and remediation has been a topic for discussion for quite a few years seeing that environmental legislature and the implementation thereof has developed progressively in South Africa (SA) and around the world over the last decade.

Diverse approaches of remediation and recovery has been successfully realized in order to reduce the impact of rock drainage on the environment, in South Africa and abroad.

Legislatively, the disposal of mineral residue waste is governed by several acts, regulations and national guidelines like the National Water Act, 1998 (Act No. 36 of 1998); Minerals and Petroleum Resources Development Act, 2002 (MPRDA); the Regulation 704 (Reg. 704) as part of the National Water Act, 1998 (Act No. 36 of 1998); as well as the Best Practice Guidelines published by the Department of Water and Sanitation (DWS). To ensure compliance to these regulations, management of rehabilitated coal discard facilities needs to be conducted in a sustainable and cost effective way as to minimise and reduce pollution emanating from these facilities.

In order to have a guideline for the management of groundwater in and around coal discard facilities one has to address certain investigations which includes, but are not limited to desktop studies coupled with fieldwork, drilling, geological and geophysical investigations.

## 1.1. Scope and objectives

The scope of this study is to develop a practical set of guidelines that can be used by the coal mining industry to better manage groundwater in and around rehabilitated coal discard facilities. The aim is for the guideline to have a series of steps and methodologies which will provide the user with practical measures to focus on after a discard facility has been rehabilitated and deemed for closure. The study also aims to amalgamate and assimilate current best practice into a single practical and usable guideline document streamlined with the current Department: Water and Sanitation (DWS) Best Practice Guidelines (BPG's) which will not only ensure legal compliance to the South African legislation but also provide practical guidelines for management of groundwater beyond compliance.

The objectives were as follow:

- Discuss the life cycle of coal mining in South Africa with a focus on processing and discard generation through to rehabilitation and post-closure.
- Expand on the current legislation applicable to coal discard facilities.
- Conduct an extensive literature review of the current management guidelines and best practices available globally.
- Discuss the case study of Springbok 2 discard facility and some of the best practices implemented.
- Develop a guideline which can practically be used to manage groundwater more effectively after discard facility construction has ceased.

## 1.2. Structure of dissertation

This study consists of seven main chapters, each having a number of sub-sections specific to each relevant chapter:

Chapter 1: Discusses the scope, objectives and structure of the dissertation.

Chapter 2: Is a discussion about coal mining in South Africa, mineral waste production and the impacts associated with it.

Chapter 3: Is a brief overview of the relevant environmental and mining legislation regarding mineral waste and discard facilities.

Chapter 4: Is a literature review of current practices and best practices for coal discard facilities. It also looks at the Hierarchy of water management principles in mining and pollution mitigation options.

Chapter 4 also discusses Conceptual Site Models (CSM's) and the importance of it as this fed into the guideline development.

Chapter 5: Looks at a case study of the Springbok 2 discard dump and the management practices implemented which forms part of the guideline development. A CSM also forms part of this chapter.

Chapter 6: Is the amalgamation of all the relevant literature reviews, best practice and case study in order to produce a practical usable document to assist with the management of groundwater in and around rehabilitated coal discard facilities.

Chapter 7: Summarises the findings and conclusions related to this study.

### **1.3. Summary: Chapter 1**

The objective of chapter 1 is to set the scene for the study. This includes introducing the physical and legal aspects and processes involved with mineral waste generation as a result of coal mining. It provides a motivation for why discard facilities need to be managed in a sustainable cost effective manner. The objectives of the study are introduced and the need for a management guideline is emphasised. Lastly the structure of the dissertation is discussed according to the relevant chapter.

## CHAPTER 2: COAL MINING IN SOUTH AFRICA

Coal reserves worldwide are considered to be 985 billion tons. Coal is an important provider in the energy production sector by accounting for 23% of the world's primary energy and provides energy in the form as fuel to account for 38% of the global energy production (Thomas, 2002). The South African coal mining industry produces sufficient coal to supply 94% of the country's energy production requirements. With South Africa in the top 5 of global coal exporters it employs more than 50,000 people and generated a gross domestic income of R101.5 billion during 2014 (Baxter, 2015). The coal mining industry has been dominated by large companies like South 32, Anglo American Coal SA, Exxaro and Glencore over the last couple of years. But due to the recent downturn in commodity prices coupled with sharp falls in share prices some companies have left the market where other smaller companies have entered the South African markets. Figure 1 indicates South Africa's main coalfields with emphasis on the central and eastern coalfields where mining is predominant. Figure 2 indicates the spatial distribution of known coal mines in the Olifants river catchment. The coal is located in eight coal fields in the central, eastern and northern parts of South Africa with a general stratigraphy consisting of 5 primary coal seams of economic value (Figure 3) (Cairncross, 2012). According to Munnik *et al.*, 2010, the country has more than 64 collieries with among the largest producers in the world. Coal mining is by underground or opencast mining methods with underground mining accounting for 51% and opencast methods accounting for 49%. South Africa's 100 year old Mpumalanga coalfield is the most important coalfield with the most number of collieries. With concentrated coal mining comes complicated environmental and social impacts (Munnik *et al.*, 2010). One such an impact is the generation of spoil and discard material as waste during the mining process. As a result of the lifecycle, oxidation of iron sulphides take place which results in the formation of Acid Rock Drainage (ARD) which needs to be effectively managed.

### 2.1. Background

Coal mining is one of South Africa's key foundations of energy (Thompson, 2005) with an assessed surplus of 55.3 billion tons of recoverable coal reserves (Eberhard, 2011).

South African coal production comprises 53% open cast mines (bord-and-pillar: 40%, stoping: 4%, longwall: 3%) (Creamer Media, 2013). The mining process used is largely dogged by the economic facet, founded on the geological appropriateness of the reserve. According to Cairncross (2001), South African coal deposits are located in the formations of the Middle Ecca Group and Karoo Supergroup with coal strata of up to 30-150m thick. The bulk of South Africa's coal mining operations are assembled in Mpumalanga Province. The province is accountable for above 84% of South Africa's coal

production (Creamer Media, 2013). The residual coal production curtails from the existing operating mines in the Waterberg coalfield, Soutpansberg coalfield, as well as several mines in the Free State and KwaZulu-Natal.

Underground and surface mining methods produce disturbances in the normal groundwater levels, influencing the water quality. The volume of waste produced will be greater at an open-pit mine than at an underground mine as the latter one is using a selective mining method. Operating mineral extraction comprises material being crushed, sorting and conveyance to the washing plant. During mineral processing waste and valuable mineral phases are divided and conveyed to stockpiles or transported to the unambiguous zones such as power plants.

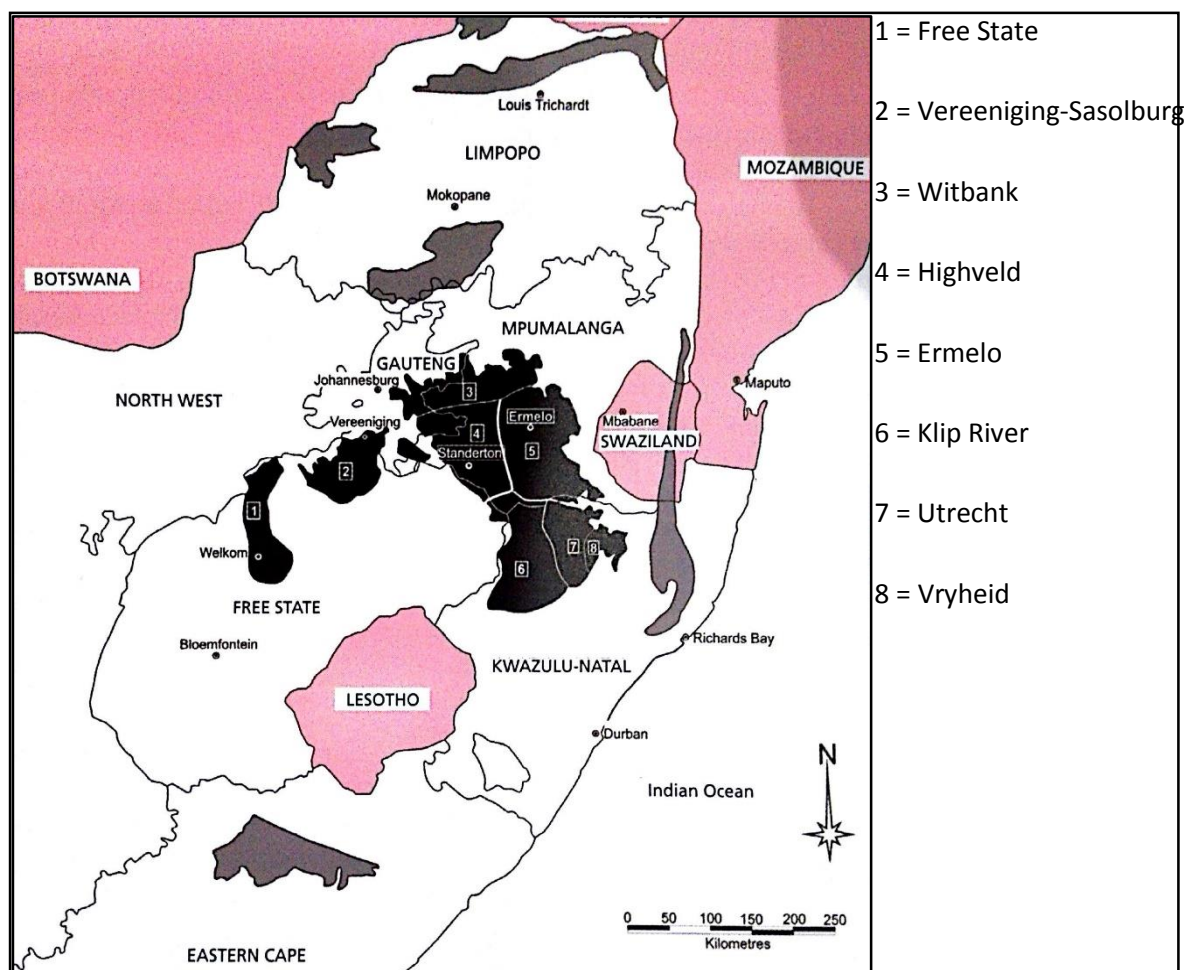


Figure 1: Locality map of South Africa’s coalfields (Cairncross, 2012).



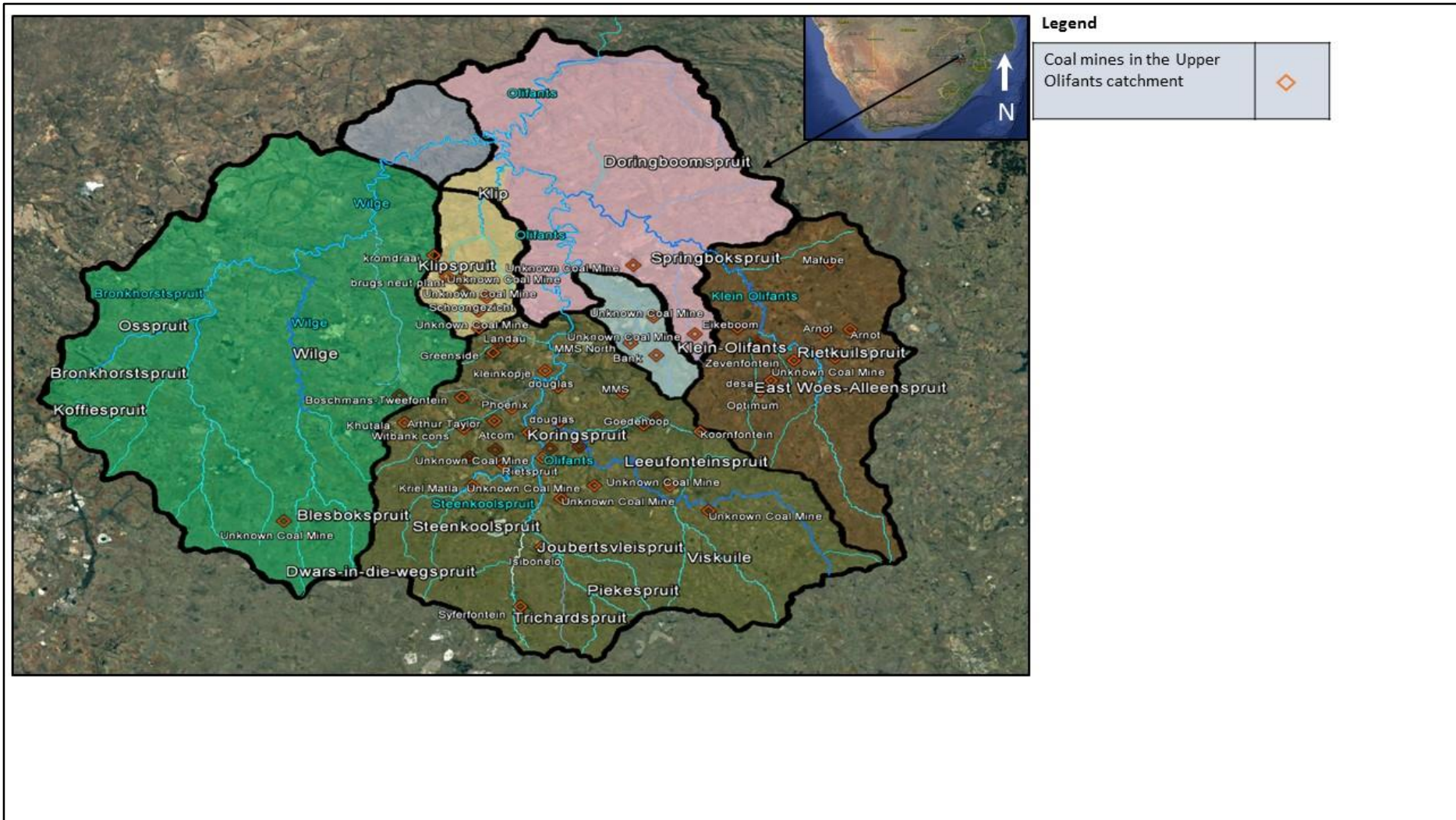
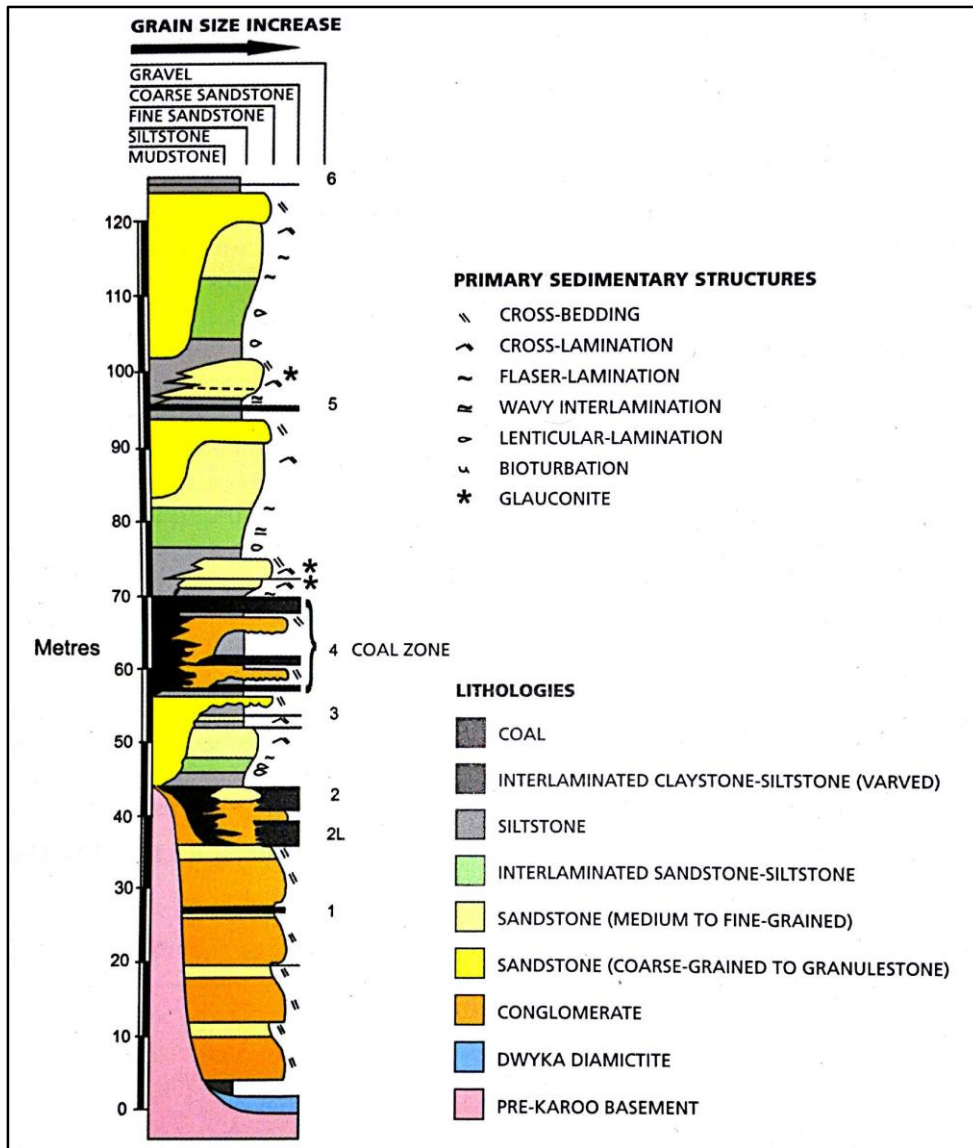


Figure 2: Spatial distribution of coal mines in the upper Olifants catchment (Curtesy of Google Earth).



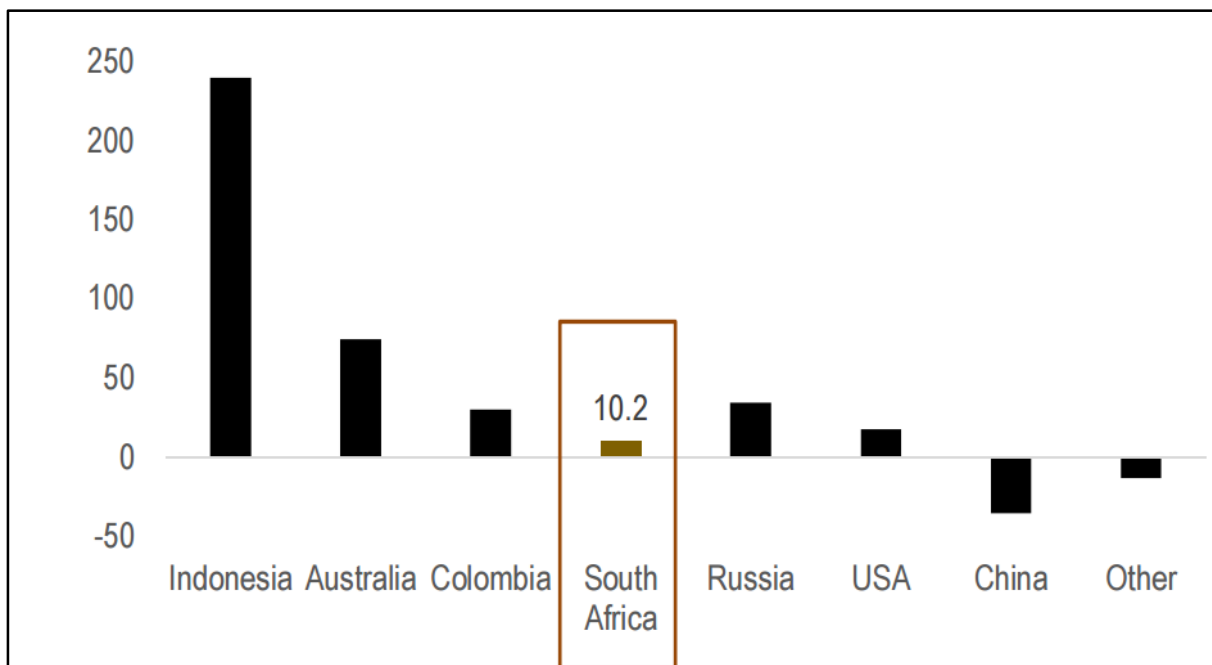
**Figure 3: Generalized stratigraphic column for the northern Karoo Basin coalfields (Cairncross, 2012).**

Energy requirements in South Africa are equally as high here as it is globally. This places a larger burden on an increase in the production of coal, as it has been a major contributor in the energy industry in terms of generating more affordable electricity. Coal is the major fuel used for over 41% of the world's electricity and contributes 29.9% to the global primary needs (World Coal Association, 2013). Coal in South Africa currently constitutes 77% of the primary energy needs; this may increase as there is lack of alternatives that could be used as energy resources (Eskom, 2012). As the population increases, it brings a rise in the need for more coal power stations to be built over the coming years. South Africa is currently regarded as part of the top ten coal producers worldwide, ranking in 7th place (Table 1); Peoples Republic of China still stands as the top coal producer (World Coal Association, 2013).

**Table 1: Table top ten coal producers (WCA, 2013).**

Countries	Million tonnes (Mt.)
PR China	3549Mt
USA	935Mt
India	595Mt
Indonesia	443Mt
Australia	421Mt
Russia	359Mt
South Africa	259Mt
Germany	197Mt
Poland	144Mt
Kazakhstan	126Mt

With regards to thermal coal exports, South Africa has grown by only 10 million tonnes (Figure 4) which is less than 5% of the total global growth (Baxter, 2015).



**Figure 4: Contribution to supply growth of thermal coal globally (export seaborne market) Mt. (Baxter, 2015).**

Figure 5 indicates South Africa’s production market share of the global total has fallen from 14% in 2004 to 8% in 2013 (Baxter, 2015).

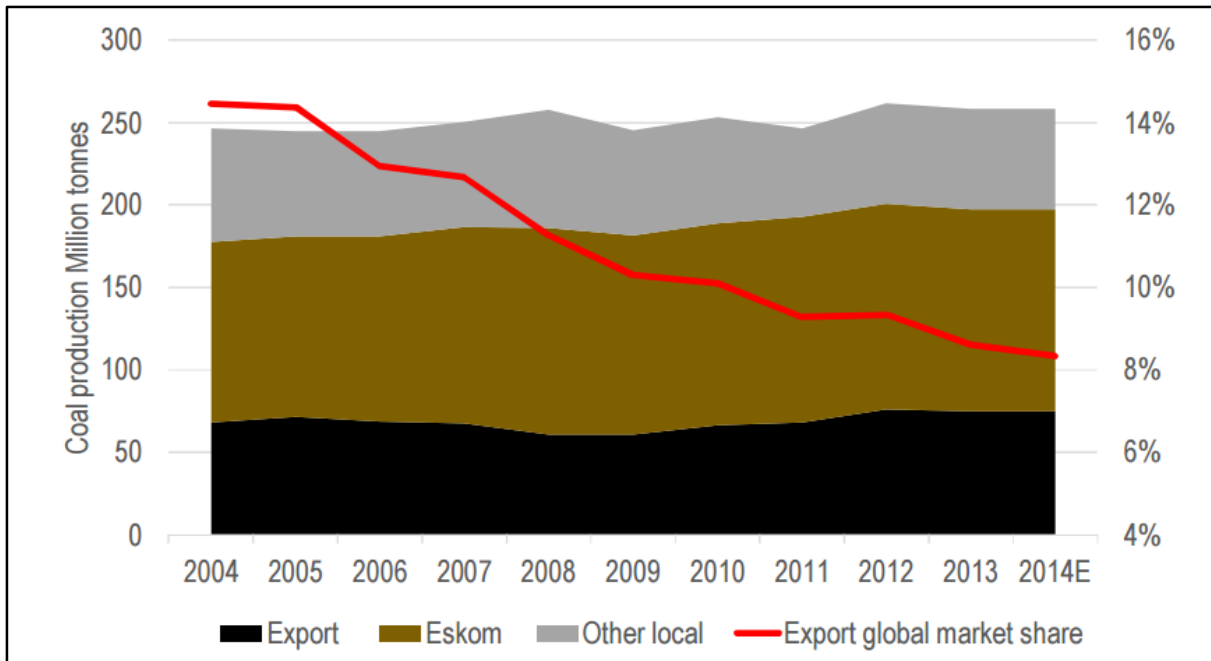


Figure 5: Total SA coal production and global export thermal coal market share (Baxter, 2015).

Coal plays a large role in the total mineral sales in SA and has remained fairly flat at around 28% since 2008 (Figure 6) (Baxter, 2015).

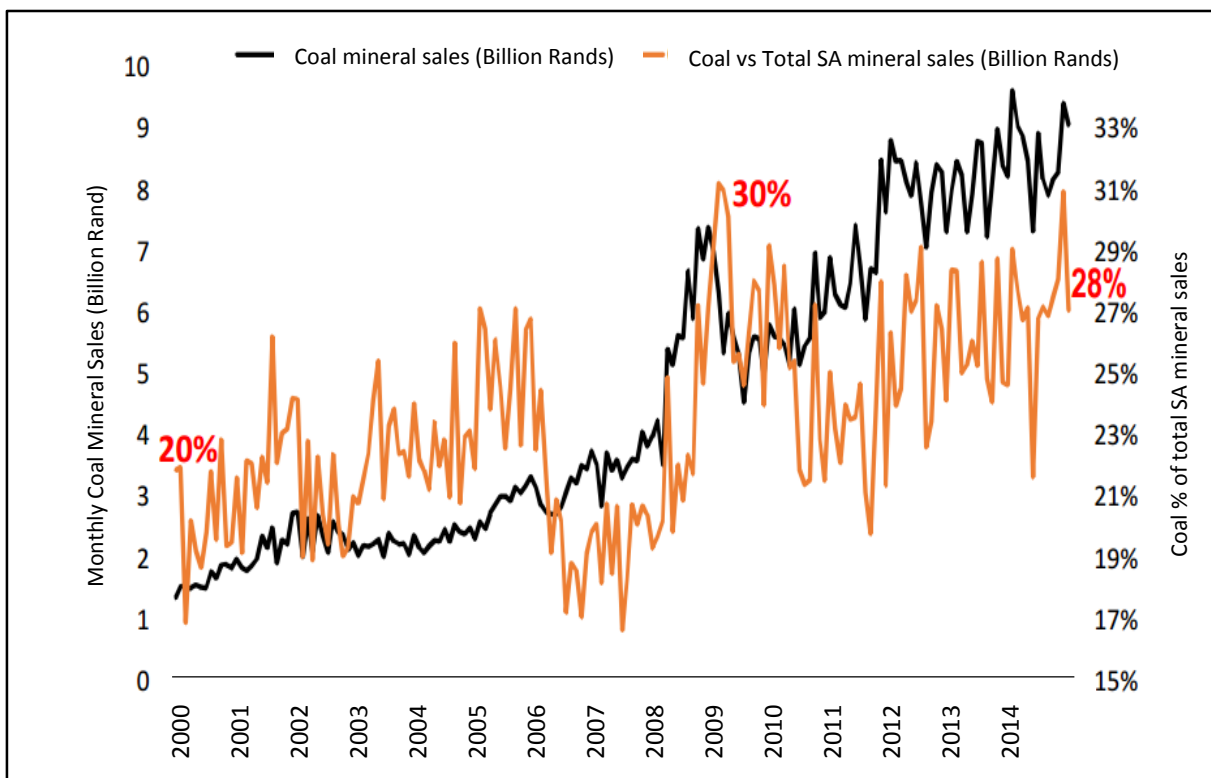
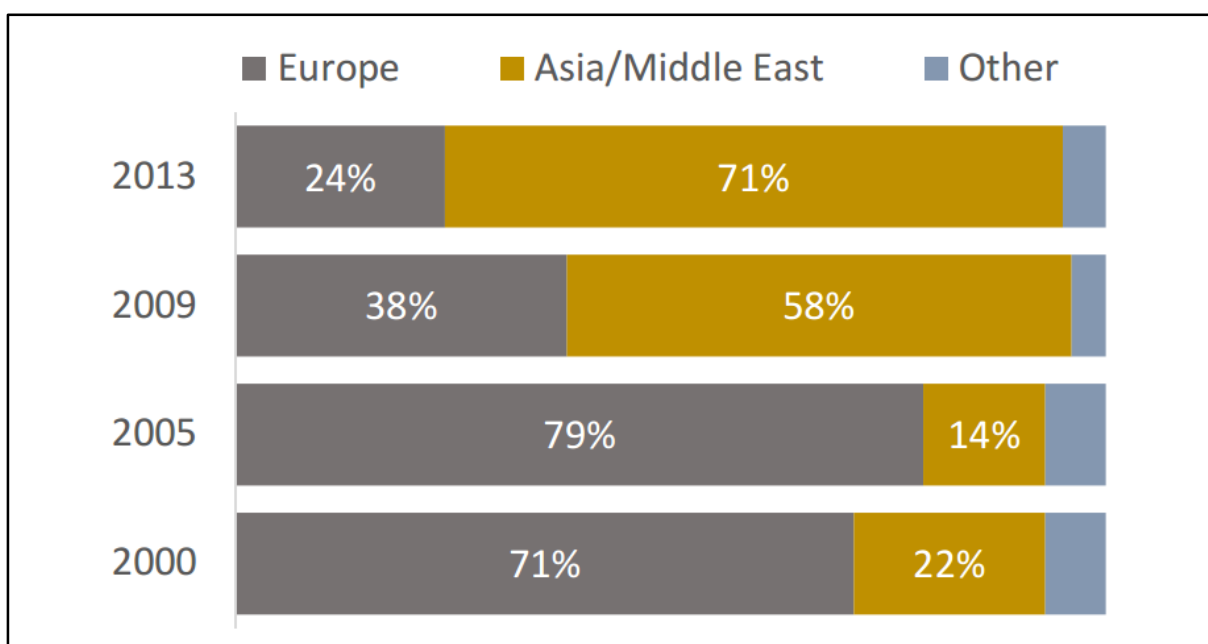


Figure 6: SA coal mineral sales vs total SA mineral sales (Rbn and %). (Modified after Baxter, 2015).

During 2014 the South African Coal mining sector was the largest component of the South African mining sector on the basis of its contribution to Gross Domestic Product (GDP), whilst also being the largest component of mineral sales with a production of 258 million tonnes of coal, valued at R102 billion. The coal mining sector employed 86 242 employees and paid them R20,6 billion in salaries and wages. Coal exports were the fourth largest mineral exporter at R47 billion behind Platinum Group Metals, Gold and Iron Ore and was a major contributor to transformation through the Mining Charter and to community development through social labour plans (Baxter, 2015).

After 2005 the coal export customer base has changed significantly from a predominantly European market to an Indian market from 2009 to date (Figure 7) (Baxter, 2015).



**Figure 7: South African coal exports by destination. (Modified after Baxter, 2015).**

Following the current economic downturn in the mining industry the following burning concerns have been identified for the coal mining sector (Baxter, 2015):

- Falling Coal export prices (-60% since 2012)
- Changing customer base, European market replaced by Indian market
- Policy uncertainty – strategic mineral discussion
- Lack of commitment from Eskom for domestic off take
- Lack of control and inefficiencies of railway line operations
- Water management and ability to feed back into water supply
- Productivity declines provides further head winds as capital injection is required for further modernisation of operations

- Cash flow margins (after capital spent) is under pressure, as global capital allocation and balance sheet management becomes more conservative
- Policy and regulatory challenges (and various government departments wanting to add extra costs on to Coal mining – e.g. Environmental legislation)
- Unexpected upward revision in coal royalties, resulting in massive unplanned increased in taxation for industry.

## 2.2. Impacts of coal mining

Coal mining has severe impacts on numerous environmental systems with the impact ranging from slight to severe, depending on the aspects which takes place during mining. The impacts range from social to health and lastly, environmental. Coal mining and all associated processes can cause impacts such as the following:

- Subsidence as a result of pillar stripping.
- Spontaneous combustion.
- Contamination of soil, water and degradation of vegetation due to poor management practices as well as the impacts experienced from discard dumps.
- Air pollution and noise pollution.
- Aesthetic impact on the environment.

There are around 6000 defunct mines in South Africa (not all coal mines), and the expenses of recovery has been assessed at 100 billion Rand (2008 Figure – US\$ 14 billion at the time) by Ms Elize Swart, Director of Environmental Policy at the Department of Mineral Resources (DMR), at that stage. Moreover, at the present rate of recovery, it will take 800 years to restore the defunct mines. In Mpumalanga the Brugspruit Water Works was operated by the local municipality to manage the ARD radiating from defunct and underground coal mines in the Witbank. The infrastructure was constructed in 1997 at a cost of R26.5 million. There has been worries about its viability because of latency brought on by staff deficiencies, cable theft and absence of upkeep. The recovery of the relinquished Transvaal and Delagoa colliery in Witbank is evaluated at R100 million (Munnik *et al.*, 2010).

### 2.2.1. Impact of pillar stripping

During bord and pillar mining, coal pillars are left set up to bolster the rooftop. The pillars, thusly, need to manage the redistributed burden inferable from the overburden, which implies that the strata promptly above and beneath the workings are subjected to increased pressure (Bell, 1988). Stress zones have a tendency to be situated at the edges of pillars where interceding roof strata tend to hang (Wardell and Wood, 1965). Surface subsidence might be a declaration of either different pillar failures or bord failures along with void movement.

Slow deterioration and failure of pillars might take place after mining operations have stopped. This is predominantly the situation if pillars are stripped on retreat, that is, as the mine is approaching the end of its working life. Obviously, the stress on a pillar rises as the extraction fraction increases (Bell *et al.*, 2001).

The roof rock in the bords may fail with time. However, if seams are shallow depth, void migration can give rise to the appearance of crown holes at the surface. Mines with extraction ratios of up to 70% often are moderately stable (Bell and De Bruyn, 1999). During the 1930's pillar stripping led to increased extraction which resulted in increased surface subsidence. Pillar stripping increased the pressure on pillars by as much as 30%. Stripping additionally modifies the form of pillars by reducing their dimension considerably whereas the pillar height remained constant. This resulted in a reduction in pillar strength to the extent that several pillars may now not support the overburden stress, with failure occurring once the magnitude relation of pillar strength to vertical stress becomes less than one. The failure of one pillar will increase the strain on close situated pillars, inflicting them to fail in domino fashion. The surface subsidence caused by multiple pillar failure are typically a couple of hectares in extent, and therefore the collapsed areas usually are delimited by close to vertical sides. Surface tension cracks around the outer edges of the collapsed areas are usually 200– 800 millimetre wide, and might extend up to one hundred meters (Bell *et al.*, 2000).

### 2.2.2. Spontaneous Combustion

The attributes that influence the susceptibility of a specific coal for self-ignition incorporate temperature, rank, surface territory uncovered, moisture, and pyrite content. Clearly, the rate of self-ignition increments as the temperature increments, once started, the ignition procedure can act naturally should there is a persistent supply of oxygen. In keeping with Michalski *et al.* 1990, as rank decreases, the seam moisture content, oxygen content, internal surface area, and air permeation tend to extend. A rise within the natural moisture content of coal will liberate heat, and larger surface area and air permeation have an equivalent result. If the mineral content of coal exceeds two percent, then, this additionally aids the self-heating method as oxidization of pyrite is an exothermic reaction.

Mining creates pathways for flow of air to coal. However, the retention of warmth by the coal is essentially captivated with the air flow, in such a way that there's a crucial rate that varies with the opposite factors where the coal undergoes oxidation. However the air flow isn't capable of removing the warmth generated. Such conditions normally exist in partly collapsed mines (Bell *et al.*, 2000).

### 2.2.3. Impact on soil and vegetation

Mining cause extreme aggravation to the soil quality and soil fertility which is a major concern around the world (Mentis, 2006). As far as South African regulations, the responsible party is required to restore the disturbances which were created. On account of the neglected and defunct coal mines, rehabilitation has not adequately been done in South Africa (Viren *et al.*, 2006).

Most plants can't endure low pH water in light of the fact that the high grouping of hydrogen ions causes inactivation of the protein frameworks, limiting breath and root uptake of mineral salts and water (Bradshaw *et al.*, 1982). Likewise, seepage water acidity and high concentrations of total dissolved solids (TDS) has an adverse impact on local vegetation.

Numerous types of green algae are well known for enduring ARD and appear to include metal reduction. Serious algal development happens in seepage zones. The green algae is related to *Mongeotia* and the red-chestnut green algae to the genus *Microspora*. Green algae will expel metals from corrosive seepage water, and these algae will have taken up iron, aluminium, copper, nickel, manganese, and lead in their cell dividers and protoplasm. Furthermore, encrustations of ferrihydrite happens on dead green algae. Henceforth, these algae, to an unequivocal degree, decreases the convergence of metals in these water types. (Bell *et al.*, 2000).

### 2.2.4. Air pollution

Smog from coal mines is largely due to the fleeting release of particulate matter and gases comprising of methane, sulphur dioxide and oxides of nitrogen. Surface mining processes like drilling, blasting, movement of hefty earth moving equipment on haul roads, collection, conveyance and management of coal, screening, sizing and segregation of different lithological units are the major sources of such releases. Underground mining releases dust from exposed coal stock piles and wastes discard facilities. The emission of CO, CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub> occurs due to spontaneous combustion and methane leakage from coal seams. Methane, a greenhouse gas, is 21 times more intoxicating in its greenhouse effect compared to carbon dioxide. Methane release from coal mining hinge on the mining method, the depth of mining, coal quality and trapped gas content within the coal seam. As mining continues, methane is released into the air and will be discharged into the atmosphere. Methane is exceedingly volatile and needs to be drained during mining processes to preserve safe working conditions. In underground coal mines in China, significant ventilation systems move considerable volumes of air, in



so doing discharging methane into the atmosphere at appropriately little concentrations (Muzindutsi & Sekhampu, 2015).

### 2.2.5. Land Subsidence

Around 60% of the world coal production originates from underground operations (Bian *et al.*, 2010). Surface subsidence is a significant impact of underground mining on the environment. Subsidence diminishes crop production and also causes other environmental problems, such as infrastructure failures, vegetation death, surface cracks and soil damage, drainage failure and structural damage, to name a few. Subsidence is grouped into two forms of distortion; continuous and intermittent. Continuous subsidence comprises the development of an even surface outline free of steps. Intermittent subsidence is branded by enormous surface movements over a restricted surface zone and by the development of steps or disjointedness in the surface outline. Surface subsidence affects land usage and the surroundings in a different way dependent upon the setting, groundwater elevations and the original land use type. Areas of eastern China, which has a simplistic geomorphology and shallow groundwater levels, was prime farmland prior to mining. Surface subsidence resulted in enormous areas being flooded. Subsequently the land use was altered as structures, streets and farm lands were totally impaired by major incidents of surface subsidence. Surface subsidence in high lying areas will prompt slope failure triggering water and soil loss due to the formation of surface fissures and overburden fractures as a result of mining (Bian *et al.*, 2010).

In South Africa numerous board and pillar sections are more than 50 and 60 years old and practise shows that severe subsidence will occur after 100 to 120 years. As the older, defunct sections increase in age, bulk subsidence may happen as a result of pillar runs and the collapse of workings (Limpitlaw *et al.*, 2005). Where diggings are close to surface, rat holing and surface subsidence will follow. Even in cases where such diggings are deep, as in Springs on the East Rand, sinkholes have proliferated 65 meters up to surface (Stacey & Page, 1983).

### 2.2.6. Surface and Groundwater Impacts

The severity of impact on water resources depends on the following aspects:

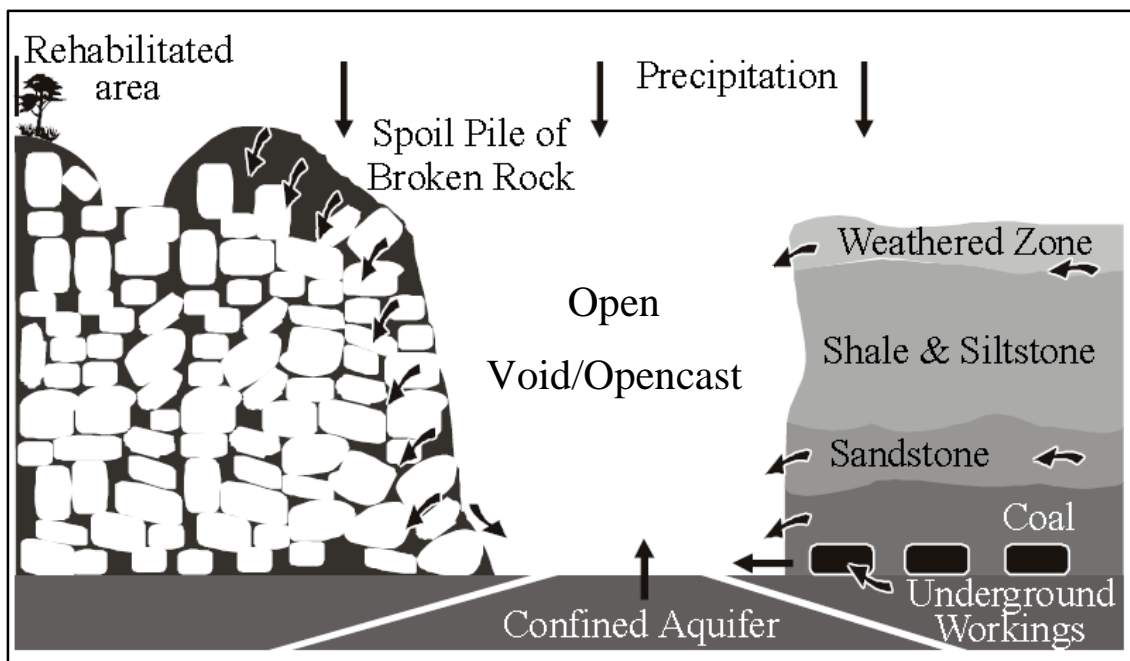
- Oxygen availability
- Water ingress
- Mining Methods
- Geology and structures
- Mineralogy of the coal seams and associated strata
- Water level heads
- Drainage region

- Waste rock material and the proximity to surface and groundwater

The impacts of coal mining on water resources depend on how mining affects the exposure of material to oxygen and water. The various mining methods (opencast strip mining, shallow or deep underground board and pillar mining and total extraction mining) and coal waste handling techniques disturbs natural water regimes, permitting water and oxygen ingress and contact with different sulphide bearing rocks. Mining changes land surface features producing changes in evaporative capacity, infiltration, and runoff characteristics. It can completely disrupt portions of aquifers and change their characteristics (Salmon, n.d.).

### 2.2.6.1. Opencast Mining

Opencast mining disrupts the geology, land surface and surface-and ground water regimes. Fracturing the rock overburden creates numerous surface areas which are then exposed to oxygen and water. Sources of water include direct precipitation, water runoff to mining pits, seepage water from spoils and water ingress from nearby streams, dams or rivers. As material is removed pressure on underlying aquifers are released, increasing the risk of water inflow from these sources. Water movement and sources during mining are shown in Figure 8 (Salmon, n.d.).



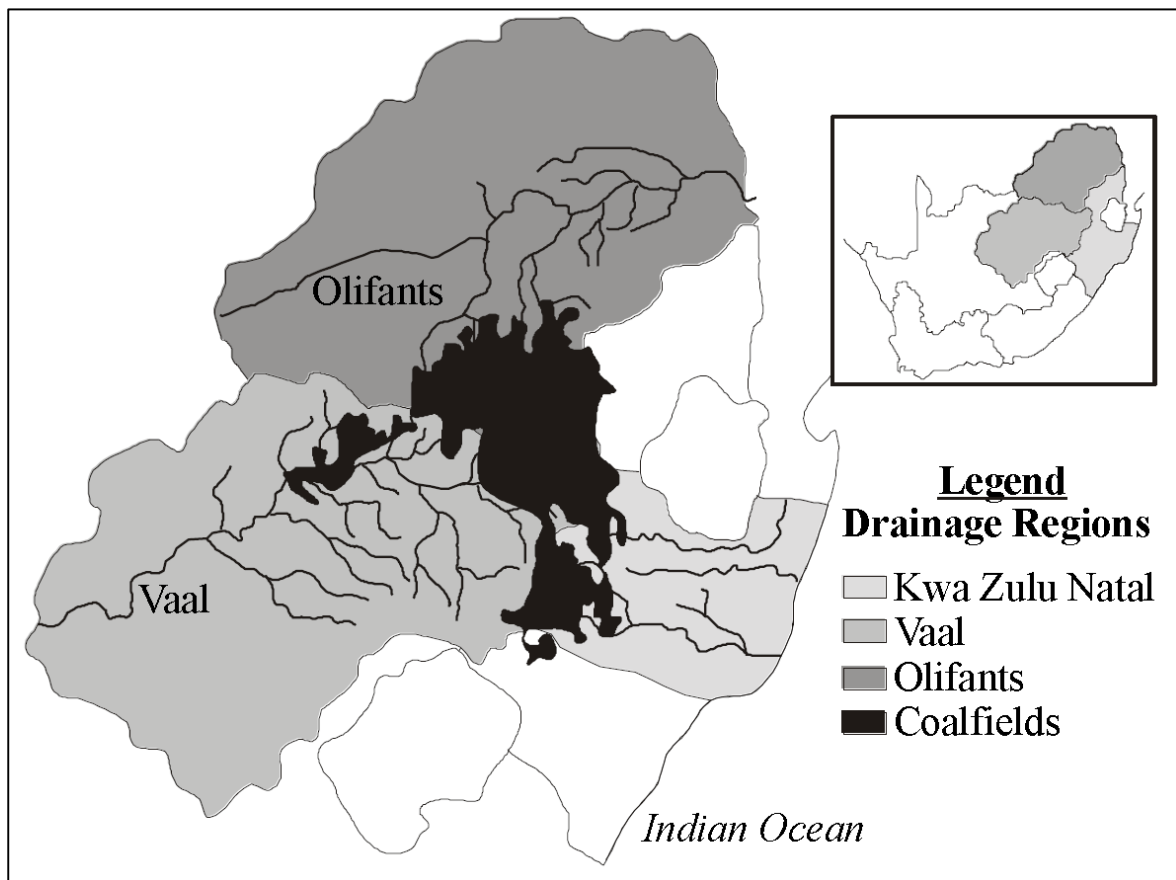
**Figure 8: Conceptual understanding of water movement in opencast and underground coal mining scenarios (Modified after Salmon, n.d).**

### 2.6.2.2. Mine closure and impacts from defunct mines

Preventing water from entering mining areas can be achieved by constructing cut-off trenches dug in front of, and behind the mining areas and constructing stream diversions or flood protection levees to divert surface water courses. During mine closure, as the water table re-establishes, spoil water

may migrate out of the pit into the upper aquifer or decant at surface from where it flows to surface water courses. Piezometric heads in underlying aquifers drive water to low pressure areas where it ponds, fills up and eventually decants to the surface environment. In the Mpumalanga context, it is projected that 35% of the salt load in the Loskop Dam originates from abandoned mines upstream (Waygood *et al.*, 2001).

The environmental impacts of polluted water from active and defunct coal mines can have international consequences. The Olifants River (Figure 9) crosses the international boundary into Mozambique, while the Vaal River is a tributary to the Orange which forms the boundary between South Africa and Namibia.



**Figure 9: Drainage regions of SA (Taken from Salmon, n.d).**

Old and abandoned coal waste dumps have an adverse impact on all water resources. Old exposed and rehabilitated discard dumps in the Mpumalanga coalfields have frequently been located in valleys and close to or even within stream courses (this is the case with Springbok 2 dump which is discussed in the case study). Understanding of the underlying geology which controls groundwater movement was hardly ever taken into account. Polluted water moves down and along geological units and eventually outcrops in valley sides where the polluted water decants at surface or seeps into tributaries. Discard dumps are placed directly on topsoil in most cases due to cost implications

associated with liners. This destroys source material used for discard dump rehabilitation and means polluted water from the discard dump can easily enter into the upper aquifer and even make its way through multiple aquifers as it flows towards the receptor. As the highly mineralised water moves towards the receptor, efflorescent salts accrue around the seepage areas and surface watercourses as a result of evaporation of sulphate-rich waters. These salts dissolve and mobilize with rainfall and are key sources of dissolved metals in watercourses after rainfall events (Chandra and Jain, 2013). The long-term effect of these pollutants on soil and groundwater mainly depends on the accessibility to minerals with adequate acid neutralization capacity and the flow conditions of the groundwater system (Rösner and Van Schalkwyk, 2000).

### 2.3. Acid Rock Drainage Formation

ARD encompasses acidic water, usually comprising an elevated concentration of sulphides and salts as a result of mining activity. The main causes of ARD consist of drainage from mineshafts, open pits, mineral waste and stockpiles which make up approximately 88% of all mine related waste made in South Africa (Manders *et al.*, 2009). ARD addition from defunct mine shafts into surface water systems occur either as decants or seepages as the mine shaft fills with water (Manders *et al.*, 2009).

Inadequate compaction of coal discard, which is associated with rehabilitation, allows easier entry of air and water, and assists the process of spontaneous combustion and the advance of ARD. Pyrite weathering gives rise to development of sulphuric acid together with ferrous and ferric sulphates and ferric hydroxide, which gives rise to the acidity in weathered spoil material. The oxidation process of pyrite within spoil is controlled by oxygen access, which depends on particle size and distribution, water saturation and compaction (Bell *et al.*, 2000). Elevated concentrations of aluminium are typically associated with ARD and are consequential of aluminium silicate minerals like kaolinite and mica.

#### 2.3.1. Types of Acid Rock Drainage (ARD)

ARD can be grouped into several rudimentary types (Skousen and Ziemkiewicz, 1996):

Type 1 ARD:

- Little or no alkalinity (pH <4.5), contains elevated concentrations of Fe, Al, Mn, and other metals, oxygen and acidity and may also refer to water that has a pH <6.0, and contains net acidity.

Type 2 ARD:

- Elevated TDS encompassing high ferrous iron and Mn, no or minimal oxygen content, and pH >6.0. With oxidation, the pH decreases substantially and becomes Type 1 ARD.

Type 3 ARD:

- Reasonable to elevated TDS, little to reasonable ferrous iron and Mn, no or minimal oxygen, pH >6.0, and higher alkalinity than acidity. With oxidation, the acid produced are defused by alkalinity present in the water.

Type 4 ARD:

- ARD with pH >6.0 and elevated total suspended solids (TSS). Settling of metal hydroxides has yet to occur. With settling time in a dam or sump, the particulates will settle and result in Type 5 water.

Type 5 ARD:

- Neutralized ARD with pH >6.0 and elevated TDS. After metal hydroxides have precipitated, the main cations left in moderate concentrations are typically dissolved Ca and Mg. Soluble anions also stay in solution. Should alkalinity or oxygen be deficient in the neutralization process, Type 5 ARD will not be reached.

Neutral drainage is another type of rock drainage occurs where sulphides and carbonates are low to moderate. The pH is normally near neutral with low specific conductance, and balanced mineral acidity and alkalinity. These are categorised as neutral waters.

Mixing between these types of water generates in-between types of water, so acceptable sampling techniques are important to define the ARD type and the concentration of its mineral acidity.

With regard to the role of bacteria, Thiobacillus Ferrooxidans and similar iron oxidizing bacteria growing in the aerobic layers of coal discard dumps play a key part in the development of ARD. Further evidence indicates the possibility that ARD might also be caused by numerous other bacterial types present in coal discard dumps experiencing acidification. Though Thiobacillus Ferrooxidans was established as the utmost important iron oxidizing bacteria in the mesophilic ( $20^{\circ}\text{C} < T < 45^{\circ}\text{C}$ ) temperature range, the roles of iron oxidizing Leptospirillum Ferrooxidans and sulphur oxidizing Thiobacillus Thiooxidans were occasionally specified (Kleinmann and Crerar, 1979).

## 2.4. Coal Mineral Waste Production

Discard material or tailings is a combination of crushed rock and water or, in some cases, washing fluids from washing plants which remain after the extraction of economic minerals, fuels or coal from the mine. The word 'tailings' is a generic term and describes the by-products of numerous extractive activities, including, coal, aluminium, oil sands, precious and base metals as well as uranium. The ratio of tailings or discard to distillate is usually high, regularly around 200:1 (Lottermoser, 2007).

Furthermore, as peak ore production is exceeded, the abstraction of lower quality ore is a recognised long-term tendency (Mason *et al.*, 2010).

The tailings or discard volume is typically far in surplus of the resource, and the often contains possibly hazardous pollutants. A priority for a sensible and accountable mining company must be to proactively separate and isolate tailings or discard to prevent them from entering groundwater and surface water systems. There is sufficient evidence showing that when drainage from tailings or discard enter these environments they may pollute soil and water. Also, the tailings or discard endure physical and chemical alteration after being placed. If the tailings or discard are stored below water, interaction with the oxygen is considerably reduced, thereby anticipating reduced interaction with oxygen. It is consequently an acknowledged practice for tailings or discard to be kept in remote confinements below water or slurry dams in co disposal facilities (Kossoff *et al.*, 2014).

Incidents related to poor mineral management practise are among the most noticeable features of the global mining industry. Spills, dam failures, decant and seepage from unrehabilitated sites result in substantial and longstanding environmental and social magnitudes (Van Zyl, 1993). Mineral waste has the possibility of providing environmental, social and economic impacts for centuries (Kempton *et al.*, 2010), as evinced by sites like the Rio Tinto estuary in Spain, here surface water pollution is still in existence from historic mining activities dating back as early as 4500 years ago (Leblanc *et al.*, 2000). Extraction of lower grades of ore, associated increase in waste production per unit reserve (Mudd, 2010), rivalry over water resources (Kemp *et al.*, 2010) have the possibility to increase future challenges related to waste management. Though inadequate mine waste management leads to extensive problems for communities, it may also enforce costs on mining companies by wearing down share value, increasing risks of momentary or perpetual closure, fines and increased remediation, monitoring or treatment.

#### 2.4.1. Coal Beneficiation

Mining is the largest producer of solid waste in South Africa, estimating that for every ton of ore that leaves the processing plants, 100 tons of mineral waste is produced. A key source in coal mining originates from poor quality discard during the beneficiation process. According to Lloyd (2002) in excess of 80 million tons of coal discard is produced in South Africa yearly. According to Vermeulen and Usher (2006), one ton of coal extracted results in eight tons of rock being removed and substituted as spoil material. According to the Department of Mineral Resources, 2 billion ( $10^9$ ) tons of coal discard material has been generated over the last 20 years with an additional 50 million tons of coal discard added each year. Beneficiation, wet or dry causes pollution.

#### **2.4.1.1. Wet Beneficiation**

Wet beneficiation involves removal of the impurities and lower quality coal to achieve the desired target. The method (Figure 10) uses in the region of 200 litres of water to produce one ton of coal. Slurried discard from wet beneficiation might comprise between 40-70% of water. These will be conveyed to the placement area through wet infrastructure which may be many kilometres long.

#### **2.4.1.2. Dry Beneficiation**

Dry beneficiation is starting to show more face as water resources diminish and is the preferred method of beneficiation from an environmental point of view (Singh and Beukes, 2006). Dry discard may contain 15-30% water, and are usually conveyed by truck or conveyor. The likelihood of spillages can be abridged through the construction of the plant and the discard facility as close by as possible, but spillages cannot be avoided completely.

#### **2.4.1.3. Placement Methods**

Dry beneficiation is starting to show more face as water resources diminish and is the preferred method of beneficiation from an environmental point of view (Singh and Beukes, 2006). Dry discard may contain 15-30% water, and are usually conveyed by truck or conveyor. The likelihood of spillages can be abridged through the construction of the plant and the discard facility as close by as possible, but spillages cannot be avoided completely. Three placement methods usually used are dewatered tailings, cycloned tailings and slurried tailings (Witt *et al.*, 2004).

According to Robins (2004), discard disposal on surface is the most widely recognised disposal method and is widely used due to the possibility of managing potential impacts on surface and above the ground water table where potential negative impacts are mostly observed. The conservative method is to construct restraining boundary impoundment walls in low lying areas or flat areas to create an artificial basin which will receive the discard material. The discard material is usually conveyed as slurry or solid waste rock material that contains water and is discharged from the coal processing plant and conveyed to the desired location via haulage or wet infrastructure. For fine residue deposits or co-disposal facilities different methods have been established to enclose the discard material and include the use of the tailings material to form the impoundment walls via the use of hydro-cyclones as shown in Figure 10, particle separation by gravity, or the use of evaporation to achieve a solid waste material as practiced in South Africa. The method is reliant on the nature of the discard material and the relevant site circumstances. Co-disposal techniques are widely practiced in the coal mining industry due to the nature of the discard material where the fine discard material is disposed with coarser discard, using the coarser discard material to retain the fine discard (Robins, 2004).

#### **2.4.1.4. Reclamation**

Reclamation of mineral waste reduce the effects that would have been caused by the discard material that would have been placed, thus reducing the volume of mineral waste produced per unit ton of coal mined. Reclaiming the discard has the prospective to deliver a financial opportunity through the rehabilitation of historical dumps to pre mining land use capability. Improved beneficiation processes means financial gains can be made through the reclamation of old discard facilities whilst providing a source of electricity to local independent power producers and Eskom. This means there is a financial incentive for adequate rehabilitation (Franks *et al.*, 2011). The discard material will be beneficiated and sent to an independent power producer which will supply the electricity back into the grid.



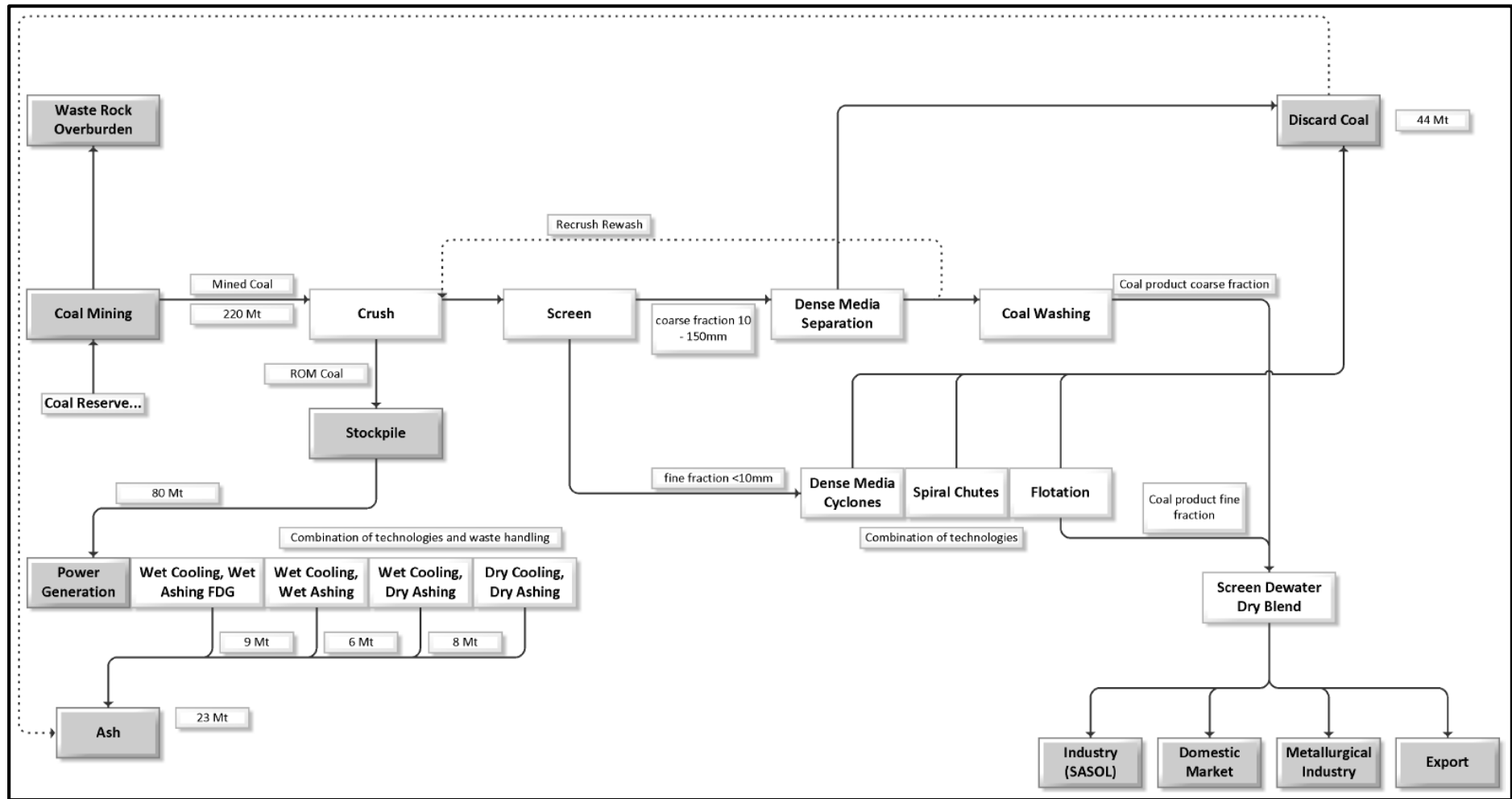


Figure 10: Coal hydrometallurgical processing flow sheet (modified after Broadhurst et al., 2007).

## 2.5. Characteristics of Coal Discard Facilities

### 2.5.1. Characteristics

Although discards can comprise of combinations of several lithological units they generally come to consist of coal roof, coal parting material as well as floor material. Oxygen pathways and preferential water canals are provided by these coarse materials and fine layers of water will be stored throughout dry spells. In older, more established dumps alkalinity and acidity is determined with more difficulty. Surface rock is not considered a true representative of the dumps total material nor of the material found within the dumps interior (Salmon, n.d.).

Thermal activity is considered to be an attribute of old defunct mines and associated discard dumps. As up to 30% of discard dumps consist of coal material contributions, continuous burning of such discard dumps is likely to occur. Burning of discard dumps can occur from exogenic processes that are initiated by external heat sources, or by endogenic ones (referring to oxidation of substances resulting in autonomous combustion, these processes come to be accompanied by the emission of heat at high amounts. (Falcon 1986).

According to Szafer (1999) the possibility of endogenic burning is likely to occur in the presence of the following factors:

- 1) Adequate amounts of materials of appropriate activity relative to oxygen,
- 2) Air access within the inner of the heap, as well as;
- 3) Heat accumulation within the discard dump.

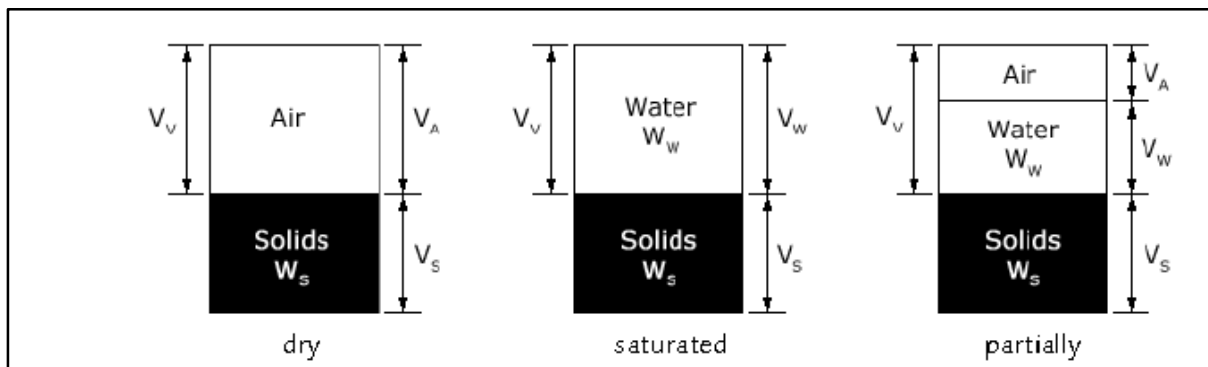
Tailings particles frequently are in angular varieties, this morphology inflicts a high resistance angle on these dry tailings. Grain size of tailings vary and generalization is difficult, specific process requirements are delineated. The presence of Si and Fe, are virtually universal and, when in combination with  $O_2$ , regularly the most plentiful elements. Al, K, Ca, Mg, Na, Mn, P, Ti and S are also major components (Kossoff *et al.*, 2014).

A significant phase of coal mine spoil is Pyrite, sphalerite, galena, pyrrhotite and chalcopyrite may be evident in detectable quantities. The chalcophilic elements (Ag, As, Bi, Cd, Cu, Ga, Ge, Hg, In, Pb, Po, S, Sb, Se, Sn, Te, Tl and Zn) are commonly elevated within coal (Dang *et al.*, 2002).

Herewith the division of tailing minerals into three comprehensive categories: 1) the gangue fraction, 2) the residual uneconomic sulphide-oxide fraction and 3) the secondary mineral fraction (Dang *et al.*, 2002).

The fine body of the tailings comprises of a combination of water, air and solid material. The composition of soil mass is made up of solid particles separated by voids or spaces. Water, air or a combination of both poses the potential to fill such voids. When voids are filled by air the mass is dry, if filled by only water saturation of the body is said to occur, partial saturations results as a combination of a mixture of air and water within the body. Figure 11 shows the three degrees of saturation in a unique volume. The indices stand for  $V_A$ - air volume,  $V_w$  water volume,  $V_s$ - solid volume. The following equation is used to calculate the degree of saturation, usually expressed as a percentage (Witt *et al.*, 2004).

$$S = \frac{\text{Volume of water}}{\text{Volume of voids}} = \frac{V_w}{V_v}$$



**Figure 11: The three degrees of saturation in a unique volume (Witt *et al.*, 2004).**

This 3-phase system of the tailings can be characterised by their chemical and their mineralogical components. For the valuation of the soil properties both criteria are important. The considerable components are:

- non-soluble mineralogical solids
- chemical soluble components
- radioactive and toxic components
- In some cases organic content

According to Witt *et al.*, (2004), the validation of the composition through a detailed mineralogical and chemical analysis is necessary for further information. Following the source-pathway-target framework the examination of environmental contaminants with its potential for emission is especially necessary. The movement of residual of additional water through tailings is directly implicated by the particle distribution and/or grain size. The advection of contaminants (movement and mixing of fluids) commonly results in contaminant or pollutant transport in ground water systems. Ground water/leachate velocity, pH and partition coefficient values are some of the factors that affect

the advection rate. The soils buffering capacity, type of chemical reactions along with absorption and ion exchange rate will be determined by the physicochemical properties of the tailings and seepage as well as the geochemistry of the aquifer. Biological reactions, ion exchange, neutralisation, precipitation, adsorption and oxidation/reduction contribute to the chemical composition of the seepage of these tailings. Two basic options exist for the controlling of contaminated water in impoundments; options are 1) capturing such water after it exits the impoundment or 2) keeping the water in the impoundment (Witt *et al.*, 2004).

### 2.5.2. Fine Grained Residue deposits

Fine-grained Mine Residue Deposits (MRD) are usually slurried and hydraulically transported to the dumping site. Likely pathways and receptors associated with fine residue MRD are shown in Figure 12 below.

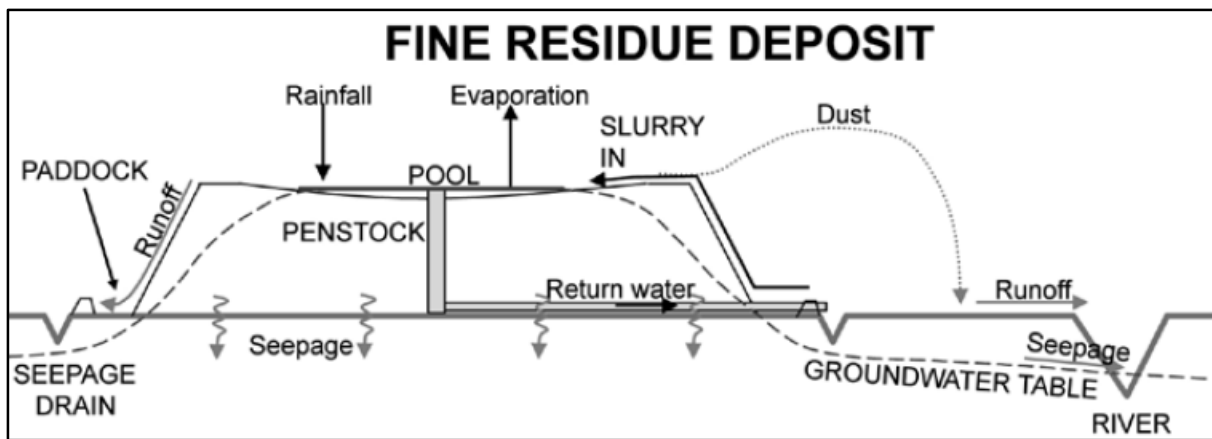


Figure 12: Sources, pathways and receptors associated with fine grained MRD (Department: Water Affairs and Forestry, 2008).

#### 2.5.2.1. Key issues and impacts which needs to be considered for all fine grained mineral residue deposits

The section below was modified after Department: Water Affairs and Forestry, (2008).

The geochemical nature of residues and the presence of reactive minerals or minerals and salts that can be mobilized by dissolution results in water quality deterioration as water migrates through the MRD, with potential impacts on ground and surface water.

The consequence of the segregation of hydraulically-placed fine-grained residues must be understood. Where the fine-grained residues are placed using cyclones or spigots, the waste segregates into a coarser outer edge with higher permeability and a finer centre with reduced permeability. This has implications for the water balance and water quality that need to be considered. The permeability of the residues as deposited must be well understood as this characteristic has a very important impact on the water balance and the water quality.

The pool size on a fine-grained or co-disposal MRD has a major impact on water conservation and seepage volume. A large pool size gives rise to elevated evaporative losses and should be avoided in the interest of water conservation. In particular, care should be taken to ensure that a large pool does not become the route to dispose of excess water that should rather be treated and discharged or reused. The large pool also increases the driving head for seepage from the base of the MRD into the underlying aquifer. The pool size is primarily affected by the relative density at which the fine-grained residue is placed and the option selected for water removal. The size of the return water dam and its ability to hold and equalize hydrologically induced flow imbalances also plays a big role in determining pool size.

The phreatic surface is typically elevated in an operating fine-grained MRD and is in contact with the underlying aquifer. The phreatic surface rapidly drops after decommissioning, exposing the fine grained residues to oxidizing conditions.

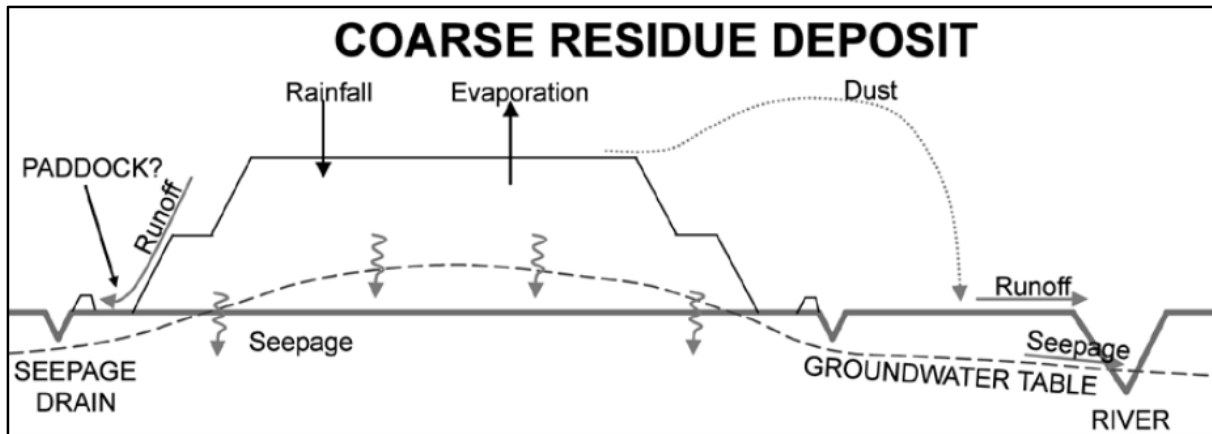
Runoff from side slopes should be captured in toe paddocks to prevent sediment load to surface water systems, although runoff may be contaminated and storage in unlined paddocks can give rise to seepage pathways to underlying aquifers. The underlying aquifers may be hydraulically connected to adjacent surface water systems and contaminated seepage may reach surface water systems through this route.

Vertical hydraulic conductivity is typically very low and fine-grained MRD are normally anisotropic, i.e. horizontal hydraulic conductivity is many times higher than vertical hydraulic conductivity. Particular considerations that may apply to different types of fine-grained MRD.

Coal slurry is normally disposed of within earth impoundment walls (or co-disposed with coarse residue) and is often recovered and sold as a product. Coal slurry also has a potential spontaneous combustion potential above the phreatic surface that needs to be assessed.

### **2.5.3. Coarse grained Residue deposits**

Coarse-grained MRD are normally transported to the disposal site by conveyor or truck. Likely impact pathways and receptors associated with coarse-grained MRD are shown in Figure 13 below.



**Figure 13 : Sources, pathways and receptors associated with coarse grained MRD (Department: Water Affairs and Forestry, 2008).**

*2.5.3.1. Key issues and impacts which needs to be considered for all coarse grained MRD*

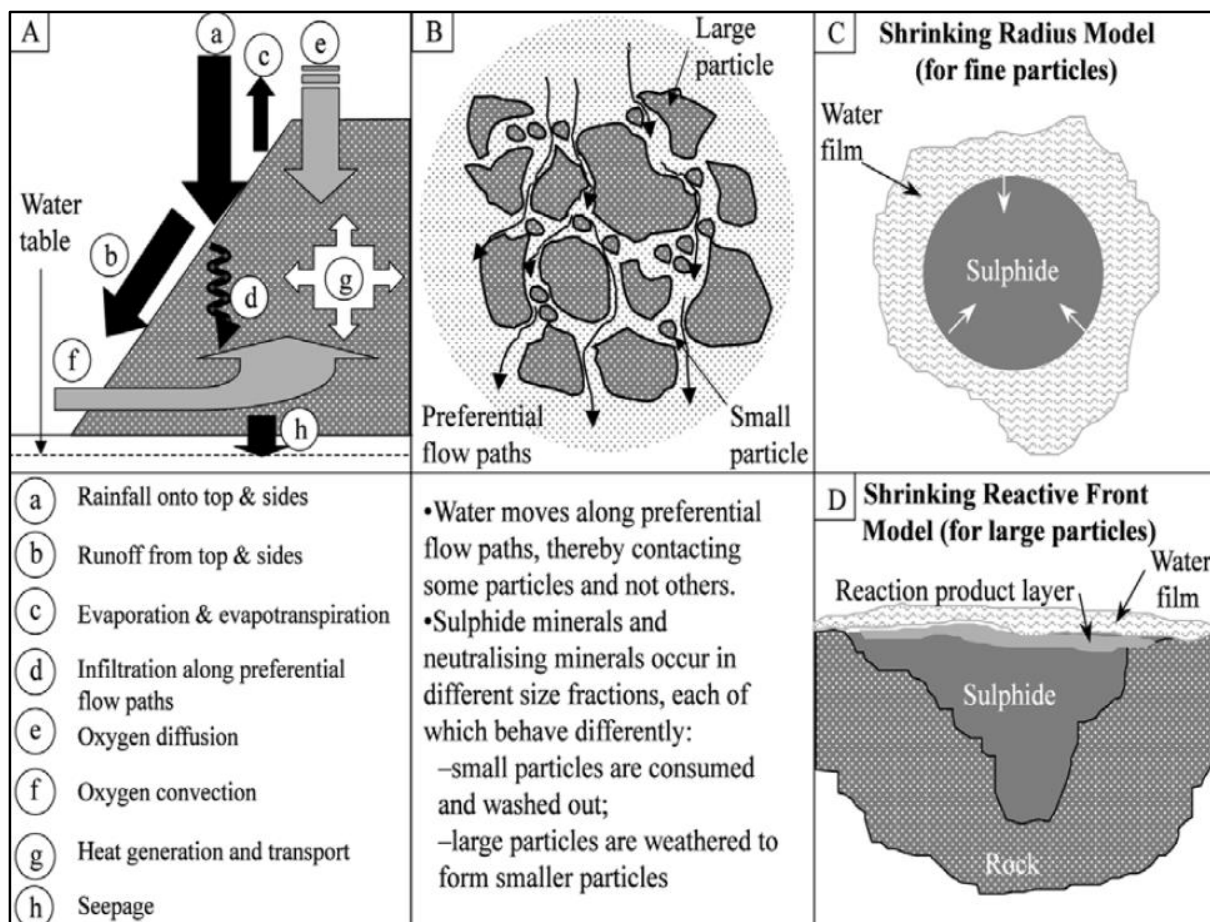
The section below was modified after Department: Water Affairs and Forestry, (2008).

Coarse-grained MRD are typically porous with high hydraulic conductivity and a significant portion of rainfall reports to seepage. While coarse-grained MRD do sometimes include toe paddocks, older facilities often do not, giving rise to direct pathways of contaminated runoff and sediment load to surface water systems.

The geochemical nature of residues and presence of reactive minerals that can be mobilized by dissolution results in water quality deterioration as water migrates through the deposit, with potential impacts on ground and surface water. While coarse-grained MRD do have lower reactive surface area per unit mass due to higher particle size, these facilities contain a wide range of particle sizes ranging from very fine to very coarse and should be considered as geochemically very reactive facilities.

The phreatic surface is typically depressed in a coarse-grained MRD but may still be in contact with the underlying aquifer. Due to the low phreatic surface, practically the complete coarse-grained MRD is exposed to oxidizing conditions.

The underlying aquifer may be hydraulically connected to adjacent surface water systems and contaminated seepage may reach surface water systems through that route. The processes to consider for the geochemical modelling of coarse-grained MRD are shown in Figure 14.



**Figure 14: processes to consider for the geochemical modelling of coarse-grained MRD (Department: Water Affairs and Forestry, 2008).**

Particular considerations that may apply to different types of coarse-grained MRD are highlighted as follows (Department: Water Affairs and Forestry, 2008):

- Coal coarse-grained residue need to be compacted in terms of Reg. 704 in order to reduce its hydraulic conductivity and to reduce its spontaneous combustion potential.
- Coal coarse-grained residue is typically geochemically very reactive and requires the placement of an engineered cover that is specifically designed to minimize long-term water pollution potential in accordance with appropriate detailed geochemical assessment techniques.
- Salinity build-up in covers due to capillary uptake of salts from underlying residues must be considered in cover design for coarse-grained MRD.
- Coarse-grained residues or waste from opencast mines may be shown, through appropriate studies and under certain conditions where very rigorous selective removal of non-reactive overburden has occurred, to have a low potential impact and can then be disposed of and managed accordingly.

## 2.5.4 Co-disposal Residue deposits

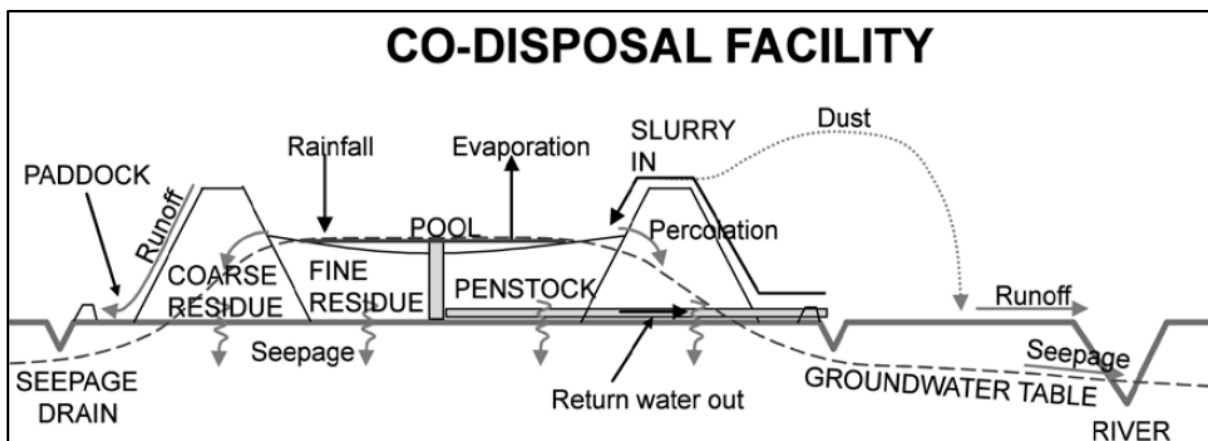
The section below was modified after Department: Water Affairs and Forestry, (2008).

Co-disposal MRD make provision for the co-disposal of fine and coarse-grained residues within the MRD facility. The coarse-grained residue is normally transported to the dumping site by conveyor or truck and the fine-grained residue is normally hydraulically transported. The most common type of co-disposal MRD found in South Africa and the associated potential impact pathways are shown in Figure 15 below.

The co-disposal method of developing a MRD does often introduce additional risks, in particular the following:

- Safety and stability, including the management of freeboard using coarse discard to build the outer wall, and;
- Water quality, particularly in instances where the supernatant pool intersects the coarse-grained residue.

These risks are however generally manageable in the co-disposal process.



**Figure 15: Sources, pathways and receptors associated with co-disposal MRD (Department: Water Affairs and Forestry, 2008).**

Considerations for all co-disposal MRD are the following (Department: Water Affairs and Forestry, 2008):

Co-disposal MRD generally pose a high water quality risk should the supernatant pool intersect the coarse-grained residue that typically makes up the outer wall within which the fine-grained residue is deposited. When this happens, water migrates or percolates through the coarse-grained residue giving rise to extremely elevated leaching conditions and generation of high volumes of contaminated seepage. This risk must be explicitly considered in the impact assessment, the design, operation, decommissioning and closure of the co-disposal facility.



Even for well-designed and operated co-disposal facilities that do not have a liner between the coarse and fine-grained residues, enhanced seepage volumes and poorer seepage quality can be expected due to the need to deposit the fine-grained residue up against the coarse-grained residue. The enhanced seepage conditions will continue until such time as a sufficiently thick layer of fine-grained residue has formed against the coarse-grained residue.

Co-disposal MRD must incorporate underdrainage systems to intercept and manage the enhanced seepage volumes.

The geochemical nature of residues and the presence of reactive minerals or minerals and salts that can be mobilized by dissolution results in water quality deterioration as water migrates through the MRD, with potential impacts on ground and surface water. Fugitive dust from the surfaces of co-disposal MRD can deposit geochemically reactive dust particles outside of the direct management area of the MRD, giving rise to potential contaminated runoff to surface water systems.

The phreatic surface is typically elevated under the fine-grained residue portion of a co-disposal MRD but may still be in contact with the underlying aquifer. This elevated water table also extends into the reactive and hydraulically conductive coarse-grained residues that are adjacent to the fine-grained material, giving rise to enhanced oxidizing conditions.

The underlying aquifers may be hydraulically connected to adjacent surface water systems and contaminated seepage may reach surface water systems through this route.

Shaping of the coarse-grained outer walls around the fine-grained residues must be in accordance with final rehabilitated profiles in order to minimize the risk of cutting through the fine-grained residues if final shaping only occurs during final rehabilitation. Co-disposal is most typically applied to the management of coal mining residues and the issues previously highlighted for coal fine and coarse-grained MRD need to be considered for such a co-disposal facility (Department: Water Affairs and Forestry, 2008).

## 2.6. Chemical Characteristics associated with Coal Discard Facilities

Tailings impoundments usually contain a diversity of sulphide minerals, each with a specific susceptibility to oxidation. Jambor (1994) observed a relative sequence for sulphide mineral oxidation proceeding from the most reactive to most resistant phases. The relative resistance of sulphide minerals to oxidation assumes that grain sizes and textures are similar within a specific tailings deposit, which is unfortunately almost never the case with coal discard facilities.

The occurrence of metals are constrained by the mineralogical and geochemical composition of tailings solids. However, the mobility in tailings pore water and drainage is controlled by pH dependent

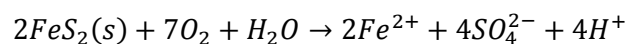
secondary precipitation, dissolution, sorption and desorption reactions, as well as biogeochemical redox processes (Nordstrom, 2011a).

Harries and Ritchie (1983) found that the moisture content of the upper 1.0 to 1.5 m of surface waste rock dumps changed with the cycle of wet and dry seasons, decreasing during the dry season. However, although the moisture and other measured physicochemical parameters varied significantly with season, it appeared that there was little variation in the pyrite oxidation rate throughout the year.

Good *et al.* (1970) also found that pyrite oxidation proceeded at a fairly constant rate between periods of precipitation, with the oxidation products accumulating in the outer mantle of the waste dumps. Erosion during periods of precipitation constantly renewed this reactive outer mantle. Although chemolithotrophic bacteria were metabolically active over a wide range of moisture contents (12%-35%), optimal pyrite oxidation rates were found at moisture levels of 23% to 35% (Belly and Brock, 1974). *Thiobacillus Ferrooxidans* could survive extended periods without rainfall, then showed increased activity after heavy rains. Rainfall would also flush the bacteria out of dumps, then decrease their concentrations in the drainage water by dilution (Tuttle *et al.*, 1968).

### 2.6.1. Oxidation Acid Generation Reactions

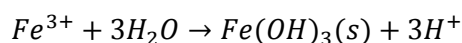
According to Witt *et al.*, (2004), oxidation of the sulphide minerals takes place through a complex series of reactions involving direct, indirect and microbiologically assisted mechanisms; some oxidation reactions result in acid generation, while others result in the dissolution and mobilisation of heavy metals. Pyrite  $FeS_2$  is the main mineral responsible for acid generation. Normally, pyrite is a stable, insoluble mineral as long as it does not come into contact with air and water. However, as a result of mining, it becomes exposed and is partially solubilised. Pyrite can be oxidized directly or indirectly. The direct oxidation of pyrite is described by the following reactions:



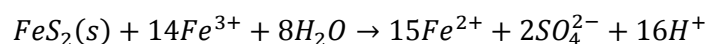
This reaction produces proton acidity; if the oxidation potential is maintained, oxidation of  $Fe^{2+}$  to  $Fe^{3+}$  by oxygen will take place, consuming part of the proton acidity produced:



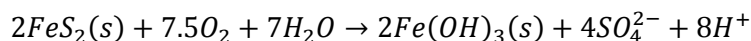
If the pH of the resulting solution is higher than 3 (as in the initial stages of the reaction), ferric iron will hydrolyse, precipitate as hydroxide and generate acidity:



Further, the  $Fe^{3+}$  generated above will oxidise  $FeS_2$  by the indirect reaction:

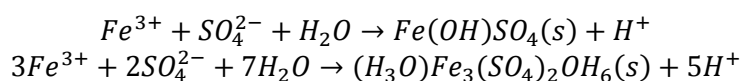


The resulting  $Fe^{2+}$  will be oxidised to  $Fe^{3+}$  and will again become available to oxidise more pyrite (autocatalysis). The overall stoichiometric reaction describing the oxidation of pyrite to result  $Fe(OH)_3$  is commonly given as:



The heat energy produced in this reaction for complete conversion of one mole of pyrite to ferric hydroxide amounts to about 1490 kJ at 25°C.

At low pH, other precipitation reactions, mostly involving ferric iron, may take place yielding basic sulphates or jarosites:



## 2.7. Rehabilitation efforts for coal discard facilities

According to Limpitlaw *et al.*, (2005), soil losses on rehabilitated land can have lasting effects after mining has ceased and this latent effect is not fully appreciated presently. This is evident even on moderate slopes of 1:5 after about 10 to 15 years. Soil losses are usually followed by erosion and poor rehabilitation or the lack thereof. In discard dumps in particular it has been found that upward salt migration also poses a serious problem for proper rehabilitation. It has been found that areas with a soil cover of less than 200 mm has a high likelihood of salt migration which has a negative impact on established vegetation. With soil layers thicker than 200 mm, layers of clay accumulation may occur where salts precipitate in these layers, 300 mm to 500 mm below surface.

The mining industry faces a large challenge is the sense that sustainable rehabilitation of discard dumps is difficult to achieve. This is partly due to the fact that discard dumps are not stable geological landforms and soil losses are enhanced by steeper slopes (1:5). Soil loss modelling indicates that the discard material within flagship facilities will be exposed within 50 years where these steep slopes are present due to erosion of the soil cladding. A discard dump in Mpumalanga showed soil losses of 30 mm and 40 mm on its 300 mm soil cover during a period of just four years. Discard dumps in KwaZulu-Natal with steep slopes (1:4) showed 150 mm to 200 mm soil losses over a 12 year period. Due to compaction and subsidence soil erosion is not consistent over the dump surface. Surface cracks and poor rehabilitation causes rilling and the development of gullies which accelerates the erosion process. This is then followed by the exposure of the discard material which causes the natural processes associated with chemical weathering like oxidation. Oxidation of discard causes vegetation

die back as a result of acid generation and salt burn. Vegetation die back also enhances soil erosion which may lead to further erosion, spontaneous combustion and the generation of acid. This in turn can lead to increased permeability which promotes groundwater pollution (Limpitlaw *et al.*, 2005).

Coal discard material produced as a result of coal mining in SA are characterised by a high pyrite content, which together with wet and oxidative circumstances results in the development of sulphuric acid through biological and chemical methods (Bell *et al.*, 2001). This method is responsible for the development of ARD and poor vegetation at coal mines and discard facilities. Compacted soil cover layers are usually applied as a liners for the containment during construction of coal discard facilities, which in turn assists in the reduction of further oxidation and enables the succeeding vegetation establishment and upkeep of the site. The instituting of long-lasting self-sustainable vegetation covers on coal discard facilities in South Africa is challenging despite annual maintenance and addition of fertilizers.

## 2.8. Hydraulic properties of coal discard facilities

According to Hatting *et al.*, (2001), the type and extent of rehabilitation required to prevent contamination of groundwater and soil is depicted by the type of contamination in the unsaturated zone. Once the contaminants associated with discard dumps have moved through the unsaturated zone into the saturated zone, the rate of further contamination increases logarithmically. Although dilution of the contaminants occur, it now occupies a larger area in spatial extent. Current groundwater remediation practice are not fully capable of remediating or containing the pollution once the contaminants have entered the saturated zone. Practices which involve active groundwater remediation is expensive and has a low rate of success.

Water flow in soils, both saturated and unsaturated, is always depicted by the potential gradient, grain size, and grain size distribution. A positive pressure gradient drives water flow in saturated soils whilst a negative pressure gradient sucks water flow in unsaturated soils. With saturated soils flow is described using saturated flow methodology which is a conservative approach as saturated hydraulic conductivity normally exceeds hydraulic conductivity of unsaturated soils (Hatting *et al.*, 2001).

The extent of rehabilitation, infiltration and factors like the makeup of constituents (coal, pyrite, clay) determines the degree of moisture in a coal discard dump (Dugan, 1975). Good *et al.*, (1970) obtained data indicating that 25% of the applied water infiltrating into a dump emerged as base flow during dry periods. Approximately 75% of the applied water came off immediately as runoff. During periods of high water flow following heavy rainfall, acid may be washed out of dumps in a surge resulting in a period of high input of acid into a drainage area or receiving stream (Dugan, 1975). This problem cause

major environmental concern world-wide. However, it can be assumed that coal seldom becomes waterlogged and that moisture evaporates quickly from exposed mine dumps in dry weather.

Pollution sources are mostly represented by the remaining tailings material as well as the top 30 to 50 cm of soil which contains the bulk of contaminants that have been leached from the overlying material. The vadose zone through which the water migrates and in which additional pollutants are being scavenged during water and rock interactions, would represent the pathway component. The receptor would be represented by the deeper aquifer in which the contaminants are being collected. The lateral distribution of pollution plumes takes place in the groundwater environment, and is a function of hydrogeological flow conditions (Hatting *et al.*, 2001).

According to Ward (1975), the factors that control the water content of the vadose zone can be expressed in the simple soil water balance for the vadose zone, considering only vertical movement of water:

$$\Delta M = f + c - d - e \pm \Delta v$$

Where  $\Delta M$  is the rate of change of soil water content,  $f$  is the rate of infiltration into the upper surface of the soil,  $c$  is the rate of water addition by capillary rise from the saturated zone,  $d$  is the rate of drainage to the saturated zone,  $e$  is the rate of evapotranspiration from the soil-vegetation surface, and  $\Delta v$  is the rate of addition or loss of water vapour.

Various forces in the soil (as described in the equation above) determine the movement of water. These forces in turn are governed by the energy or the potential of the water in the vadose zone. Soil water potential relates the total potential energy of the soil water to that of water in a standard reference state at atmospheric pressure (Ward, 1975). Yong *et al.*, (1992) defines soil water potential as a measure of the energy with which the soil water (with the various ions and solutes) in soil pores is held to the soil particle. The potential decrease as water content increases so that water is held more strongly by dry soils than wet soils.

Hillel (1982) states that soil water is subject to a number of force fields, which causes the potential of soil water to differ from that of pure, free water. The forces that interact with soil water result from the attraction of the soil matrix for soil water (matrix potential), the presence of solutes, the action of external gas pressure and the action of gravitation. Accordingly the total potential of soil water can be thought of as the sum of the separate contributions of the factors stated above, with the matrix potential being the most important component (Ward, 1975).

Ward (1975) lists soil structure, structural stability and biotic factors as the main components that are causing non-capillary porosity. The average porosity of a clayey soil is low but large spaces permitting

high flow rates for long periods may exist as a result of flocculation. Thus, the degree of aggregation of a soil determines the non-capillary porosity of a soil. Another example is active clays that swell, resulting in decreased pore sizes, and shrink, resulting in increased pore sizes, causing the soil to be the least permeable when wet. Biotic factors, such as earthworms or other borrowing insects or animals or the decay of plant roots also increase non-capillary porosity in soils.

According to Vermeulen and Usher (2009), when large-scale geological structures such as grabens and dykes exist on such sites, they can have a significant impact on the hydrology and water quality distribution. With regard to the case study discussed in Chapter 5 geophysical techniques and standard hydrogeological approaches were used to determine the impact of potential structures and the hydrogeological properties and consequent water quality distribution.

According to Witt *et al.*, (2004), water flow, whether perennial or constant, can cause piping and erosion in a discard facility. Once erosion has exposed areas where further erosion can occur, contaminants enter these pathways through possible stormwater runoff. Internal erosion is also to blame for reducing slope stability as a result of steepening the gradient which was originally used for the design of the facility. If there is a hydraulic gradient in the weathered material and it coincides with voids or open cracks which act as pathways for water ingress, it provides the perfect conditions for the development of internal erosion. It may also be possible for fine grained material to migrate through the voids of the coarser material without the presence of cracks or voids. Piping would normally occur where there has been loss in the integrity of the outer walls of the facility as a result of deformation and settlement. Discard facilities which are fine grained in nature will take longer after rehabilitation to develop cracks seeing that the moisture is retained for longer periods. Erosion and deterioration may be prevented by developing a proper design, constructing the facility according to the design, improved planning and ongoing maintenance and control post closure. The preventative measures required will depend on the physical properties of the discard dump, design, construction and climatic conditions. Adequate management of coal discard facilities is needed as it poses a level of safety concern to the surroundings, depending on the operation and the location. Adequate management should aim to reduce the number of responsible operators in order to reduce risk to a more acceptable level (Witt *et al.*, 2004).

## 2.9. Summary: Chapter 2

The objective of chapter 2 is to set the scene for coal mining on a global and national level. Insight is provided into financial and socio-economic aspects of this industry with market trends and the position of coal as a commodity, as well as South Africa's role in the global market. The biophysical impacts of coal mining is discussed and an overview of the conceptual understanding of coal mining and the role of water is outlined. The role of water in coal mining is further broken down through the discussion on the formation of ARD and the different types, which is directly associated with discard production and the impact thereof. Insight is provided into the coal beneficiation processes which results in the formation of discard material. Lastly, the chemical and physical characteristics of coal discard facilities are discussed while providing an overview of rehabilitation efforts and hydraulic properties of coal discard facilities.

## CHAPTER 3: APPLICABLE SOUTH AFRICAN LEGISLATION

Until recently residue stockpiles and more so, coal discard facilities were governed by national environmental legislation also applicable to mining in general. These acts require several management practices to be in place to conform to the requirements. Some of these acts related to responsible management include: the National Environmental Management Act, 1998 (Act No. 107 of 1998) (NEMA), the Mineral and Petroleum Resources Development Act, 2002 (Act No. 28 of 2002) and the National Water Act, 1998 (Act No. 36 of 1998). Specifically with regard to disposal of mine residue the applicable regulations include the Government Notice No. 704, dated 4 June 1999 (Reg. 704) and the SABS Code 0286. With changes in legislation came the National Environmental Management: Waste Act, 2008 (Act No. 59 of 2008) which after being amended requires residue stockpiles to be classified as hazardous waste and not just residue stockpiles. Chapter 3 explores the legislation currently applicable to coal discard facilities as a mine waste product. References for this section was supplied through word of mouth by consultation with the Anglo American Legal Department.

### 3.1. South African legislation applicable to coal discard facilities

It is genuinely understood that it is for all intents and purposes difficult to acquire a closure certificate for a decommissioned mining operation. This as an aftereffect of the trouble in relieving ecological effects and preventing negative impacts users downstream of the source. It additionally identifies with the recovery of such mines and the condition of the area after the mine has shut down. The South African Minerals Act of 1991 was the principal demonstration that constrained all mining operations towards sustainable and accountable land use and rehabilitation as opposed to simply tending to the tasteful issues. The Act articulates that the mine remains the property of the proprietor until a closure certificate is received. Subsequent to the execution of the Minerals Act of 1991, the quantity of certificates of closure has declined to a point where almost none are issued. This is a noteworthy as large amounts of money have been put into the closure fund for the management of these issues post closure. The MPRDA succeeded this law.

According to Vermeulen and Usher, (2006) this Act expresses that no certificate of closure might be issued unless the risk of potential contamination to water resources has been tended to. Mine rehabilitation must form part of mine planning prior to commissioning. The ramifications of Section 19 of the National Water Act (1998) means that the mine will be considered accountable for its impact on water resources, even after formal closure and the receipt of a closure certificate from the Department of Minerals and Energy.



## 3.2. Regulations regarding the planning and management of residue stockpiles

This section deals with the regulations regarding the planning and management of residue stockpiles and residue deposits from a prospecting, mining, exploration or production and closure operation. This summary can be used as a separate legal guideline for the management of environmental impacts associated with coal discard facilities.

### 3.2.1. Impact of Waste Act on Mine Residue Deposits and Stockpiles

Residue deposits and stockpiles are classified as waste, specifically hazardous waste, for purpose of the National Environmental Management: Waste Act, 59 of 2008 (Waste Act).

The Regulations Regarding the Planning and Management of Residue Stockpiles and Deposits were published on 24 July 2015, resulting in the management of residue deposits and stockpiles now being regulated within the ambit of the National Environmental Management: Waste Act, 59 of 2008.

### 3.2.2. Application of Regulations

The new regulation applies to residue stockpiles and residue deposits which includes, discard, slurry, tailings, slimes, waste rock, ash etc. or any other product derived from a mining operation which is stockpiled, stored or accumulated for potential reuse or disposal.

### 3.2.3. Classification of Mine Residue Deposits and Stockpiles

The classification of residue stockpiles must be done in accordance with provision as set out in Regulation 5 (Reg. 5) of Planning and Management of Residue Stockpile and Residue Deposit Regulations.

Reg. 5 requires that classification must be done on basis of:

- Characteristics of the residue.
- Location and dimension of the deposit.
- Importance and vulnerability of the environmental components that are at risk.
  - Spatial extent, duration and intensity of potential impacts.
  - Pollution control barrier system compliant with the proportionate norms and standards for disposal to landfill.
- Waste Classification and Management Regulations, 2013 therefore does not apply to classification of mine residue deposits and stockpiles.
- Classification must be conducted by a competent person, i.e. person who:
  - Is qualified by virtue of his/her knowledge, expertise, qualifications, skills and experience.
  - Is knowledgeable with provisions of NEMA, Waste Act, MPRDA and other provisions.

- Has been trained to recognise any potential or actual problem in the performance of their work.
- Is registered with the legislated regulatory body for the natural science profession or;
- Is an appropriate legislative body.

As part of the classification a risks analysis needs to be conducted and documented on all residue deposits and stockpiles.

#### **3.2.4. Design of Mine Residue Deposits and Stockpiles**

The regulations prescribe how residue stockpiles and deposits should be designed and what mitigation measures should be put into place to manage the impacts.

The design of the pollution control barrier system must be defined by:

- National Norms and Standards for the Assessment of Waste for Landfill Disposal, 2013.
- National Norms and Standards for Disposal of Waste to Landfill, 2013.

#### **3.2.5. Obligations and Duties**

Residue stockpiles and residue deposits must be categorised and classified in order to investigate and identify a suitable site for the establishment of the residue stockpiles and deposits.

Identification and assessment of the environmental impacts arising from residue stockpiles and residue deposits must be done as part of the NEMA Environmental Impact Assessment (EIA) process and a risk analysis must be done based on the characteristics and classifications set out in Regulation 4 (Reg. 4) & Reg. 5 to determine appropriate management and mitigation measures. Any deviations from the design must be approved by the DMR and the Environmental Management Programme report (EMPr) must be amended accordingly.

Measurements of all residues transported to the site and surplus water removed from the site must be recorded as part of monitoring system and an appropriate monitoring systems must be identified and implemented.

#### **3.2.6. Management of Mine Residue Deposits and Stockpiles**

- Residue stockpiles and deposit must be constructed and operated in accordance with approved EMPr.
- Must be managed in accordance with conditions and measures set out in the Environmental Assessment (EA), EMPr and Waste Management Licence provisions.

### 3.2.7. Amendments to the list of waste management activities

#### 3.2.7.1. Original list of waste management activities

##### Category A:

A person who wishes to commence, undertake or conduct a waste management activity listed under this Category, must conduct a basic assessment process set out in the Environmental Impact Assessment Regulations made under section 24(5) of the National Environmental Management Act, 1998 (Act No. 107 of 1998) as part of a waste management licence application contemplated in section 45 read with section 20(b) of this Act.

- *Storage of waste*
  - (1) The storage of general waste in lagoons.
- *Recycling or recovery of waste*
  - (2) The sorting, shredding, grinding, crushing, screening or bailing of general waste at a facility that has an operational area in excess of 1000m<sup>2</sup>.
  - (3) The recycling of general waste at a facility that has an operational area in excess of 500m<sup>2</sup>, excluding recycling that takes place as an integral part of an internal manufacturing process within the same premises.
  - (4) The recycling of hazardous waste in excess of 500kg but less than 1 ton per day calculated as a monthly average, excluding recycling that takes place as an integral part of an internal manufacturing process within the same premises.
  - (5) The recovery of waste including the refining, utilisation, or co- processing of waste in excess of 10 tons but less than 100 tons of general waste per day or in excess of 500kg but less than 1 ton of hazardous waste per day, excluding recovery that takes place as an integral part of an internal manufacturing process within the same premises.
- *Treatment of waste*
  - (6) The treatment of general waste using any form of treatment at a facility that has the capacity to process in excess of 10 tons but less than 100 tons.
  - (7) The treatment of hazardous waste using any form of treatment at a facility that has the capacity to process in excess of 500kg but less than 1 ton per day excluding the treatment of effluent, wastewater or sewage.
  - (8) The remediation of contaminated land.
- *Disposal of waste*
  - (9) The disposal of inert waste to land in excess of 25 tons but not exceeding 25 000 tons, excluding the disposal of such waste for the purposes of levelling and building which has been authorised by or under other legislation.

- (10) The disposal of general waste to land covering an area of more than 50m<sup>2</sup> but less than 200m<sup>2</sup> and with a total capacity not exceeding 25 000 tons.
- (11) The disposal of domestic waste generated on premises in areas not serviced by the municipal service where the waste disposed exceeds 500kg per month.
- *Construction, expansion or decommissioning of facilities and associated structures and infrastructure*
  - (12) The construction of a facility for a waste management activity listed in Category A of this Schedule (not in isolation to associated waste management activity).
  - (13) The expansion of a waste management activity listed in Category A or B of this Schedule which does not trigger an additional waste management activity in terms of this Schedule.
  - (14) The decommissioning of a facility for a waste management activity listed in Category A or B of this Schedule.

#### Category B:

A person who wishes to commence, undertake or conduct a waste management activity listed under this Category, must conduct a scoping and environmental impact reporting process set out in the Environmental Impact Assessment Regulations made under section 24(5) of the National Environmental Management Act, 1998 (Act No. 107 of 1998) as part of a waste management licence application contemplated in section 45 read with section 20(b) of this Act.

- *Storage of hazardous waste*
  - (1) The storage of hazardous waste in lagoons excluding storage of effluent, wastewater or sewage.
- *Reuse, recycling or recovery of waste*
  - (2) The reuse or recycling of hazardous waste in excess of 1 ton per day, excluding reuse or recycling that takes place as an integral part of an internal manufacturing process within the same premises.
  - (3) The recovery of waste including the refining, utilisation, or co- processing of the waste at a facility that processes in excess of 100 tons of general waste per day or in excess of 1 ton of hazardous waste per day, excluding recovery that takes place as an integral part of an internal manufacturing process within the same premises.
- *Treatment of waste*

- (4) The treatment of hazardous waste in excess of 1 ton per day calculated as a monthly average; using any form of treatment excluding the treatment of effluent, wastewater or sewage.
- (5) The treatment of hazardous waste in lagoons, excluding the treatment of effluent, wastewater or sewage.
- (6) The treatment of general waste in excess of 100 tons per day calculated as a monthly average, using any form of treatment.
- *Disposal of waste on land*
  - (7) The disposal of any quantity of hazardous waste to land.
  - (8) The disposal of general waste to land covering an area in excess of 200m<sup>2</sup> and with a total capacity exceeding 25 000 tons.
  - (9) The disposal of inert waste to land in excess of 25 000 tons, excluding the disposal of such waste for the purposes of levelling and building which has been authorised by or under other legislation.
- *Construction of facilities and associated structures and infrastructure*
  - (10) The construction of a facility for a waste management activity listed in Category B of this Schedule (not in isolation to associated waste management activity).

### 3.2.7.2. Amendments Published under General Notice Regulation 633 of 24 July 2015

- The List of Waste Management Activities under the Waste Act (General Notice Regulation 921) were amended on 24 July 2015, adding an additional category to the List of Waste Management Activities which now requires a waste management licence.
- Under this amendment, a new activity (15) was added to Category A and a new activity (11) was added to Category B of the List.
- If either of these activities will be triggered, the holder is required to first obtain a waste management licence before the activity can commence.

#### Activity (15) under Category A

the establishment or reclamation of a residue stockpile or residue deposit resulting from activities which require a prospecting right or mining permit, in terms of the MPRDA.

#### Activity (11) Under Category B

The establishment or reclamation of a residue stockpile or residue deposit resulting from activities which require a mining right, exploration right or production right in terms of the MPRDA.

- Category 'A' Activities, must follow a Basic Assessment process, whereas Category B Activities must follow a full scoping and EIA reporting process.

### *3.2.7.3. Pending EMPr Applications*

If an EMPr application is pending under the MPRDA regulations, it must be processed under the MPRDA regulations, despite the coming into effect of this amendment to the waste management activities.

## **3.2.8. Impact of regulations on projects**

### *3.2.8.1. New Projects*

Application needs to be lodged for a Waste Management Licence for any mine residue stockpiles and deposits to be established or reclaimed. The application for a Waste Management Licence will be in addition to the application for an environmental authorisation.

It is necessary to initiate an integrated environmental authorisation / waste management licence application process. One needs to ensure that the integrated EIA identifies all impacts and suggest appropriate management measures for the mine residue deposits and stockpiles.

It is important that the pollution control barrier system for these mine residue deposits and stockpiles must be defined by the National Norms and Standards for Assessment of Waste for Landfill Disposal as well as the National Norms and Standards for Disposal of Waste to Landfill as published under the Waste Act. In circumstances where the mine residue deposits and stockpiles are classified as hazardous, the outcome of the assessments done in terms of the design of the pollution control barriers, may prescribe that certain liners be put into place, as mitigation measure which will be discussed as part of the guideline in Chapter 6.

Consideration towards the following needs to be taken into account:

- Lining a waste rock dump will be extremely expensive.
- Backfilling of pits with waste rock, may also, arguably require that the pit should be lined before backfilling can take place.

### *3.2.8.2. Existing Projects*

Existing residue stockpiles and deposits which were approved in terms of the MPRDA, as at 24 July 2015, must be regarded as having been approved under the regulations. Existing MPRDA rights holders must continue to manage their mine residue deposits and stockpiles in accordance with the approved mitigation measures prescribed in the holders approved EMPr.

Existing EMPr's which have been approved under the MPRDA, are deemed to have been approved as a Waste Management Licence under the Waste Act. There are no requirement to obtain a new Waste Management Licence in terms of existing approved residue stockpiles and deposits. However, it is important to note that the Minister of Mineral Resources (as the competent authority under the

Waste Act for mining related activities) does have a discretion to issue a directive to holders of existing approved EMPr's to upgrade their EMPr's to address any deficiencies identified. This is likely to occur in circumstances where the Minister is of the opinion that the mine residue deposits and stockpiles are likely to result in significant pollution, degradation or damage to the environment.

#### *3.2.8.3. Unauthorised Mine Residue Deposits and Stockpiles*

If the residue stockpiles and residue deposits of an existing operation are not legally authorised in the existing EMPr for the operation, it would appear that such mine residue deposits and stockpiles would then be unlawful under the Waste Act.

It is therefore recommend that operations seek the support from a legal entity as an application under section 24G of the National Environmental Management Act, 107 of 1998 might be required to rectify the issue. Section 24G of the National Environmental Management Act, 107 of 1998 refers to the consequences of unlawful commencement of a listed activity.

### **3.3. Summary: Chapter 3**

The objective of chapter 3 is to provide legal context for the management of coal discard facilities and should be used hand in hand with Chapter 6. The legal foundations and obligations under regulations prior to the promulgation of Waste Act is introduced. An introduction of the Waste Act and the classification of coal discard as a hazardous waste material is explained. It is followed by a discussion of the current legislation applicable to coal discard facilities, inclusive of the Waste Act and is further broken down into the application thereof from a prospecting, exploration, mining and closure point of view. Insight is provided into the classification of coal discard dumps under the Waste Act together with physical, administrative and legislative requirements for these residue deposits. Legislative management guidelines in accordance with existing EMPr's are explored. This provide context for amendments published in 2015 associated with activity classes relevant to coal residue deposits. Lastly, an overview of the physical and administrative requirements for new and existing projects are presented which includes the legal position of unlicensed coal residue deposits.

## CHAPTER 4: CURRENT AND BEST PRACTICE REVIEW

The literature study involved a review of all relevant available information pertaining to current and ideal coal discard dump management practices relevant to groundwater.

A comprehensive literature search was carried out on the following:

- Coal discard facilities post closure management principles
- Current Industry, national and international guidelines and practices
- Best practice associated with management of coal discard facilities

The review of the different topics also gave light to the identifications of guideline practices which have been drawn up into a practical guideline, discussed in Chapter 6.

The major findings of the literature review are incorporated into text for ease of reference and use.

### 4.1. Coal discard facilities post closure management principles

Apart from soil remediation and rehabilitation efforts, Robins (2004) identified four closure principles which have been assimilated into this study forming the foundation for groundwater management associated with coal discard facilities:

- Symptom treatment
- Encapsulation of coal discard facilities to prevent seepage to groundwater
- Render the tailings material inert prior to deposition (not applicable to the objective of this study).
- Reclamation and reprocessing

These principles have been assimilated with the hierarchy of mine water management which is presented in Chapter 6.

#### 4.1.1. Base case

According to Robins (2004), this method is usually accepted as capital and operating costs related to discard disposal are minimised (Figure 16). Projects are warranted on this foundation and business models are not harshly impacted by the budgets available at the end of the project life to assist closure.

With this method the intolerable impacts of discharge, diminutive long-term physical stability, atmospheric emissions and unwanted aesthetic issues are treated as and when they happen. Mining companies adopting this method mostly attempt to embark on the least that is required by legislation.

Difficulties that can be predicted with this selection include on-going responsibility in treating the symptoms, future accountability issues as environmental standards are raised up and recent



creativities such as the 'Polluter Pays Principle' that pursues to transfer the cost of pollution management to the original polluters. Once site characterisation has taken place, a high confidence CSM can be established which will need to inform the development of a comprehensive water monitoring programme.

Before commissioning a groundwater monitoring programme clear goals must be defined. According to Barnes and Vermeulen (2012), objectives act as a measure of efficiency of the goals that needs to be delivered. The management objectives must be simple. Dragged out objectives will merely cause extra expenditure and misunderstanding. The monitoring programme's objectives should revolve around 3 questions of 'why', 'how' and 'who'. Barnes and Vermeulen, (2012) developed guidelines for groundwater monitoring in the coal industry. These guidelines are incorporated into overall groundwater management guidelines for coal discard facilities, discussed in Chapter 6.

The recommended 7 stages for a groundwater monitoring programme are listed below (Barnes and Vermeulen, 2012):

1. Conceptual model and site selection
2. Risk assessment
3. Drilling of targeted monitoring boreholes
4. Borehole construction
5. Sampling of monitoring boreholes
6. Water quality analyses and interpretation
7. Review and update of database

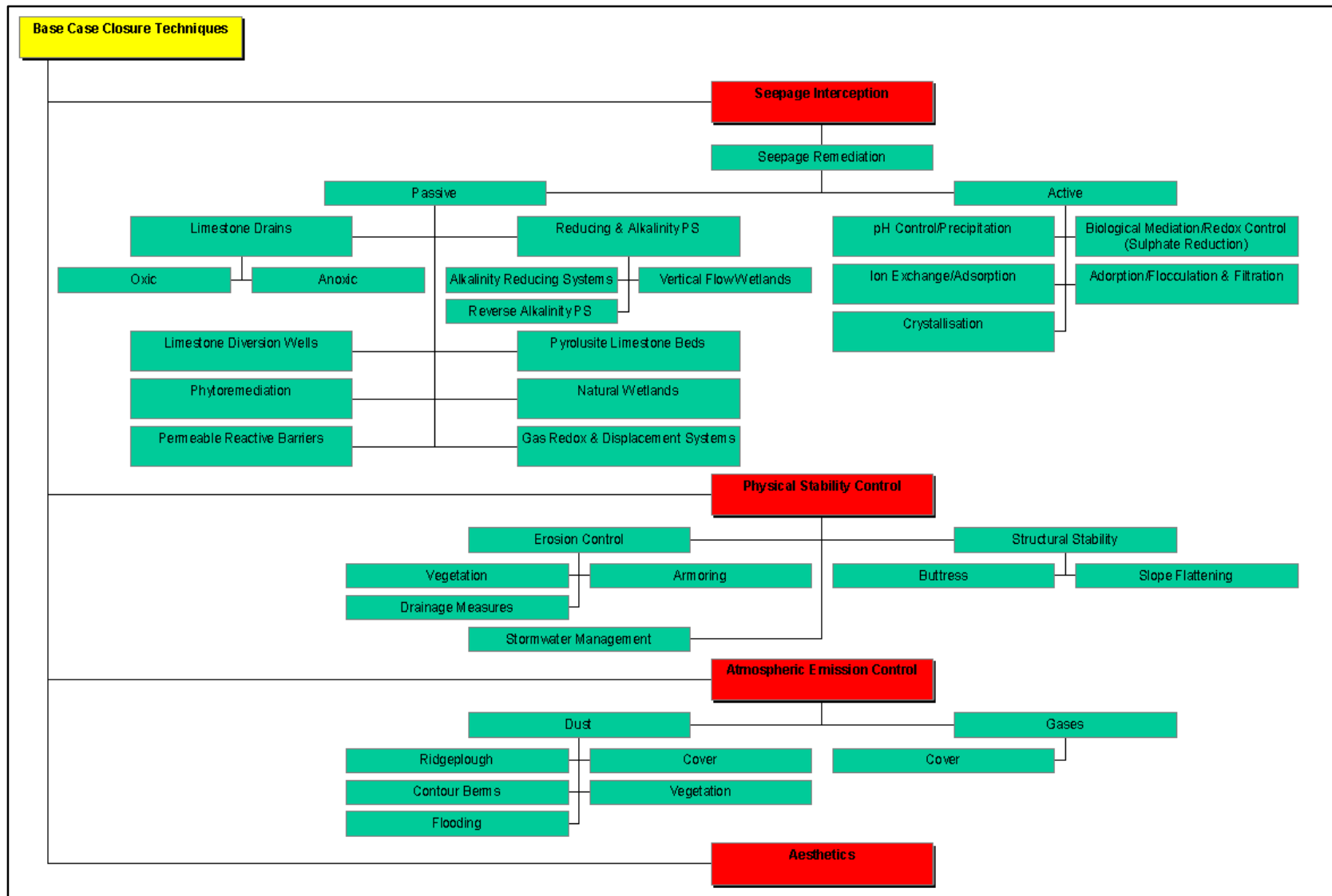


Figure 16: The base case closure techniques commonly practised by mining companies with the closure of coal discard facilities (Robins, 2004).

#### **4.1.2. Encapsulation Case**

This technique signifies a more advanced level than the base case as pollution prevention efforts are made to prevent discharge of pollutants to the environment and removing the need to treat symptoms faced with the base case. Some symptoms though remain due to discard deposition techniques and technology available at the time.

According to Robins (2004), this method (Figure 17) traps pollutants within the facility encapsulation of the material or via setting of the potential contaminants within the discard particles themselves. The former is achieved by lining of the base of the facility prior to deposition to prevent seepage to the groundwater table, which is not applicable to this study. The second method occurs by covering of the upper surface and slopes of the facility after deposition has ceased. The latter could be accomplished through synthetic coating so as to alter of contaminants or of the surfaces of the tailings particles with an impermeable and solid material preceding, or amid deposition.

Possible drawbacks with this technique are that liners are usually costly, impacting the financial state and profit margins, and that miniscule expenditure associated of chemical addition during operation accrues to considerable amounts with increased waste tonnages produced. Additional difficulties include potential for long-term damage and degradation of the liners and covers resulting in future problems that would be costly to remedy at that stage.



Figure 17: Encapsulation techniques (Robins, 2004).

#### 4.1.3. Detoxification Case

This case (Figure 18) is one in which potential pollutants are removed or treated prior to tailings deposition and is not applicable to this study as is as this study focusses solely on existing and rehabilitated facilities. Therefore this principle has been modified in Chapter 6 to refer to the increase of alkalinity and buffer capacities within discard facilities. This technique can anticipate the need for smaller disposal facilities to deal with parted contaminants. Most of the ventures related to this case have already minimised water consumption and reagent usage.

Normally the potential contaminants which needs to be dealt with are sulphides that can cause ARD, heavy metals, and salinity but can be mitigated through increasing the buffer capacity of the discard dump.

This part presently represents a growing trade as mining companies are comprehending the necessity to advance upon past environmental performance. Beneficial advantages are evident as mines gain from more efficient reagent usage, water-use efficiency and higher recovery rates of saleable product during the depositional phase.

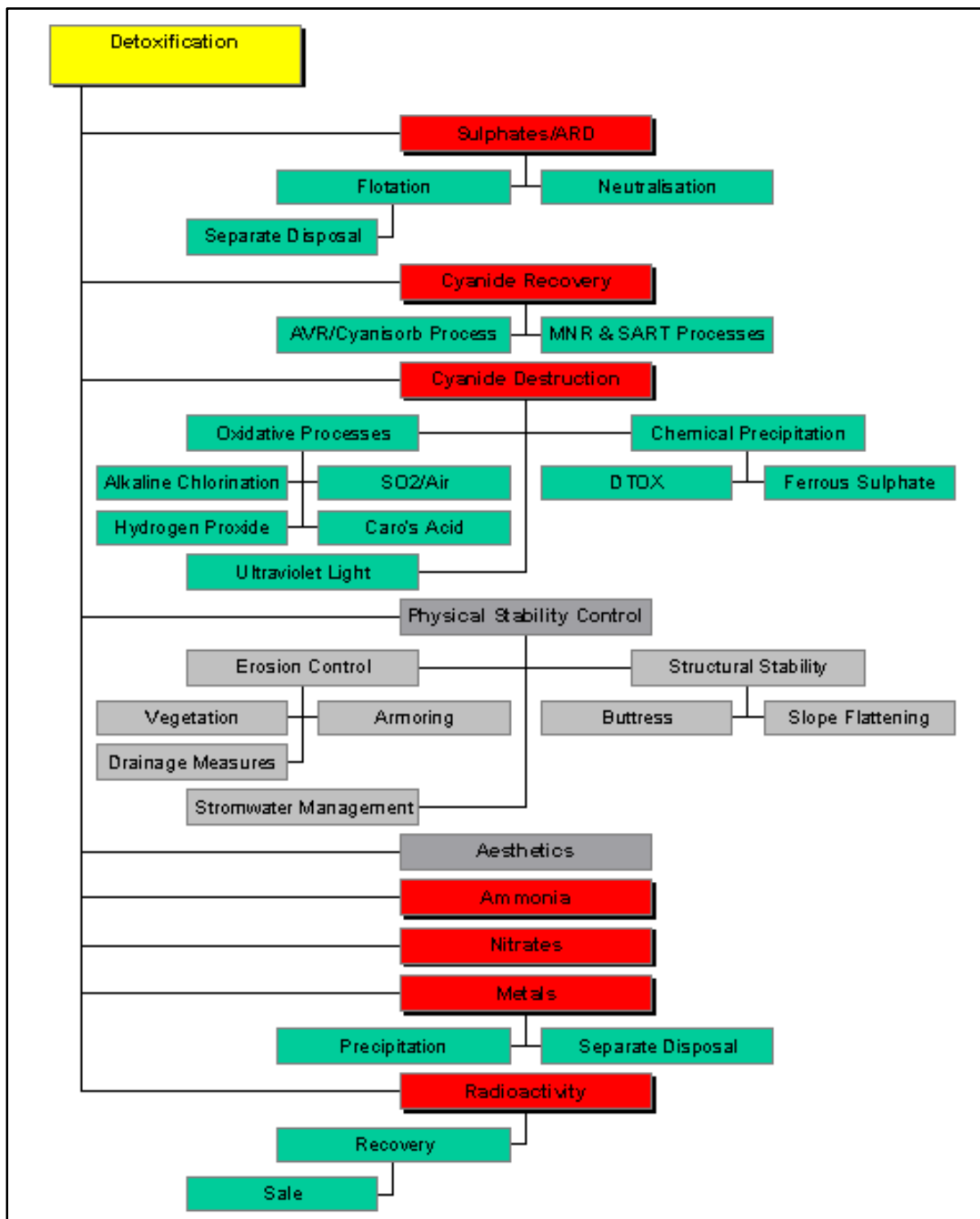
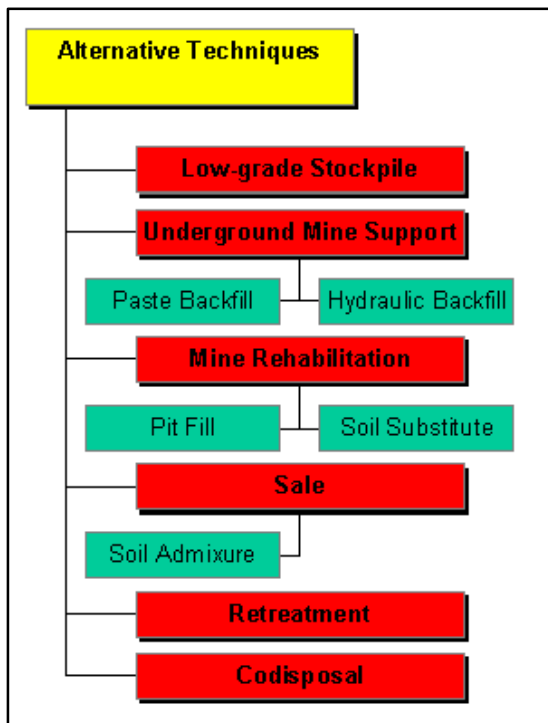


Figure 18: Detoxification techniques (Robins, 2004).

#### 4.1.4. Alternative Case

This case (Figure 19) signifies an assortment of options which needs to be thought of for possible application. These methods have not been included in the management guideline as there are legislative constraints associated with these techniques. Should there be a change in legislation these techniques can be further investigated as it forms the top priority in the hierarchy of controls for mine water management. Currently the sale of waste is captured as removal of the source or reprocessing of the discard material and forms part of the management guideline discussed in Chapter 6.



**Figure 19: Alternative techniques (Robins, 2004).**

The four options described in the preceding sections were obtained from Robins, (2004) and some points have been incorporated into overall groundwater management guidelines for coal discard facilities, discussed in Chapter 6.

## 4.2. Industry guidelines

Various mining houses take after set rules for managing groundwater identified with coal disposal facilities where others stick to their own in-house standards. Due to the sensitivity connected with these contamination sources merely a few were keen to share their strategies and guidelines. They are as follow:

### Anglo American

According to Human (2014), Anglo American adheres to in-house best practice principles and polices which includes commitment to comprehensive life-cycle management of pollution sources. This again relates more to treatment of the symptom than prevention or isolation of the source. Anglo American is committed to responsible decommissioning and closure of tailings facilities to protect human health and the environment. Closure planning forms part of the decommissioning phase and is recommended during the pre-feasibility and conceptual stages with consequent evaluation and update. Rehabilitation and water treatment trials are investigated on a regular basis during the operational phase, however, financial constraints limit research and development in non-production areas. Aftercare and post-rehabilitation monitoring requirements are outlined and forms part of the principles incorporated in Chapter 6. Mining is only a temporary land use and clear rehabilitation and mine closure objectives which are aligned needs to be consistent with the proposed future land use of the area. These are in turn defined as per the Anglo American Mine Closure toolbox. The general rehabilitation guidelines anticipate that the rehabilitated site be:

- Safe to humans, plants and wildlife.
- Non-polluting.
- Stable and permanent land forms.
- Able to sustain an agreed post mining land capability and use.
- Does not have maintenance needs greater than the surrounding “natural” land.
- Have no adverse environmental, safety and health effects outside the lease area.

The commitments as a result of these guidelines are as follow and involves the development of a guideline document outlining the key considerations for developing site specific rehabilitation plans including:

- A free draining design so that clean water can run off without causing soil erosion and minimize the volumes of recharge resulting in polluted discharge and seepage.
- Selectively place problematic spoil (e.g. acidic, dispersive, vulnerable to spontaneous combustion) if practically possible and financially viable. If not, alternative mitigation

measures must be implemented to minimize the environmental and health impacts (e.g. compaction of discard to minimize oxygen ingress and the liming of acidic generating discards).

- Strip and conserve all useable topsoil and subsoil for later use in the rehabilitation process.

#### AngloGold Ashanti Ltd

According to Robins (2004), AngloGold Ashanti Ltd uses a management framework to cover all aspects of mineral waste disposal through their complete life-cycle. The framework encompasses principles with minimum standards of practice. Decommissioning is covered through the following standards:

- Decommissioning the tailings facility properly to ensure a sustainable solution in accordance with planned tailings facility land use.
- Adopt a 'final design for the environment' approach to tailings design.
- Launch environmental baselines and equivalent sites.
- Continuous re-evaluation of tailings related risks present upon termination of operations.
- Development of site-specific closure principles.
- Preparation of detailed final closure strategy.
- Planning and implementation procedures as to manage stormwater run-off.
- Controlled releases of likely contaminants from decommissioned tailings facilities in order to protect human health and the water environment.
- Deliver economic guarantees for the decommissioning of tailings facilities within mine rehabilitation planning activities consistent with legislative requirements.
- Implement a monitoring and aftercare programme to confirm that procedures and controls are effective.
- Delivering on transparent reporting.

#### Barrick's corporate goals with respect to tailings facility closure are (Espell *et al*, 2004):

- Design the decommissioning processes such that tailings are stable under current and anticipated closure standards of performance.
- Uphold hydraulic segregation between the tailings material and surface and groundwater systems.
- Return the region to a feasible post-mining land-use able of supporting a pre-defined post-mining land use.
- Attain facility closure inside a minimum period.
- Permit long-term environmental liability.



### South 32

South 32 follows management standards that form the basis of company management systems at all levels (Robins, 2004). The standards cover the entire life-cycle of operations including decommissioning, closure and rehabilitation. A strong emphasis is placed upon risk assessment. South 32 requires that closure, decommissioning, remediation and rehabilitation plans are established, fully costed, documented and annually reviewed.

### Newmont

Newmont reflects that decommissioning of mining operations deliver a chance to generate a constructive heritage for their host communities (Robins, 2004).

They manage mineral waste, heap leach facilities and water containment facilities via a set of management guidelines that covers design, operational and closure aspects.

The guidelines supports:

- All characteristics of the design should be carried out with the view to facilitating safe, environmentally satisfactory and cost effective closure of tailings facilities
- Noteworthy environmental monitoring throughout the operation confirming performance according to the design and planning assumptions in order to enable the development of a comprehensive closure plan.
- Stripping and stockpiling of topsoil.
- Progressive rehabilitation.

International government guidelines are very generic and does not provide specifics on groundwater management guidelines, except that all aspects related to waste facilities and the environment be adequately investigated and managed. Therefore the European Union Guideline is included and quoted below as it was deemed encompassing of the generic statements present in other international guidelines.

### European Union

The European Commission has tabled a draft reference document on tailings and waste management (European Commission, 2003). The document includes a review of techniques to consider in the determination of best available technology, best available techniques and emerging techniques for the management of tailings and waste rock in mining activities.

Recommended elements of a closure plan include:

- Determination of background data including site history, infrastructure, process flow controls, system operations, mineralogy and topography.

- Hydrology and water management.
- Hydrogeology.
- Soil capability.
- Re-vegetation.
- Impact assessment.
- Long-term maintenance.
- Geotechnics.
- Chemistry and geochemistry.
- Monitoring programme.
- Effluent management or treatment requirements.
- Communications.
- Financial assurance.
- Stakeholder consultation.
- Potential end land use.
- Closure technology (dry or wet cover, flooded, wetlands, perpetual treatment or vegetative cover).

The closure plan should:

- Include closure costs in the assessment of alternatives.
- Adopt a risk assessment approach.
- Be maintained throughout the active life of the facility and routinely updated taking into account any modifications to the design and during operation.
- Encourage facility design to facilitate premature closure if necessary.
- Minimise the need for active aftercare management.

### 4.3. Current best practices associated with management of coal discard facilities

#### 4.3.1. Water volume reduction and diversion

From practical experience it is proposed to install cut off trenches at designated depths upslope of rehabilitated discard dumps. This also depends where gradients so dictate, to reduce the water reporting to and/or flowing over the rehabilitated discard facility. Evidence of this practice is shown in Chapter 5.

According to Robins (2004), the surface profile of the tailings facility should rather be domed than terraced. This practice is also standards for Anglo American and will become evident in Chapter 5. The domed, free draining profile is preferred as it results in the least amount of infiltration and promotes surface runoff and limits erosion, which in turn promotes vegetation growth.

Depending on the hydrogeological regime and aquifer parameters dewatering boreholes can be drilled up gradient to reduce groundwater inflow and mounding inside discard facilities, however this practice have not been proved feasibly in the coal environment as yet. More self-sustainable solutions are the use of water consuming trees such as Eucalyptus (blue gum) which can consume between 75 and 240 litres per day (per mature four year old tree), and can be planted around the dumps to ensure water uptake is maximised, thus potentially decreasing contamination of the surrounding aquifer. This option has been implemented successfully across numerous mines, however the acidity does have an influence on you saplings.

Hatting *et al.*, (2001) states that decreasing surface infiltration would result in increased precipitation of minerals because of the increased concentration of chemical species per volume water. Moreover, the pH qualities would diminish essentially and would take a long time to recoup compared with alternate situations. Sulphate concentrations in the seepage water would however remain moderately low, yet would experience issues returning to background levels due to the low flow rates. Despite the fact that the concentration might be generally low, the aggregate salt load for the model period will be similar to the other management situations. Relative low concentrations of sulphate exuding from the soil ought not to be mistaken for low salt load concentrations.

#### 4.3.2. Soil amelioration, rehabilitation and infiltration reduction

Rösner and Van Schalkwyk (2000) recommends soil management measures such as liming to avoid the pollutant movement from the topsoil into the subsoil and then to groundwater. It also serves a purpose of providing suitable agricultural circumstances, enabling future land use. Lime or limestone can be applied with a surfactant, ensuring percolation of the alkaline water, increasing the buffer capacity of the source material.

From a case study on soil cover effectiveness to mitigate ARD, Loos *et al.*, (2000) made the following recommendations in connection with techniques and procedures for improved rehabilitation of coal discard facilities comprising the building of clay and soil covers in order to avoid ARD formation and other undesirable occurrences, such as spontaneous combustion:

1. The use of covers consisting of two layers, namely, an underlying less permeable clay or clayey soil layer and an upper topsoil layer, both of a suitable thickness, is recommended. For example an underlying layer of 30 cm or 70 cm compacted Estcourt soil covered by 70 cm or 30 cm, respectively, of uncompacted Avalon soil resulting in a total thickness of 1 metre. This was proven effective over a period of 4 years.
2. Use of a of a single soil type, exemplified by Avalon soil is not recommended, even though a 1 metre cover of 70 cm compacted and 30 cm uncompacted Avalon soil greatly slowed acidification of the coal waste in the present study and showed the greatest reduction of water outflow. 30 cm and 50 cm thick covers of Avalon soil had no or little delaying effect on acidification of the coal waste, although the latter was comparable with the double soil covers in limiting water outflow.
3. Coal waste should be compacted during construction of a dump to counteract spontaneous combustion and soil or clay covers should be vegetated to prevent erosion.
4. The inhibition of acidification of the coal waste below a cover depends on the effectiveness of the cover as a barrier to oxygen diffusion into the dump. It is recommended that oxygen in coal discards below covers be monitored routinely using permanently buried probes that extend through the covers into the coal discard. Using an appropriate meter, the oxygen concentration in the atmosphere of the coal waste below each probe can be measured in turn. An immediate result is obtained. Anaerobic conditions (no oxygen) indicate that the cover should be effective in blocking acidification. However, the presence of oxygen indicates that it is not.
5. Acidification below covers should also be monitored regularly by sampling coal waste below the cover by auger and measuring its pH.

Liners and covers ensure the avoidance of movement of pollutants into the adjacent soil and biosphere, and also prevents rainwater infiltration and in turn then limits the risk of water resource contamination (Melchior *et al.*, 1993). Although many investigations have been performed on the efficiency of compacted clay liners and covers for mineral waste residue deposits, there remain difficulties associated with the usage of these materials. For example, compacted clay tends to parch from above or below and forms fissures unless adequately protected. Clay liners are also vulnerable to damage from freeze and thaw and should be protected through the application of suitably thick soil cover.

Mentis (1999) reported on extensive field studies evaluating the progress and success of rehabilitation of opencast coal mines on the Mpumalanga Highveld. This is done through the establishment of grass pastures on mined out areas backfilled with spoil and covered with topsoil. The existence of a vegetation cover ought to prove valuable, by prevention of erosion of soil covers on coal discard dumps and reducing the water and oxygen ingress.

While limestone or lime is routinely added to the soil to enhance reclamation and vegetation growth, it has also been used as a surface amendment to improve ground water quality (Caruccio and Geidel, 1996). The concept of surface application is that rainwater in contact with limestone will generate alkalinity and the alkalinity will create a wetting front which moves through the spoil. This technique has had limited success and, unless the seeps or discharges were initially low in acidity (400 mg/L acidity as  $CaCO_3$ ), the limestone only minimally improved seep quality.

Alkaline recharge trenches have also been constructed with  $CaO$  and  $Ca(OH)$  on top of an 8 hectare coal discard disposal site, which produced ARD (Nawrot *et al.*, 1994). After installing the alkaline recharge pools, acidity reductions of 25 to 90% were experienced with 70% to 90% reductions in Fe and sulphate within the seepage. The following conclusions and recommendations were made:

1. Use highly soluble alkaline materials (e.g.  $CaO$ ,  $Ca(OH)$ )
2. Maximize water volumes through trenches by directing surface water flow into the pool;
3. Use multiple alkaline recharge pools to increase chances of influencing groundwater flows;
4. Construct infiltration paths into the backfill to improve alkaline diffusion and flushing; and
5. Allow sufficient time (possibly 3 to 5 annual cycles) for the effect to become apparent.

Hatting *et al.*, 2001 is of opinion that potential remediation strategies can be divided into treatment technologies or utilising on-site management. Treatment technologies refer to soil and water treatment technologies in order to reduce the concentration of contamination or to reduce the extractable concentrations to an acceptable level. On-site management usually involves either isolating the soils from interacting with the surrounding environment or it involves the implementation of a strategy that reduces the bioavailability of the existing contaminants.

#### 4.3.3. Water treatment

Water treatment has gained increasing popularity over the last decade and it has become apparent that it is seen as a silver bullet to curb the ARD problems faced by the mining industry. However, this is not the case as numerous water treatment plants in the Mpumalanga coalfields are struggling with the ongoing maintenance and the cost thereof. Also, the generation of by products have become a source of secondary pollution which are not currently beneficiated further for commercial application. Hence the need for sludge and brine treatment initiatives. Therefore, it is emphasized that the

management guidelines follow the hierarchy of controls published in numerous Best Practice Guideline documents (Department: Water Affairs and Forestry, 2008), this entails:

1. Pollution prevention
2. Reuse or recycle contaminated water (not applicable to this study)
3. Water treatment
4. Reuse of treated water (not applicable to this study)
5. Discharge or disposal

Adherence to the water management hierarchy, i.e. first optimise pollution prevention options, then impact minimisation options, then reuse and reclamation options (with or without treatment) before considering any discharge to or impact on the water resource.

Mine water treatment technologies have evolved substantially over the last decade as a result of mines becoming more dependent on water treatment prior to discharge or reuse. Water treatment can be broken up into four categories namely (Bezuidenhout, 2012):

1. Neutralization
2. Metals removal
3. Desalination and;
4. Specific target pollutant treatment

These categories can further be substantiated into:

- a) Active Treatment
- b) Passive Treatment and;
- c) In-Situ Treatment

Due to the many complexities around water treatment and specifically pairing treatment technology with pollution sources, a decision tree for both active and passive treatment (Figure 20) was developed to ensure that the correct treatment method is used for its intended purpose.

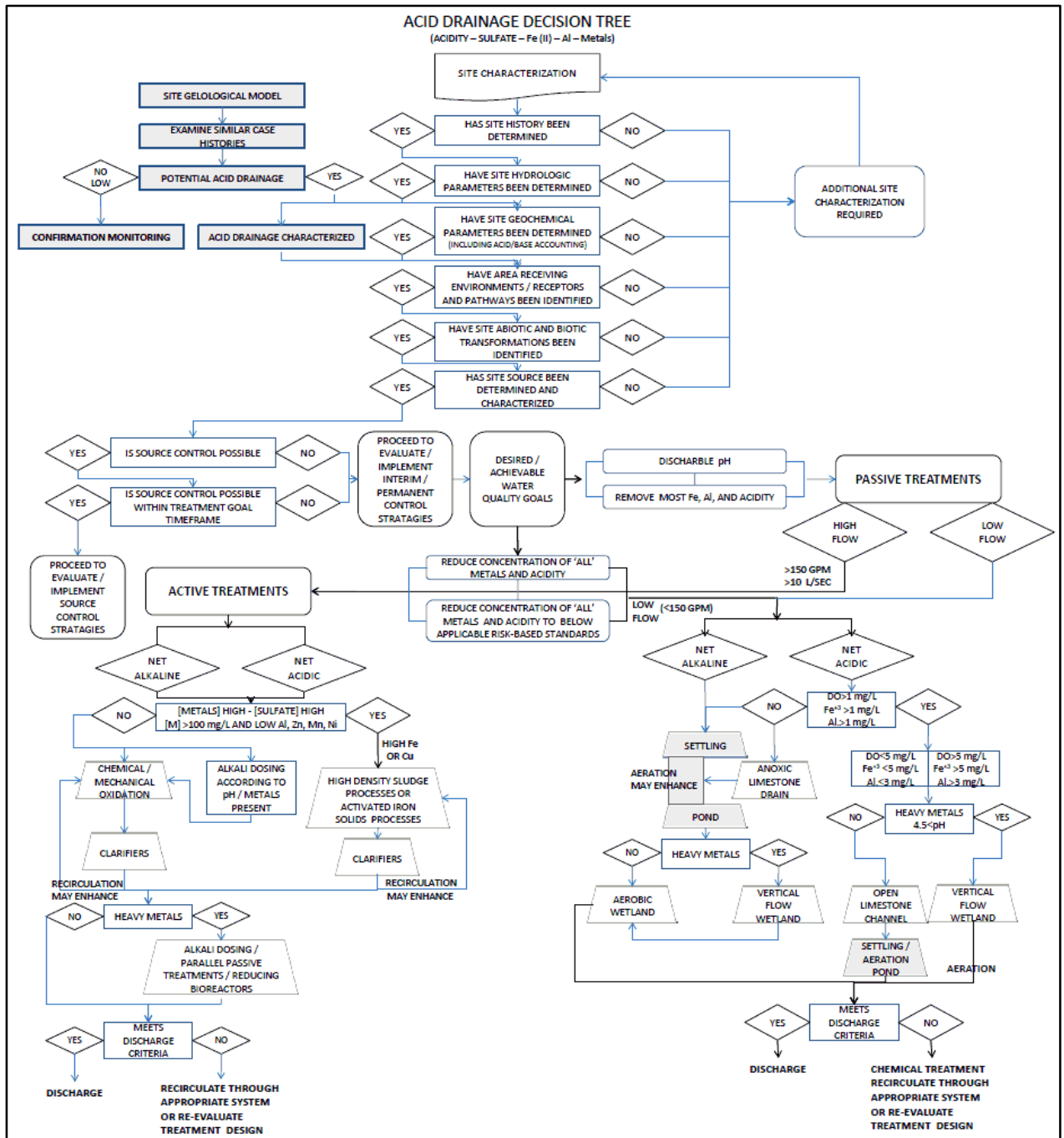


Figure 20: ARD treatment decision tree (Bezuidenhout, 2012).

Different types of active and passive treatment technologies exist and Table 2 shows a comparison between active treatment technologies, all of which can be applied to rehabilitated coal discard facilities, depending on the site conditions and site characteristics. Active treatment technologies are made up of:

1. Chemical Precipitation
2. Membrane Treatment
3. Ion Exchange and;
4. Biological sulphate removal

Whilst passive treatment entails:

1. Aerobic Wetlands
2. Anoxic Limestone drains
3. Anaerobic wetlands
4. Reducing and alkalinity producing systems
5. Open limestone drains



**Table 2: Comparison of different active treatment and their specific applications (Bezuidenhout, 2012).**

Selection Criteria	Mine Drainage Treatment Technology			
	Chemical Precipitation	Membrane Treatment	Ion Exchange	Biological Sulphate Removal
Proven technology on commercial scale	Proven with many demonstration scales, large commercial plants	Proven with many large commercial plants	Demonstrated on pilot scale, commercial plants in the works	Proven, with limited number of commercial plants
Specialised application	General application to high metals, high SO <sub>4</sub> mine water	General application, but with appropriate pre-treatment	Demonstrated for CaSO <sub>4</sub> type waters with appropriate pre-treatment	Specialised application to high SO <sub>4</sub> mine water
Water recovery	High water recovery >95%	High water recovery >90%	High water recovery not confirmed	Very high water recovery >98%
Waste sludge/brine production	Large waste sludge production	Sludge and brine production	Large waste sludge production	Small waste sludge production
Potential by-products recovery	Potential for CaSO <sub>4</sub> recovery	Potential but not demonstrated	Potential for CaSO <sub>4</sub> recovery	High potential for sulphur recovery
Chemical dosing	High chemical dosing	Limited chemical dosing	High chemical dosing	Process depends on carbon source dosing
Energy usage efficiency	Moderate energy usage	High energy usage	Moderate energy usage	Moderate energy usage (heating of anaerobic reactors)
Reliable and robust performance	Robust process	Process good performance, but sensitive to pre-treatment	Process performance and resin recovery subject to interference	Biological process sensitive to toxins, fluctuating feed water quality and environmental conditions
Capital investment cost (per m <sup>3</sup> /day capacity)	R5000 - R20000	R8300 - R16700	Highly variable dependant on water quality	R13400 - R25000
Operational and maintenance cost (R/m <sup>3</sup> treated)	R3 - R25	R8 - R16	Highly variable dependant on water quality	R11 - R25

Applications for passive treatment is shown in Table 3 and indicates how passive treatment technology can be applied to different types of water quality. This is of greater importance than conventional active treatment due to the fact that rehabilitated coal discard dumps are predominantly located in remote areas where infrastructure and electricity are limited or non-existent.

**Table 3: Applications for passive water treatment (Bezuidenhout, 2012).**

Passive Treatment Technology	Application to mine drainage
Aerobic wetlands	Net-alkaline drainage
Anoxic limestone drains	Net-acidic, low Al <sup>3+</sup> , low Fe <sup>3+</sup> , low dissolved oxygen drainage
Anaerobic wetlands	Net-acidic water with high metal content
Reducing and alkalinity producing systems	Net-acidic water with high metal content
Open limestone drains	Net-acidic water with high metal content, low to moderate SO <sub>4</sub>

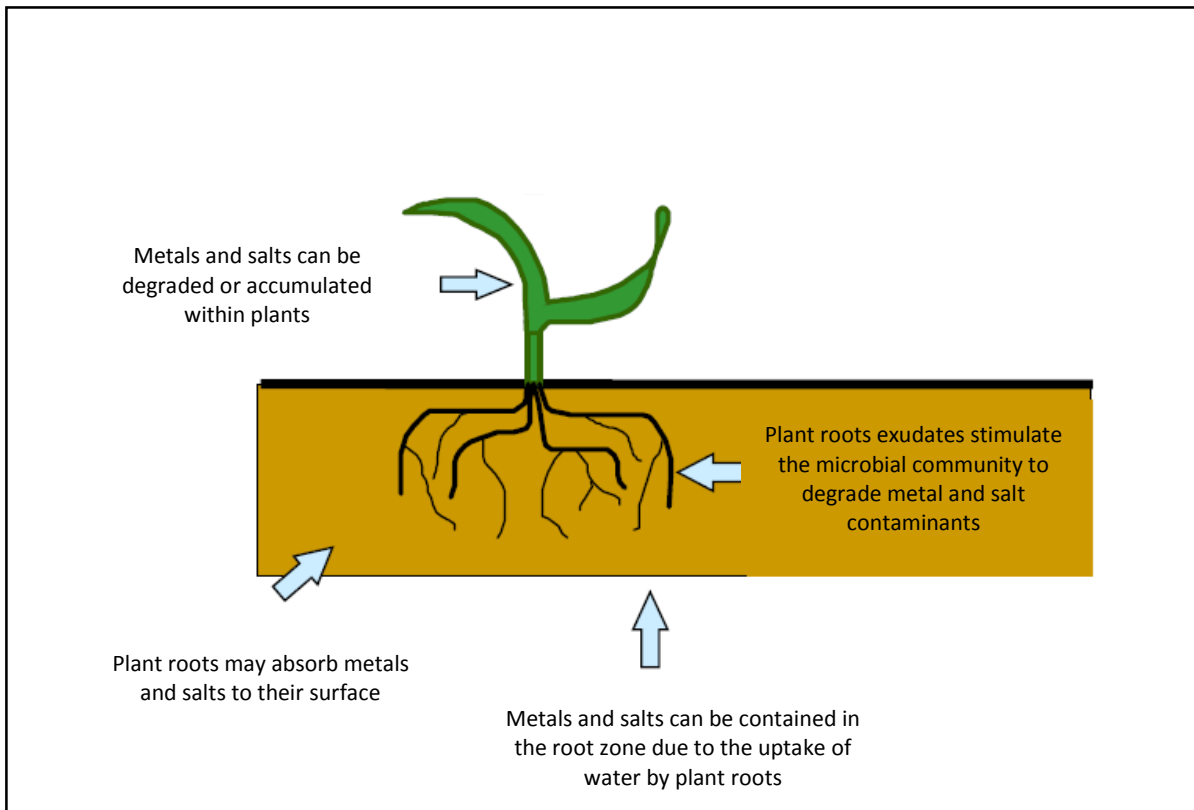
#### 4.3.3.1. Emerging Technologies: Phytoremediation and Permeable Reactive Barriers (PRB's)

According to Frick *et al.*, (1999), in-situ treatment comprises the use of phytoremediation and permeable reactive barriers (PRB's) and are discussed accordingly as emerging technologies which have become more applicable due to the fact that these approaches range from intensive engineering techniques to natural attenuation, a "hands-off" approach relying entirely on natural processes to remediate sites with no human intervention. The advantages, applications and limitations of in-situ treatment methods phytoremediation and PRB's are elaborated on in Table 4.

##### Phytoremediation

Phytoremediation is the in situ use of plants and their associated microorganisms to degrade, contain or render harmless contaminants in soil or groundwater (Cunningham *et al.*, 1996) (Figure 21). In essence, phytoremediation employs human initiative to enhance the natural attenuation of contaminated sites and, as such, is a process that is intermediate between engineering and natural attenuation. Because phytoremediation depends on natural, synergistic relationships among plants, microorganisms and the environment, it does not require intensive engineering techniques or excavation. Human intervention may, however, be required to establish an appropriate plant-microbe community at the site or apply agronomic techniques (such as tillage and fertilizer application) to enhance natural degradation or containment processes.

Table 4 indicates a comparison, advantages and limitation of different in-situ treatment initiatives, including phytoremediation.



**Figure 21: The different mechanisms involved in in-situ treatment through phytoremediation (Frick et al., 1999).**

Table 4: Comparison, advantages and limitation of different in-situ treatment initiatives, including phytoremediation (Cunningham et al., 1996).

Characteristics	Phytoremediation	Natural Attenuation	Engineering	Bioremediation
1. <i>In Situ</i> or <i>Ex Situ</i>	<i>in situ</i>	<i>in situ</i>	<i>ex situ</i> or <i>in situ</i>	<i>ex situ</i> or <i>in situ</i>
2. General Description	Use plants and microbes to degrade, contain, or transfer <sup>1</sup> contaminants	Use plants and microbes to degrade, contain, or transfer <sup>1</sup> contaminants	<i>Ex situ</i> = excavation, landfilling, incineration. <i>In situ</i> = soil vapour extraction; chemical or thermal treatment, solidification; pump-and-treat; vacuum extraction; sparging	Use microbes to degrade or contain contaminants; <i>ex situ</i> involves excavation coupled with solid-phase or slurry-phase treatment
3. Human Intervention	Yes; agronomic – tillage, fertilizer, inoculation, planting	No	Yes; extensive	Yes; extensive – provide proper temperature, oxygen, and nutrients to optimize microbial activity
4. Direct Benefits	<i>In situ</i> ; solar driven; well-suited to large areas of surface contamination; good esthetics; favorable public perception; plants as indicators of contamination; microbes degrade a variety of contaminants; plants transfer oxygen to rhizosphere; plants help contain contaminants, relatively easy to apply	<i>In situ</i> ; no disturbance	Dependable; leaves clean site; has definite starting and end points; <i>ex situ</i> especially faster than other remediation methods; proven to be effective; vacuum extraction is not limited by depth to groundwater	Limited disturbance with <i>in situ</i> ; proven to be effective
5. Indirect Benefits	Improves soil quality, prevents erosion; plants help eliminate secondary air- and water-borne wastes, including greenhouse gases; trees can reduce noise from industrial sites; hardy plants can help other less hardy plants grow on contaminated sites	Hardy plants can help other less hardy plants grow on contaminated sites; once established plants help prevent erosion and help eliminate secondary air- and water-borne wastes		
6. Limitations	Contamination must typically be shallow; plants may not grow if contamination high; slower than <i>ex situ</i> methods; contaminants may not be bioavailable; environmental conditions have to be right; leaching or volatilization may occur before phytoremediation	Slower than any other remediation method, therefore longer period of higher risks to human and ecosystem health; plants, microbes, or environmental conditions most beneficial to remediation may not be naturally present	Highly disruptive, especially excavation, landfill only transfers contaminants to a second site; disposal issues of fly ash with incineration; pump-and-treat does not treat soils directly and is very slow	Highly disruptive with <i>ex situ</i> excavation; <i>in situ</i> requires extensive collection systems; treatment longer than engineering but not as long as attenuation; may not work if contaminant toxic to microbes; requires intensive monitoring
7. Cost	\$17 to \$100/m <sup>3</sup> ; \$3US/m <sup>3</sup> each year; cropping system = \$0.02 – 1.00US/m <sup>3</sup> per year	No operational costs; may have costs associated with monitoring	Generally, from \$10 to over \$1,000/m <sup>3</sup> ; \$10-100US/m <sup>3</sup> for volatile or water-soluble contaminants <i>in situ</i> ; \$60-300US/m <sup>3</sup> for landfilling or low-temp. thermal; \$200-700US/m <sup>3</sup> for special landfill or high-temp. thermal; incineration or secured landfill costs of \$260-1064 per m <sup>3</sup> ; <i>in situ</i> typically cheaper than <i>ex situ</i>	\$50 to \$133/m <sup>3</sup> for <i>in situ</i> ; \$133 to \$400/m <sup>3</sup> for <i>ex situ</i>

### Permeable Reactive Barriers and Grout Curtains

Efforts can be made to reduce groundwater contamination by putting reactive materials into man-made drains to neutralise the acidity emanating from coal discard dumps.

Table 5 indicates the advantages and limitations of various reactive barriers used in PRB technology (Thiruvengkatachari *et al.*, 2008). These permeable reactive barriers in the form of e.g. lime or limestone grouts, dug into the soil around the discard facility would ensure water seeping from the dump and through the soil would pass through these grouts and potentially be neutralised, before it seeps into the aquifer.

According to Skousen *et al.*, (1998), grout curtains can be incorporated to separate acid yielding material and groundwater. Injection of grout curtains could significantly lessen groundwater volumes moving through spoil material and in turn reduce the volume of ARD being emanated from a site.

An international example is listed below:

Gabr *et al.*, (1994) characterised the flow of groundwater at a reclaimed acid producing site where a grout curtain wall was developed by pumping a mixture of cement and fly ash into boreholes closely associated with a highwall. This practice reduced the influx of groundwater by 80% from the highwall to the spoil material over a two year period. It also meant that seepages from the sources were reduced which in turn reduced the volume of pollution generated.

Foreman *et al.*, (1973), developed a grout curtain wall next to road in Pennsylvania to refute seepage through an inadequate coal barrier pillar and overlying geology which caused ARD generation and pollution plume development towards a river draining to the Clarion River. The grout curtain wall was developed through the installation of grout injection boreholes along the road. Grouting was initiated constantly horizontally along the length of the cut from the base to the ground surface. Minimal to no discharges were observed following this exercise.

**Table 5: Advantages and limitations of various reactive barriers used in PRB technology (Thiruvengkatachari et al., 2008).**

Material	Advantages	Limitations
<b>Zero valent iron (ZVI)</b>	Most commonly used reactive barrier material. Vast amount of background data available	Not effective on all types of organic compounds especially certain dense non-aqueous phase liquid compounds like 1,2-dichloroethane and dichloromethane
	Ability to be used in different states: as a pile, powder/granular, filling, colloidal, nanosized, emulsion that can be injected	Lifetime of the material could be reduced due to the formation of surface coating due to geological condition of the site
	High reactivity with organic and inorganic contaminants	Increase in pH during reaction induces corrosion and subsequent precipitation of minerals would lead to decreased permeability of reactive material
	Ability to combine with other treatment methods, e.g. bioremediation	H <sub>2</sub> gas produced and the microorganism (biofouling) could reduce the porosity of reactive material
	Less or no major problems associated with occupational health and safety (OHS) in handling this material	Limited information available on long term performance of the system especially on the build-up of surface precipitates and biofouling. Compounds like silica or natural organic matter (NOM) have passivating effect; reducing the iron reactivity. Competitive reaction inhibits the reactivity in the presence of certain compounds. In the presence of nitrate the dehalogenation of chlorinated compounds is decreased
<b>Activated carbon</b>	Different types (with different reactivities) of activated carbon can be obtained from low cost natural products, e.g. coconut shell based	Vast data on ex situ water and wastewater treatment. But very limited data on in situ treatment under field conditions
	Effective in the treatment of organic and heavy metal contaminants	Rapid breakthrough and thus frequent carbon change-outs or regeneration. Requires optimization studies
	Excellent material to combine with bio treatment	Performance highly dependent on temperature and other extrinsic parameters
	Chemically stable material	Surface coatings may decrease sorption capacity. Competitive adsorption
<b>Lime (calcium carbonate or hydroxide)</b>	Low cost reactive PRB material	Slow reaction time
	Effective in neutralization; reducing the solubility of certain metals or conditioning hydrochemical system to assist with other treatment processes, e.g. bioremediation  Used extensively for acid mine drainage remediation or acidic agricultural soils	Loss in efficiency of the system because of coating of the limestone particles with iron precipitates  Difficulty in treating acid mine drainage with a high ferrous–ferric ratio, and ineffectiveness in removing manganese. Limestone treatment is generally not effective for acidities exceeding 50 mg/L. Voluminous sludge is produced with hydrated lime (calcium hydroxide)
<b>Microbial bioremediation</b>	Less expensive and easy to install	A perceived lack of knowledge about biodegradation mechanism
	Natural processes to treat contaminants	Specific contaminants may not be amenable to biodegradation
	Capability to degrade organic contaminants into relatively less toxic end products	In the case of mixed wastes, some are amenable only under aerobic condition and some only under anaerobic condition
	Reduced risk of human exposure to contaminated media Remediation is not restricted to the treatment zone alone. Works well for dissolved contaminants and contamination adsorbed onto higher permeability sediments (sands and gravels)	Site characterization and optimization studies are required for each contaminated site. Chemical characteristics of the contaminants dictate the extent of biodegradability

The selection of the construction technique to be used depends upon the site characteristics such as depth of PRB, geotechnical consideration, soil excavation: space for handling and disposal of soil (contaminated), health and safety of personnel.

#### Pump-and-treat

Pump-and-treat is an in situ method that works to reclaim groundwater. With this method, water is pumped out of extraction wells, treated and then re-injected into injection wells, facilitating the movement of mostly water-soluble contaminants toward the extraction wells. Water pumped into the injection wells may contain added nutrients and other substances that increase degradation or recovery of the contaminant. Contaminated water pumped to the surface can be remediated using a variety of physical, chemical or biological techniques (Pierzynski *et al.*, 1994).

For all treatment technologies there are general considerations which need to be taken into account:

- Relative production in terms of volumes and quality
- Chemical composition of the receiving water body as well as the discharge quality
- Hazardous classification of pollution source material
- Potential impacts on surface and groundwater
- Disposal options

#### 4.3.4 Reclamation and pollution source elimination

According to Skousen *et al.*, (1998) encapsulation has been attempted after reclamation. If ARD is coming from a site, geophysical techniques are used to map the location of conductive zones in a medium by the use of conductivity or resistivity measurements. Boreholes are drilled into the conductive zones in order to locate acid material. A grout mix is then pumped down the wells to encapsulate or permeate through the acid-producing material. However the most attractive option would be to remine old discard facilities which may be quite feasible in the near future within the Mpumalanga coalfields. Where ARD occurs, remining reduces acid loads by:

1. Decreasing infiltration rates,
2. Covering acid-producing materials, and
3. Removing the remaining coal which is the source of most of the pyrite.

Remining has been combined successfully with alkaline addition and special handling to change water quality from acid to alkaline at specific sites. It is recommended by Rösner and Van Schalkwyk, (2000) that the primary source of contamination should be completely removed from the reclaimed sites in order to prevent further acid and salt generation.

#### 4.3.5. Induced leaching

According to Hatting *et al.*, (2001), induced leaching or paddocking refers to the containment of precipitation and operational fluids within the confined space of the residue deposit, thereby creating a scenario where maximum infiltration of fluids into the polluted area are being allowed. Sulphate concentrations peak quite quickly. The precipitation of secondary mineral phases last for a very short period and the pH levels do not reach acidic values. The question is however whether it is preferable to leach the contaminants out or whether the contaminants should remain near the concentrated source which is the footprint of the discard facility. Rehabilitation must be accustomed consequently.

#### 4.3.6. Predictive simulations and modelling

According to Zhu *et al.*, (2001), predictions on the evolution of pollutants in groundwater associated with coal discard facilities involves geochemical and numerical modelling, laboratory and field studies. Such predictive tools are commonly applied to forecast physical and chemical processes operating within and around coal discard dumps, including the development and evolution of ARD. Monitoring the rehabilitation efficiency of a discard dump allows the determination and evaluation of the required remediation techniques. Studies of rehabilitated coal discard dumps made during mine closure with actual post-rehabilitation data are rare and is regarded as best practice.

#### 4.3.7. Planning, risk assessment and conceptual understanding

To adequately understand the processes which governs the dynamics of water flow and chemistry inside a discard facility it is recommended by Hatting *et al.*, (2001) to draw up a detailed conceptual model that provides a general idea of the geochemical and hydrological processes involved in the migration of pollution underneath coal discard facilities. The model must incorporate geological, soil and hydrogeological data to enable an indication of the source, path and receptor with flow directions and possible volumes. The conceptual approach needs to involve a simple snap shot in time through the affected system. Soil profiles should be drawn up indicating characteristic properties of the discard and soils.



#### 4.3.8. Conceptual Site Model (CSM)

A comprehensive CSM synthesizes chemical data with geologic, hydrogeological, and other site information to enhance a project team's ability to develop solutions to ensure protectiveness, effectively manage resources, and limit the environmental footprint of site clean-up activities. Simple drawings and concepts are commonly used to communicate early project stage CSMs. As the level of information and complexity increases, the ability of a CSM to capture and synthesize new data in support of decision making can be significantly improved through the use of visualization platforms, appropriate data management strategies, and decision support tools.<sup>1</sup> These tools and strategies enable the CSM to be revised as more site information is collected and adapted to support the changing decision making needs of a project (United States Environmental Protection Agency, 2011).

This conceptual model should also incorporate data obtained from site investigations and a simple preliminary sampling and analytical campaign. The conceptual model is used in subsequent steps to develop a comprehensive sampling program (Department: Water Affairs and Forestry, 2008).

Risk assessments should always the following components (Hatting *et al.*, 2001):

- Source: contaminated source with the potential to cause harm;
- Pathway: a mechanism of movement by which a receptor could be exposed to in order to move towards the receptor;
- Receptor: a particular entity that is being adversely affected by the contaminated source via the selected pathway.

The S-P-R concept is used to visualise the factors involved in groundwater protection. In Figure 22, the 'source' equates to the hazard, the 'receptor' is groundwater and the 'pathway' represents the means by which the receptor could be exposed to the hazard. Figure 23 shows a pathway network receptor diagram, which is commonly used as a CSM to support risk assessment.

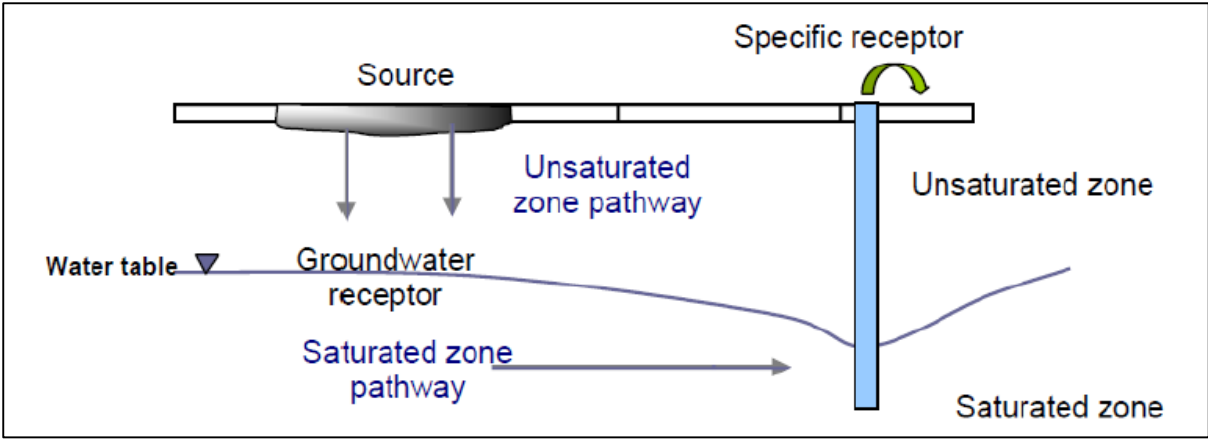


Figure 22: Source–pathway–receptor concept (United States Environmental Protection Agency, 2011).

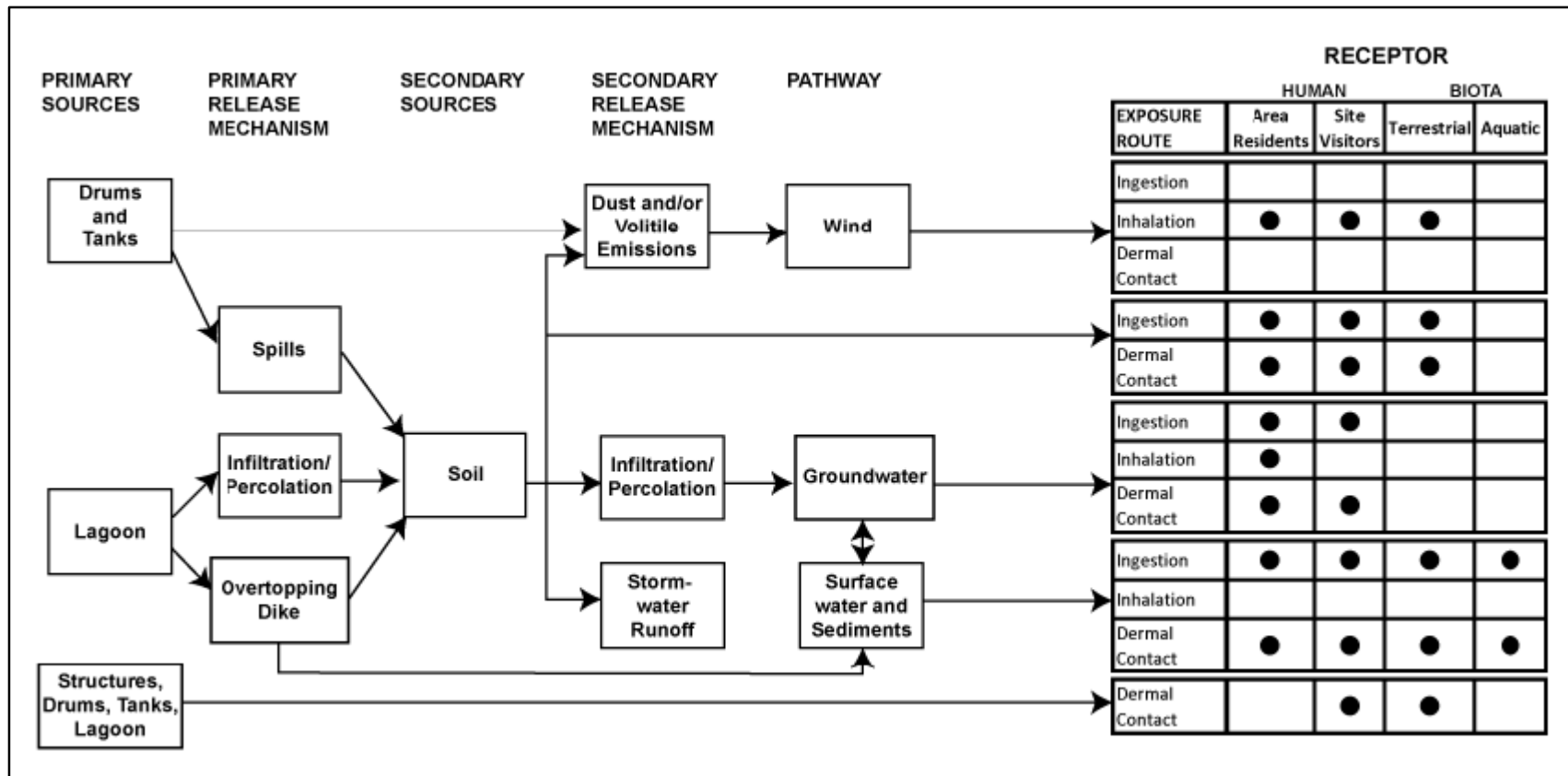


Figure 23: Pathway network receptor diagram, which is commonly used as a CSM to support risk assessment (United States Environmental Protection Agency, 2011).

#### 4.4. Summary: Chapter 4

The objective of chapter 4 is to provide context in line with global and local best management practices and principles associated with coal discard facilities relevant to groundwater impacts and the mitigation and remediation thereof. Insight is given into acceptable and current guidelines and practices. This leads to an overview of industry guidelines and how major mining companies perceive and manage the risk associated with mineral waste production. It is then further narrowed down to the exploration of current best practices associated with coal discard dumps which follows the hierarchy of controls. It starts off with the prevention of the problem down to the least attractive, but probably the most abundant practice, treatment of the symptom. The most attractive options are discussed and entail reducing water flows towards pollution sources whilst concentrating efforts on soil amelioration and rehabilitation. For the treatment of the symptoms, water and soil treatment options are explored in the form of active, passive and in situ treatment scenarios. The importance of assessing risk is mentioned which provides the foundation for the conceptual site model, a main objective and deliverable for the development of the management guidelines as discussed in Chapter 6.

## CHAPTER 5: CASE STUDY

### 5.1. Introduction

The approach presented in this section addresses the key processes that are active underneath coal discard facilities and takes account of the availability and pathways of key contaminants. The assessment will showcase a number of investigations conducted related to groundwater monitoring rehabilitation, surface aesthetics and the objective of mitigating or reducing the impact on groundwater. The link has also been made between the soil and water environments so that contaminated land assessment and remediation should succeed in addressing all potential impacts in one overall risk-based approach.

One site have been selected for this case study and is owned and operated by one of Anglo American Coal SA's collieries. The Springbok 2 coal discard facility is located approximately 25km south of the town of Witbank in the province of Mpumalanga (Figure 24).

For the development of groundwater management guidelines, the Springbok 2 discard facility was chosen and conforms to several of the best practice techniques regarding shape, design and the objective of preventing infiltration and seepage.

The development of the management guidelines were facilitated by the studies and exercises conducted at Springbok 2 discard facility, as well as the best practices and industry standards which were explored in Chapter 4. This holistic guideline is presented in Chapter 6.

*It should be noted that the structure of the case study does not follow a normal site description or hydrogeological study as these parameters are listed as individual parameters which were pursued and developed into a framework which forms part of a management guideline. Therefor chronological order is not of importance for the guideline application.*

#### 5.1.2. Discard Dump Historical Characteristics

The record of rehabilitation history of Springbok 2 discard dump was poorly documented. The grandfather study is the first chronological timeline of its kind for one of Anglo American Coal SA's discard facilities.

Springbok 2 discard dump was formally decommissioned in 1996 after operating from the early 1960's up to the end of 1995 when reworking of materials with ripping and reseeding was started. At the time, the design and civil structures were inadequate to prevent infiltration and increase surface runoff. Historically, the 2 meter thick layer of topsoil on which the discard dump was constructed was

never prepared or compacted, which gave way to a preferred pathway of contaminant migration downstream of the discard dump. Initial rehabilitation efforts left the discard dump with inadequate vegetation cover, severe erosion gullies and acid seepage, which resulted in the redesign and shaping of the discard dump during 1997 from a terrace design to a whale back design. The reshaping was followed by reseeding and application of fertilizer in 1998. The rehabilitation efforts seemed to be successful but continuous seepage was still visible at the toe of the discard dump. This led to the placement of additional soil on top and reshaping the surface to improve surface water runoff and decrease infiltration.

During rehabilitation of the toe seep dam, which was a depository of salts and fines, the material was folded in behind the impermeable pollution control dam (PCD) wall and covered with a layer of approximately 300 millimetres of topsoil from a nearby borrow pit. A considerable amount of toe seep occurred around the dump over the years, which led to the precipitation of salts on surface. In 2012 interception trenches to a depth of 2.5m has been dug on the northern and eastern perimeters of the dump to direct surface and subsurface flow away from the dump. This has substantially reduced the toe seep. Table 13, summarises the monitoring borehole information.

### 5.1.3. Background information

Springbok 2 discard facility is a rehabilitated coal discard dump roughly 60 000 m<sup>2</sup> in size. The dump has been rehabilitated in the 1990's and have been seeping acid water from its toe ever since. It has been established that groundwater as well as surface water infiltration is the cause of the problem at hand. The discard facility currently has a whale back design which shows less of an environmental impact than initial and conventional terrace designed discard dumps.

The dump is underlain by sediments of the Karoo Supergroup. The discard facility is also underlain by a dolerite dyke to the east of SBH06 which resulted in shallow water levels above it (<5 m below surface) and deeper water levels to the west (>10 m below surface). Water levels in the Karoo sequence to the west of the dolerite dyke do not follow the topography and appears to be influenced by mining activities.

At present the permanent installation of clean water interception trenches are being considered to mitigate the precipitation of salts on the western face of Springbok Dump 2. These trenches will intercept clean groundwater before it interacts with the discard facility. In order to ensure that the proposed mitigation will deal with the salt precipitation noticed to the west of the dump, it had to be verified what causes the deposition of salts. The primary source of pollution is the discard dump with a backfilled pollution control dam at the toe acting as a secondary source of pollution.

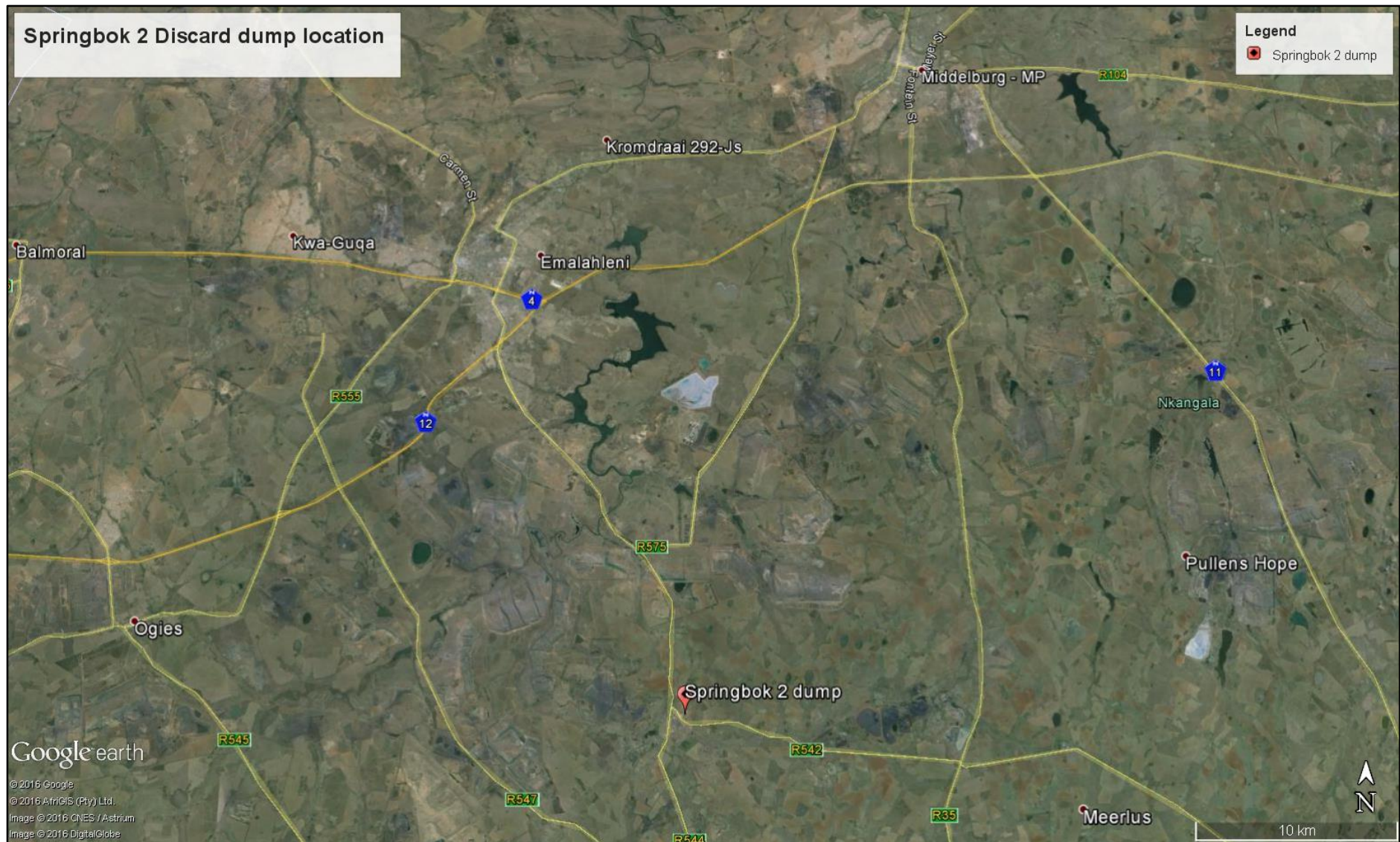


Figure 24: Location of Springbok 2 coal discard dump (Courtesy of Google Earth).

## 5.2. Methodology

The methodologies which were followed during this investigation are quantitative and qualitative in approach. A qualitative assessment of risk is sufficient to identify the key issues at a contaminated site, providing it includes the full range of contaminants encountered, takes account of the direct and indirect exposure pathways and considers relevant receptors. Where the source – pathway – receptor linkage is established, the qualitative approach can usefully provide an initial ranking of risks as a function of site-specific factors. In order to adequately manage a rehabilitated coal discard dump, one needs to implement a comprehensive sampling programme and apply the hierarchy of water management controls. This can only be done with the successful development of a conceptual site model which, in turn, is developed from initial site characterization.

## 5.3. Site Characterization

At the stage of project initiation toe seepage was observed throughout the year with no management measures put in place (Figure 25 (a) and Figure 25 (b)). These figures have been captured during February 2012. Since project inception, a number of specialist studies, drilling and field excavations have been conducted which played a major role in the development of the guideline (Table 6).

For a site to be adequately characterized one first need to determine the characteristics of the rehabilitated discard dump. In order to improve the conceptual hydrogeological understanding, the site history and geology needs to be adequately determined. Uncertainties regarding hydrological parameters and chemistry needs to be addressed to obtain a holistic picture. Should there be shortfalls on these points, one needs to conduct intrusive studies based on gaps or shortfalls. Should these parameters be sufficient, it enables the development of a conceptual site model.





**Figure 25: The original state of the rehabilitated Springbok 2 coal discard facility during February 2012 (top image-side view, bottom image – plan view).**

**Table 6: Summary of specialist studies conducted at Springbok 2 discard dump, value and reference.**

<b>Activity</b>	<b>Value added</b>
Desktop and field studies	Obtain historical plans, rehabilitation efforts, soil types
Water and soil quality analysis	Establish baseline and extent of pollution impact
Acid base accounting	Determine acid generating potential
Auger holes	Depth to vadose zone (CSM)
Geophysical study	Extent of conductive zone (pollution plume)
Installation of monitoring boreholes inside dump	Water quality and water level inside dump, inform CSM and interception trench installation
Hydrogeological study	Determination of flux and effectiveness of interception trenches, result in conceptual pollution mitigation options (Table 11)
Options analysis and risk assessment	Cost vs value add
Temporary north and southeast trench installed	Interception of clean water prior to contamination
3 Piezometers installed Indicated as P1A, P2A and P3A	Water level inside discard dump
5 Water monitoring boreholes installed SBH01, SBH03, SBH04, SBH05, SBH06	Confirm water levels, qualities and lateral extent of pollution
5 Zones of improvement identified	Surface and groundwater improvement, aesthetics
Grandfather study	History of dump design, construction and operation, timeline of events

### 5.3.1. Springbok 2 dump characteristics

#### Objective:

Determination of the discard dump characteristics is needed to produce the foundation for the CSM. It also improves the conceptual hydrogeological understanding of the processes involved in the rehabilitated coal discard dump.

#### Considerations:

To address the objective of characterizing the discard dump the following parameters were identified and investigated:

1. Chemical and Mineralogical analysis.
2. Presence of thermal activities.
3. Particle size distribution.
4. Degree of saturation.
5. Presence of liners or underdrainage systems.
6. Design and rehabilitation criteria.
7. Obtain all available maps, plans and photos.

#### Results:

With project inception there was no available water and soil quality analysis. Water quality analysis was done on 5 drilled boreholes around the discard facility to establish the baseline and extent of pollution impact. Water quality was analyzed on a monthly basis from 2012 to date in order to build up a database which will inform the approach to be taken with remediation techniques. Table 8 indicates the average water quality for the period 2012 to 2016.

Excavations on the toe of the dump was done to determine the presence of thermal activities (absent) and to investigate particle size distribution. It was found that the particles distribution is highly variable due to the placement of coarse and fine discard during operation. Reference to particle size distribution is made in figure 27. This practice makes obtaining representative chemical sampling of the host material very difficult. The degree of saturation was informed by the drilling of 3 boreholes into the dump to determine the saturation of the discard.

No liners or underdrainage was installed when the dump was constructed. However, the approximately 2 m thick unconsolidated soil zone beneath the dump acts as a permeable layer transporting recently recharged water above the relatively impermeable weathered Bainsvlei soils.

Design and rehabilitation criteria was discussed in section 5.1.2. as part of the historical characteristics. Relevant photos and maps are included and discussed in more detail in the grandfather study.

### 5.3.2. Site Geology

#### Objective:

Determination of the site geological conditions is needed to produce a geological model (in this case CSM), sight water monitoring and geological drill holes and to improve the general hydrogeological understanding by taking cognisance of the rehabilitated discard dump characteristics which was determined in the previous section.

#### Considerations:

To address the objective of determining the site geological conditions, the following parameters were identified and investigated:

1. Soil assessments and porosity.
2. Mine geological logs.
3. Geophysical surveys – Electromagnetic and Magnetic.

#### Results:

The soil assessment was done internally by the Anglo American Coal SA land manager. It was found that the same soil present around the discard dump was used for rehabilitation purposes. The soil was classified as a weathered Bainsvlei soil with moderate compaction.

The geology across Mpumalanga is not very diverse and consists mainly of three to four main lithological units.

The occurrence and movement of groundwater, as well as the groundwater quality, are functions of the geological host rock in which the groundwater occurs, including the alteration thereof as a result of human activities, such as mining.

The study area is underlain by the Vryheid Formation of the Karoo Supergroup, where the rocks are primarily asymmetrical. The Vryheid formation rests directly on the Dwyka Group and gives rise to variations in thickness.

Reference can be made to appendix B which indicates the geological logs for drill holes GHC6890 and GHC6891 which were used to describe the geology. The soil consists initially of a brownish clayey soil and a reddish clay layer directly underneath the soil. This clayey soil and clay layer stretches between 4 to 6 meters below the surface according to the auger holes and test pits around the discard dump.

The geology underlying the clayey soil and clay layers consist of sedimentary units of the Vryheid Formation of the Ecca Group. The Dwyka Formation comprises consolidated products of glaciation (with high amounts of clay) and is normally considered to be an aquiclude. The Ecca Group comprises of sediments deposited in shallow marine and fluvio-deltaic environments with coal accumulated as peat in swamps and marches associated with these environments. The sandstone and coal layers are normally reasonable aquifers, while the shale serves as aquitards. Several layered aquifers perched on the relative impermeable shale are common in such sequences.

The aquifer that occurs at Springbok 2 is formed in the weathered zone and is also perched on fresh bedrock, this lead to the belief that a shallow weathered/ perched aquifer occurs here. This aquifer is classified within the weathered and weathering related fractured zone of the Vryheid Formation host rock matrix. The aquifer stretches across the entire study area and varies in thickness and extends down to about 10 meters. This top most section is comprised of transported colluvium and weathered sediments, which overlays consolidated sedimentary rocks. Groundwater occurring in these types of aquifers has a tendency to follow the pattern of the topography and may lead to springs forming at topographic lows in some instances.

Due to the top part of the aquifer being very weathered at Springbok 2 discard dump, the top part of the unsaturated zone can be defined by the land surface. The bottom of the unsaturated zone in turn is defined by the top of the groundwater table, thus the unsaturated zone can be defined as being the distance between the land surface and the groundwater table. This zone of the study area is between 10 meters and 30 meters thick, based on the groundwater levels measured in some of the existing boreholes. The top of the aquifer consists of colluvial sediments and is underlain by sandstone, siltstone and/or mudstone of the Ecca group. This residual material becomes less weathered to a depth of about 5m and consists of eolian sand and is followed by complete- to moderate weathered Ecca sediments, to a depth of 10m.

The top of the saturated zone is defined by the groundwater table. The bottom of the saturated zone is seen at the start of the fresh bedrock interface. The saturated thickness is estimated by subtracting the ground water level from the top most part of the fresh bedrock contact. The ground water table varies between 5 to 15 meters and the contact of the fresh rock from 10 to 30 meters.

The exact thickness of the saturated zone cannot be calculated, due to the lack of information of the specifics of the boreholes. However it can be deduced that the saturated zone can stretch from 5m to 25m.

Nine traverse lines (figure 26) were geophysically surveyed with the magnetic and electromagnetic methods. These techniques were employed to locate and delineate any possible geological features as well as to identify high conductivity zones that might indicate the presence of a pollution plume.

The objective for the magnetic method was to locate and delineate any possible magnetic structures e.g. dolerite dykes that may be present in the survey area. The objective for the electromagnetic survey was to accurately locate and delineate high conductivity areas associated with deeply weathered bedrock conditions that could act as possible trap sites or conduits for polluted groundwater.

For the magnetic method a Geotron G5 Proton magnetometer, which measures total field, was used for the survey. Magnetic data was collected on 9 lines and readings were taken at 10m station intervals.

For the electromagnetic method a GEONICS EM 34-3 frequency domain instrument was used during the survey. The 20-meter coil separation was used to collect data at 10-meter intervals along 9 traverses. Readings were taken both in the horizontal and the vertical dipole modes.

The magnetic method has successfully located and delineated magnetic structures in the survey area (Figure 27).

The electromagnetic method has successfully located and delineated high conductivity zones possibly associated with deeply weathered bedrock conditions acting as trap sites or conduits for polluted groundwater (Figure 28). The presence of fences, railway and power lines affected the geophysical readings. No maps of buried services were available for any of the sites. Borehole positions were sited on high conductivity values from the electromagnetic, horizontal dipole data.



Figure 26: Geophysical traverse positions for Springbok 2 discard dump.

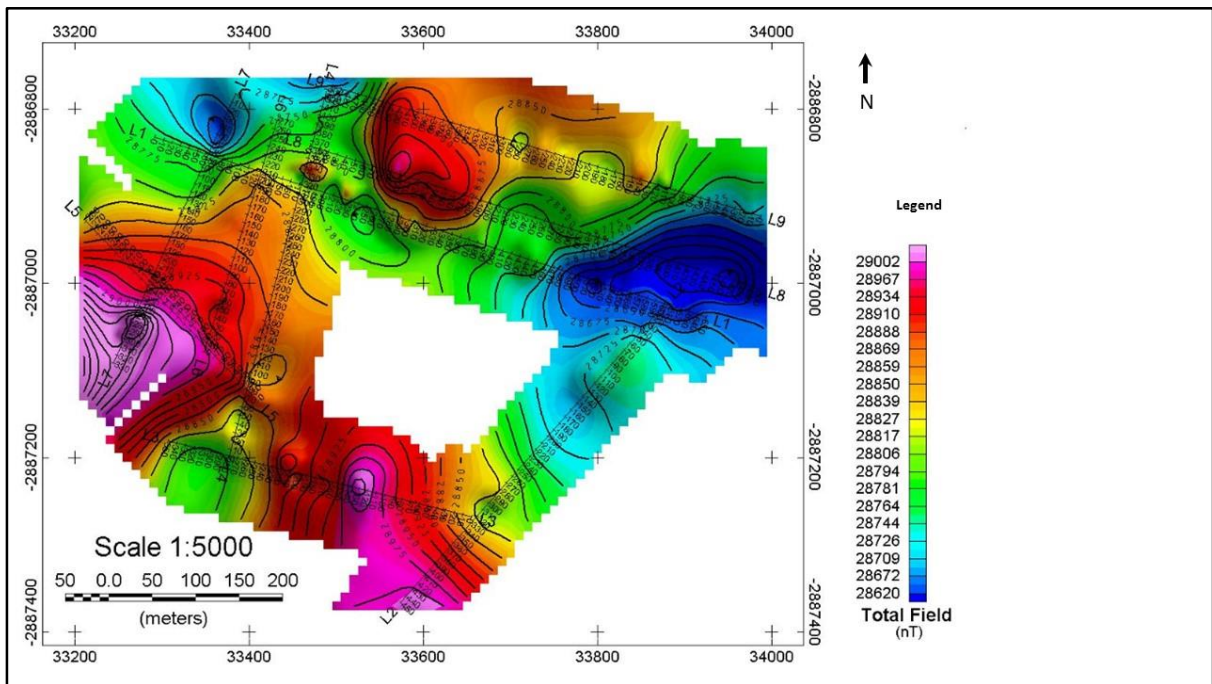
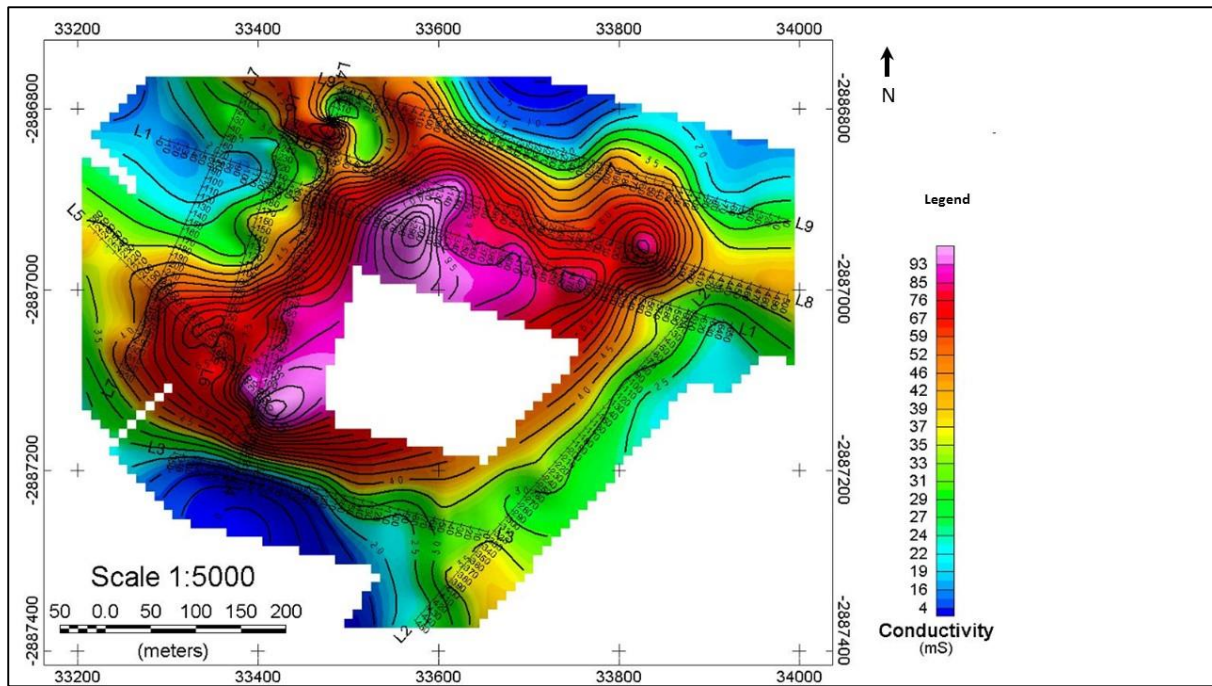


Figure 27: Delineation of magnetic structures at Springbok 2 discard facility.



**Figure 28: Delineation of high conductivity zones at Springbok 2 discard facility.**

The electromagnetic method has successfully located and delineated high conductivity zones possibly associated with deeply weathered bedrock conditions acting as trap sites or conduits for polluted groundwater. However, the presence of fences, railway and power lines affected the geophysical readings and no maps of buried services were available for any of the sites. Borehole positions were sighted on high conductivity values from the electromagnetic, horizontal dipole data. These boreholes are plotted on figure 31. The white block in the centre has not been covered by the traverses as it is the discard dump area.



### 5.3.3. Determination of Site History

#### Objective:

Determination of the site history is needed to produce a grandfather study and improve the conceptual hydrogeological understanding. The grandfather study is a timeline of chronological events. In most cases old rehabilitated coal discard dumps have very little documentation (which was the case with Springbok 2 dump) available on chronological events and it is necessary for the investigator to go beyond a simple desktop study and engage with historical sources of information.

#### Considerations:


To address the objective of determining the site history, the following parameters were identified and investigated:




1. Historical maps and plans.
2. Historical aerial photographs.
3. Discussions with previous employers.
4. Presence of infrastructure and historical mine workings.




#### Results:




The following table (Table 7) represents the timeline which has been built for Springbok 2 discard dump and will also be highlighted in Chapter 6 as a key component to the guideline for management of groundwater in and around coal discard facilities. The grandfather study focusses on the timeline 1990 to 1999 which shows the operational and rehabilitation phases. Post 1999 no actions were taken to monitor or maintain the facility, until 2009 when the desktop studies were initiated.




**Table 7: Grandfather Study timeline of the construction and rehabilitation of Springbok 2 coal discard dump.**



Date	Action	Photos
1960's	Springbok 2 discard dump constructed. Operated up to 1996.	No image available.
1995	Springbok 2 still operational, rehabilitation started on certain sections. Toe seep dam present.	
1996	Springbok 2 discard dump formally decommissioned. No rehabilitation scheduled as budget included pure decommissioning costs like removal of infrastructure.	No image available.



<p>1997</p>	<p>Rehabilitation commenced, drainage of Springbok 1 pollution control facility.</p>	
<p>1997</p>	<p>Toe seep dam wall breached to drain toe seep dam.</p>	
<p>1997</p>	<p>Drainage of toe seep dam.</p>	

<p>1997 / 1998</p>	<p>Springbok 2 rehabilitation commence, shaping of dump; toe seep dam wall folded in. Both sites were treated with lime before subsoil was added.</p>	
<p>1998</p>	<p>Toe seep dam outer wall was folded in and covered with topsoil. Surface of toe seep area show evidence of being moist during topsoil placement.</p>	
<p>1998</p>	<p>Placement of topsoil and shaping.</p>	




<p>1998</p>	<p>Subsoil placed was severely compacted. This assisted with deferring minimising water infiltration.</p>	
<p>1998</p>	<p>Material was obtained from a nearby borrow pit to the north of the dump and placed ~300 mm thick.</p>	
<p>1998</p>	<p>Ripping was done with a grader and contributed to compaction of placed soil.</p>	

<p>1998</p>	<p>Topsoil shaping completed.</p>	
<p>1998</p>	<p>Lime application on top of topsoil.</p>	
<p>1998</p>	<p>Lime application extending north where fine discard material was originally placed. This explains the current situation of soil burn and lack of vegetation as there are still remaining discard material left behind.</p>	

<p>1998</p>	<p>Dump seeded; black lines indicate irrigation system installed.</p>	
<p>1998</p>	<p>November of 1998 shows vegetation growth on the dump. It also indicates a clear seepage line as seen today (15 years later). Erosion is evident. It is evident that vegetation did not establish itself on the pollution control dam and from the first and third picture one can see trees that have died which were not the case earlier as seen on previous images.</p>	

		
<p>1998</p>	<p>Southern side of dump is indicative of minor erosion and initial vegetation establishment, no acid seep visible. Northern side indicates good vegetation growth with no visible signs of acid seep.</p>	



<p>1998</p>	<p>Good initial growth of vegetation on northern and eastern slopes.</p>	
<p>1999</p>	<p>Good growth of vegetation on dump slopes.</p>	
<p>1999</p>	<p>March 1999 indicates well established cover on dump, side slopes</p>	

1999

March 1999 also indicative of pollution and salt precipitation towards the road in line with the current acid seep.



### 5.3.4. Determination of Hydrological and Geochemical parameters

#### Objective:

Determination of the site hydrological and geochemical parameters are needed to improve on the current conceptual hydrogeological understanding and to inform the selection of the hierarchy of water management controls (pollution prevention, pollution minimization, treatment).

#### Considerations:

To address the objective of determining the site hydrological and geochemical parameters, the following parameters were identified and investigated:

1. Site surface contours.
2. State of current rehabilitation.
3. Site meteorological data.
4. Identification of surface water bodies.
5. Chemical and Mineralogical analysis.
6. Geochemical testing like acid base accounting.

#### Results:

##### **Site Meteorology**

Site surface contours play a role in the determination of site topography and surface drainage. There is no specific contour spacing required as it will merely provide a general idea of slope and where water will drain towards. It is acceptable to use the contour data in a format which the investigator can understand and use.

The state of rehabilitation was done as part of the soil assessment which concluded that the discard dump was adequately rehabilitated and vegetation cover exceeds 90%.

Springbok 2 discard facility falls within the Highveld-Type climate, with hot and humid summers and cold and dry winters. Rain gauges at the mine indicates a mean annual precipitation (MAP) that ranges between 620 and 750 mm/annum. Rainfall in this area typically occurs in the form of thunderstorms during the summer months.

Springbok 2 discard facility falls within the Olifants Water Management Area (WMA) and is sub divided into the Quaternary catchment, B11G. The Mean annual run-of ranges between 1 million  $m^3$  and 14

million  $m^3$ . The Mean annual Run-off for the Primary Catchment, the Olifants catchment, is estimated to be between 2386 million  $m^3$ /annum and 3360 million  $m^3$ /annum.

Surface drainage occurs from east to west and in turn drains in a south, south-western direction. The Mean Annual Recharge (MAR) to the groundwater system of the study area is estimated to be between 37mm and 50mm per annum, which relates to about 6.5% of the mean annual rainfall (MAP). The groundwater contribution to surface stream base flow is relatively low, estimated between 10mm and 25mm per annum.

The recharge to the shallow weathered zone aquifer at Springbok 2 discard facility occurs primarily through infiltration of rain water and surface water bodies. Although no aquifer recharge tests were conducted during the field investigation, recharge in similar aquifers has been calculated to range between 1% and 3% of the Mean Annual Precipitation.

Previous recharge tests using the Chloride method done on the aquifers within the study area indicate that the recharge to the shallow weathered zone aquifers is estimated to vary between 2% and 3.5% of the MAP, which accumulates to 17.38 and 24.33 mm/annum.

No surface water bodies are present at Springbok 2 discard dump, but applying the guideline the investigator would need to investigate surface water systems and its proximity to a rehabilitated coal discard facility as surface water systems are a regular receptors of seepage from any form of discard facility.

### **Groundwater Quality**

The current groundwater quality will be discussed with reference to the boreholes which were drilled at Springbok 2 discard facility.

The boreholes used to describe the groundwater quality of Springbok 2 discard facility are BH1, BH3, BH4, BH5 and BH6. The positions of these boreholes relevant to Springbok 2 are presented in figure 29 below.



**Figure 29: Location of monitoring boreholes around Springbok 2 discard facility.**

The chemistry of these boreholes with reference to SANS241: 2006, Drinking Water Standard follows below in table 8.

**Table 8: Average water qualities associated with the Springbok 2 discard facility.**

Mg/l	BH1	BH3	BH4	BH6	BH5	Northern Trench	SANS241 max allowable
pH	3.09	3.57	7.46	6.75	3.21	5.58	4-10
EC (ms/m)	1946	48.3	48.7	37.5	202	118	150-370
TDS	35138	354	342	248	1728	908	1000-2400
Total Alkalinity	Nil	Nil	151	86	Nil	6	NA
Total Acidity	15680	97.6	8.19	17.8	290	14.3	NA
Ca	370	18.1	36.8	33.6	193	85.9	150-300
Mg	2664	21.8	20.4	13.5	123	61.1	70-100
K	12.2	4.58	7.50	5.39	11.0	6.29	50-100
Na	48.9	17.6	33.5	21.8	22.8	82.8	200-400
SO4	27217	231	109	87.9	1223	624	400-600
Cl	7.0	8.0	12	17	9.0	19	200-600
P	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	NA
NH3	1.90	<0.20	0.44	0.32	1.46	1.10	1-2
N	<0.1	1.22	1.00	0.34	0.44	0.63	10-20
Fe	7147	17.2	0.2	0.08	49.3	0.06	200-2000
Mn	517	3.4	0.25	0.77	9.56	3.02	100-1000
Al	903	0.96	0.06	0.05	2.66	0.57	300-500
B	6.36	<0.01	<0.01	<0.01	0.08	<0.01	NA

BH1 and BH5 are non-compliant with most of the standards set for the different elements. These boreholes are situated to the West and North-western direction from Springbok 2 discard facility. TDS and SO<sub>4</sub> values are extremely high in BH1 and BH5.

## **Geochemistry**

The geochemical work had the following objectives:

- To assess the ARD potential of the PC Dam sediments and discard; and

The geochemical work conducted will serve as supporting information for the remediation option(s) for the Discard Dump and PC Dam.

The tasks comprising the ARD assessment were:

- Laboratory test work: The samples were submitted for the following static geochemical tests:
  - Distilled water shake flask tests (1:2 solid to liquid ratio) - the extracts were quantified for chemical parameters (pH, TDS, EC, Alkalinity), major anions (SO<sub>4</sub>, Cl, NO<sub>3</sub>), major metals (Ca, Mg, K, Na and Fe and trace metals.
  - Mineralogical (XRD) tests; and
  - Acid-Base Accounting (ABA) with sulphur speciation.

Five (5) discard samples and two (2) sediment samples were from the Springbok 2 Discard Dump and PC Dam respectively (figure 30). The samples were taken using hand augers and test pits excavation. Standard sample collection, storage and transport protocol was followed. Table 9 below documents the samples collected and field observations.



**Figure 30: Location of sample sites for geochemical analysis.**

**Table 9: Samples collected for geochemical analysis.**

Sample Location	Sample Name	Depth (m)	Sampling Methodology
Springbok 2 Discard Dump	GHS07 0.4m-0.8m	0.4 - 0.8	Hand auger
	GHS07 0.8m-1.15m	0.8 - 1.15	
	GHS07 1.15m-2.0m	1.15 - 2	
	GHS08 0.4m-0.8m	0.4 - 0.8	
	GHS08 0.8m-1.7m	0.8 - 1.7	
Old PC dam	GHTP1.1	0.85 -1.2	Excavator
	GHTP1.2	1.2 -1.7	

Static geochemical tests were conducted for selected individual and composite samples. The detailed laboratory certificates for all analysis is present in appendix A.

### *X-Ray Diffraction (XRD)*

Table 10 presents the XRD results for the GHTP 1.2 (collected at 1.2 m to 1.7 m depth).

**Table 10: XRD analysis for sample GHTP 1.2.**

<b>Mineral</b>	<b>Composition (%)</b>
Gypsum	17
Jarosite	48
Quartz	29
Kaolinite	6.0
Total	100

The XRD results revealed the presence of secondary minerals (Gypsum, Jarosite and Kaolinite). Jarosite is the dominant secondary mineral formed by oxidation of primary reactive sulphide minerals like pyrite and or pyrrhotite. The presence of fast reacting neutralising minerals such as calcite and dolomite was not detected. The presence of sulphide minerals in the sediments was not detected by XRD. The sulphide mineral is likely to be present below the detectable limits (1 %); and Gypsum was observed indicating geochemical solubility controls for dissolved Ca and SO<sub>4</sub> concentration in the seepage.

### *Acid-Base Accounting and Sulphur Speciation*

The Acid-Base accounting (ABA) method compares the potential for acid generation relative to the total available alkalinity in a sample. The Acid Potential (AP) can be determined from either; the total sulphur content of a sample based on the assumption that the total sulphur content is equal to the reactive sulphide sulphur and is termed Total Acid Potential (TAP) or from the sulphide sulphur content and is termed Sulphide Acid Potential (SAP).



Table 11 displays the summary of ABA results and sulphur speciation results for the Springbok 2 samples.

**Table 11: ABA results for Springbok 2 samples**

Sample Name	Paste pH	Total Sulphur	Sulphide ( $S^{2-}$ ) Sulphur	$SO_4$ Sulphur	Total Acid Generation Potential (TAP)	Sulphide Acid Generation Potential (SAP)	Neutralisation Potential (NP)	Nett Neutralisation Potential (NNP)
Units	s.u	%	%	%	kg $CaCO_3$ /t	kg $CaCO_3$ /t	kg $CaCO_3$ /t	kg $CaCO_3$ /t
GHS 07 0.4m - 0.8m	2.8	1.2	N/A	N/A	38	N/A	0	-38
GHS 07 0.8m - 2.0m	3.2	2	N/A	N/A	63	N/A	0	-63
GHS 08 0.4m - 1.7m	2.4	2.9	N/A	N/A	90	N/A		
GHS 07 1.15m - 2.0m	N/A	2.1	0.21	1.5	66	6.6	0	-66
GHTP 1.1 0.85m – 1.2m	2.6	0.9	0.04	0.82	27	1.3	0	-27
GHTP 1.2 1.2m – 1.7m	2	4.9	2.9	1.9	152	91	0	-152

The following can be concluded from Table 11:

- The paste pH for the discard and the sediments samples are acidic (2.0 – 3.2 pH units);
- The sulphide- sulphur content from the same test pit in the PC Dam samples differ by an order of magnitude at depth;
- The Total Acid Potential (TAP) and Sulphide Acid Potential (SAP) of the tailings samples were found to range from 27 to 152 kg/t  $CaCO_3$  and 1.3 to 91 kg/t  $CaCO_3$  respectively. The TAP is conservative since it is calculated using the total sulphur contents rather than the sulphide content which is used for calculating the SAP;
- The Neutralising Potential (NP) was found to be 0 kg/t  $CaCO_3$  and indicates no available neutralising minerals present during the analysis; and
- The negative Nett Neutralising Potential NNP (-0.38 to -152 kg/t  $CaCO_3$ ) indicates that these samples have a potential to generate acidic drainage and that there is insufficient availability of neutralising minerals to buffer acid generation.

### Distilled water shake flask tests

Distilled extraction requires that a sub-sample of material is reacted with deionised water (pH 5.5) to assess the likely mobilisation of potential contaminants from the PC Dam and Discard Dump material by infiltrating rainfall. The test involves continuous shaking (16 hours) of 500 g of sample with 1000 ml of distilled water. The resulting (distilled water) extract was quantified for the constituent of concern. Shake flask test results were conducted for one Discard Dump sample (GHS 07 1.15 – 2m) and one PC Dam sample (GHTP 1.2). Distilled water was used to extract soluble constituents. The results are summarised in Table 12.

**Table 12: Summary of distilled water and seepage analysis results.**

Parameters	Units	Discard dump	PC dam	
		GHS 07 1.15 - 2m	GHTP 1.2	Seepage GHTP6
pH	pH Unit	2.5	2.2	3.4
Suspended Solids	mg/l	N/A	N/A	1840
TDS	mg/l	8680	10438	67650
SO <sub>4</sub>	mg/l	7024	7993	44215
Al	mg/l	208	351	937
Ca	mg/l	492	492	286
Co	mg/l	0.3	4.2	N/A
Cr	mg/l	0.2	0.1	N/A
Cu	mg/l	0.3	0.2	N/A
Fe	mg/l	350	267	>1000
Mg	mg/l	579	543	3923
Mn	mg/l	25	149	202
Na	mg/l	3	4	82
Ni	mg/l	0.3	1.4	N/A
Pb	mg/l	0.06	0.06	N/A
Zn	mg/l	1	1.3	N/A

It is evident from Table 12 that the seepage emanating from the PC Dam and Discard Dump is acidic. The seepage water collected from the test pit is also acid. The suspended solid in the seepage is an indication of the mixing effects or dissolution of secondary mineral occurring in the pore spaces of the PC Dam (Table 10). The SO<sub>4</sub> concentration (7 000 mg/l to 8 000 mg/l) in shake flask extract is an order of magnitude lower than the seepage sample collected from the PC Dam (44 000 mg/l). Assuming a field capacity of 33% (or 1:3 liquid to solid ratio) for the discard dump, then multiplying the extract concentration by a factor of six to consider the shake flask test and field capacity solid to liquid ratio; the seepage from the Discard Dump is estimated as 42 000 mg/l to 48 000 mg/l.

The metals contributing to the salt load of the extracts from the tailings samples are Al, Fe, Mn; Ca; Mg and Na. Trace metals contributing to the salinity are Pb, Ni, Cr, Cu and Co. The seepage sample collected from the test pit gives an indication of the interstitial pore water seeping from the PC Dam into the receiving environment. The elevated dissolved ion concentration in the seepage is an indication of ARD. It is likely that during sampling dissolution of secondary minerals could have occurred resulting in a higher dissolved concentrations in the seepage sample collected. Jarosite, Gypsum (Table 10) and other Fe hydroxide minerals are the geochemical controls that will limit the dissolved Fe, Ca and SO<sub>4</sub> content in the seepage. This can be confirmed by geochemical modelling which was not conducted as part of this work.

### *Geochemical conclusions*

From the test work it can be concluded that:

- The ABA results indicate the paste pH of the discard and the sediments is acidic. The samples were observed to have a negative Nett Neutralising Potential NNP (-0.38 to -152 kg/tCaCO<sub>3</sub>) implying that these samples have a potential to generate acidic drainage and that there is insufficient availability of neutralising minerals to buffer acid generation;
- The total sulphur for the samples is 0.9% to 4.9%. Sulphur speciation for one sample from the Discard Dump was found to have 0.21 % sulphide content.
- The test pit in the PC Dam was found to have a variation in the sulphide sulphur content with depth. The lower sulphide sulphur percent in sample GHTP 1.1 (collected at depth 0.85 m to 1.2 m) is due to a higher oxidation rate compared to the sample (GHTP 1.2) collected at 1.2 m to 1.7 m;
- The discard shake flask results and seepage collected from the test pit was found to be acidic (2.2 to 3.4) with elevated SO<sub>4</sub> concentration (42 000 mg/l to 48 000 mg/l) and indicates that ARD has happened and could continue based on the sulphide- sulphur content of the discard and sediments;
- XRD results indicated the presence of secondary minerals (Jarosite and Gypsum) in the PC Dam sediments. The presence of secondary minerals is indicative of the first stage of mine site drainage. The second stage occurs when all the reactive primary sulphide minerals have either dissolved or dissolve at negligible rates.

### 5.3.5. Intrusive Studies

#### Objective:

Intrusive studies can take place at any given time during site characterization. Albeit sufficient boreholes or test pits, other studies like geophysics, site history, dump characteristics, geochemistry or hydrogeological information, there may be a requirement for additional intrusive studies. Intrusive studies are needed to produce soil profiles and geological logs. It also enables the determination of quality of rehabilitation, groundwater depth and groundwater quality. It enables the establishment of dewatering, should it be required, enables soil and water sampling and improves the conceptual hydrogeological understanding of the site.

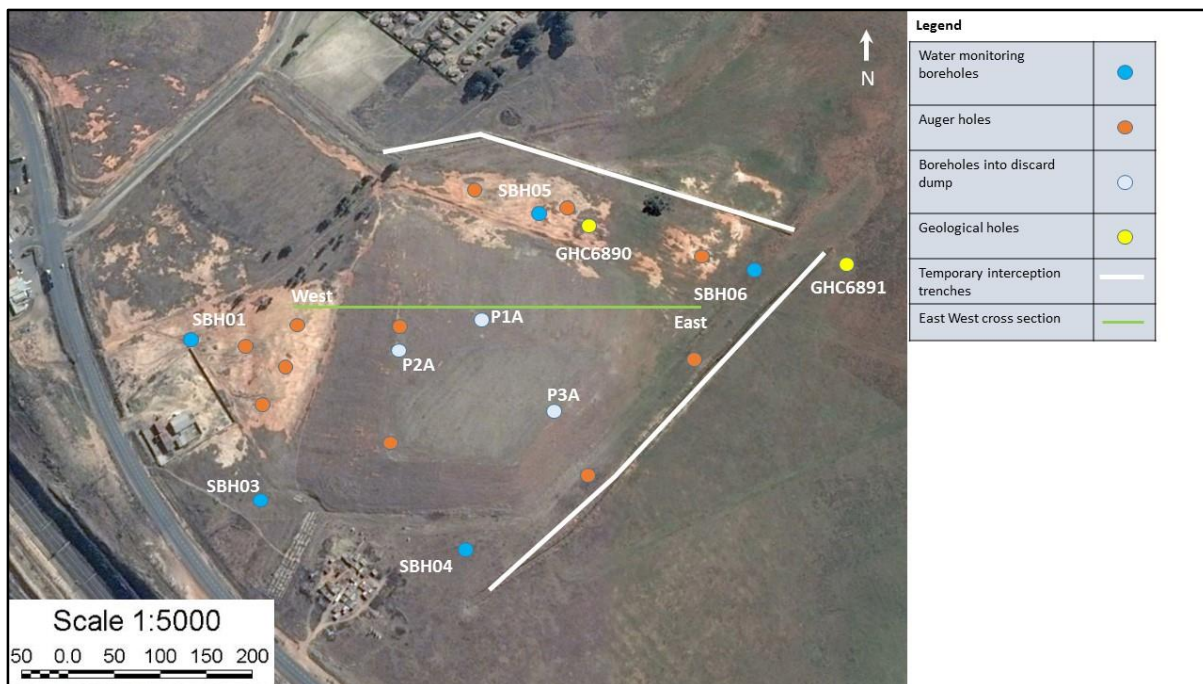
#### Considerations:

To address the objective of enabling intrusive studies, the following parameters were identified and investigated:

1. Test pits and soil profiling.
2. Auger holes.
3. Drilling of boreholes based on geophysics.

#### Results:

Figure 31 indicates the auger holes (orange dots) which were augered to establish the depth to the vadose zone as well as the collection of samples for geochemical testing. The auger holes were positioned around the outer perimeter of the discard dump. The auger holes were placed along the source and pathway of the pollution source. The monitoring boreholes are indicated as SBH01, SBH03, SBH04, SBH05, SBH06. These boreholes were sighted based on the geophysical survey results. The boreholes drilled into the dump are indicated as P1A, P2A and P3A. These boreholes were sighted according to coal floor contours which mimic surface contours. Table 13 summarises the borehole information. The white lines indicate the trenches which were installed which captures clean groundwater and a portion of surface runoff before it comes in contact with discard material. The shaded area associated with SBH01 shows the extent of pollution which were observed on surface prior to the installation of the interception trenches. Section E-W is shown in figure 28. The outputs from intrusive studies have been covered in the previous sections.



**Figure 31: The current state of the rehabilitated Springbok 2 coal discard facility (plan view). June 2016.**

Test pits, auger holes and drilling enabled the establishment of a general soil profile across the site, this is indicated by figure 32 below. This profile was also used in a seepage model to determine flux underneath the Springbok 2 discard dump.

**Table 13: Summary monitoring borehole information.**

Monitoring Point	X Coordinate	Y Coordinate	Elevation (mamsl)	Collar Height (m)	Depth of Water Level (m) Average 2012-2015	Water Level Elevation (mamsl) Average 2012-2015
P2A	33527.93	-2886755.78	1581.88	0.65	12.40	1568.83
P1A	33604.67	-2886714.56	1581.47	0.21	11.23	1570.03
P3A	33694.38	-2886801.46	1584.23	0.40	10.73	1573.10
SBH04	33559.73	-2886987.20	1572.50	0.68	12.13	1559.69
SBH05	33852.15	-2886654.61	1574.99	0.38	3.51	1571.10
SBH06	33611.76	-2886600.79	1569.74	0.54	2.86	1566.34
SBH01	33322.12	-2886750.91	1561.13	0.48	17.92	1542.73
SBH03	33393.48	-2886918.80	1566.76	0.74	15.43	1550.59
GHC6890	33548.00	-2886598.00	1568.79	Exploration Boreholes (core holes)		
GHC6891	33682.00	-2886616.00	1571.58			

	>90% effective cover with minimal erosion patterns visible	Thickness not assigned. Root penetration of 50-150mm according to Land management specialist.
	Top layer of cover	100-300mm. Cover not uniform over total area.
	Bottom layer of cover	100-300mm. Cover not uniform over total area.
	Coal discards	<p>1. Thickness variation from &lt;1m around toe to approximately 20m in centre of dump. Site specific information used, where available.</p> <p>2. Slurry disposal from fines dam in front of toe (where slurry disposal was done separate or combined).</p> <p>3. Fractions assumed to be 5-75mm for co-disposal and 25-75mm for discard disposal.</p> <p>4. Surface contact distribution areas estimated.</p>
	Compacted footprint	Assumed compacted footprint ( $10^{-6}$ cm/s).

**Figure 32: Conceptual soil profile used in seepage calculation.**

To determine the flux underneath Springbok 2 discard dump, the model calculated flux uniformly over the dump. Please note that site rainfall conditions were used for ease of reference.

Results of the seepage calculation is as follow:

- Volume of discard dump seepage:  $12.1 \text{ m}^3/\text{d}$
- Volume of groundwater seepage:  $7.3 \text{ m}^3/\text{d}$
- Total seepage:  $19.4 \text{ m}^3/\text{d}$
- Total seepage percentage (Dump/groundwater): 62:38

From the results above, it can be concluded that the dump seepage calculated is the volume of ground water that will be captured at the toe of the dump if all water can be intersected at the down-gradient side of each dump.

Should groundwater be intercepted above the discard dump, the following will apply:

- 1 meter deep trench will capture 59% of groundwater seepage.
- 1.5 meter deep trench will capture 70% of groundwater seepage.
- 1.8 meter deep trench will capture 86% of groundwater seepage.

A 1.8 meter deep trench was seen as the most optimal in terms of effectiveness vs cost. The effectiveness only exceeds 90% once the trench/drain is some 3.7 meters deep. In order to capture all groundwater seepage (upstream and downstream from the dump) a trench/drain in excess of 6 meters deep is required which is simply not practical.

#### 5.4. Conceptual Site Model (CSM)

For the development of the CSM the case study was used to develop site characterization. The site characterization comprises of discard dump characteristics, geology, site history, geochemical and hydrological parameters and intrusive studies. The assimilation of this information informs the development of the CSM.



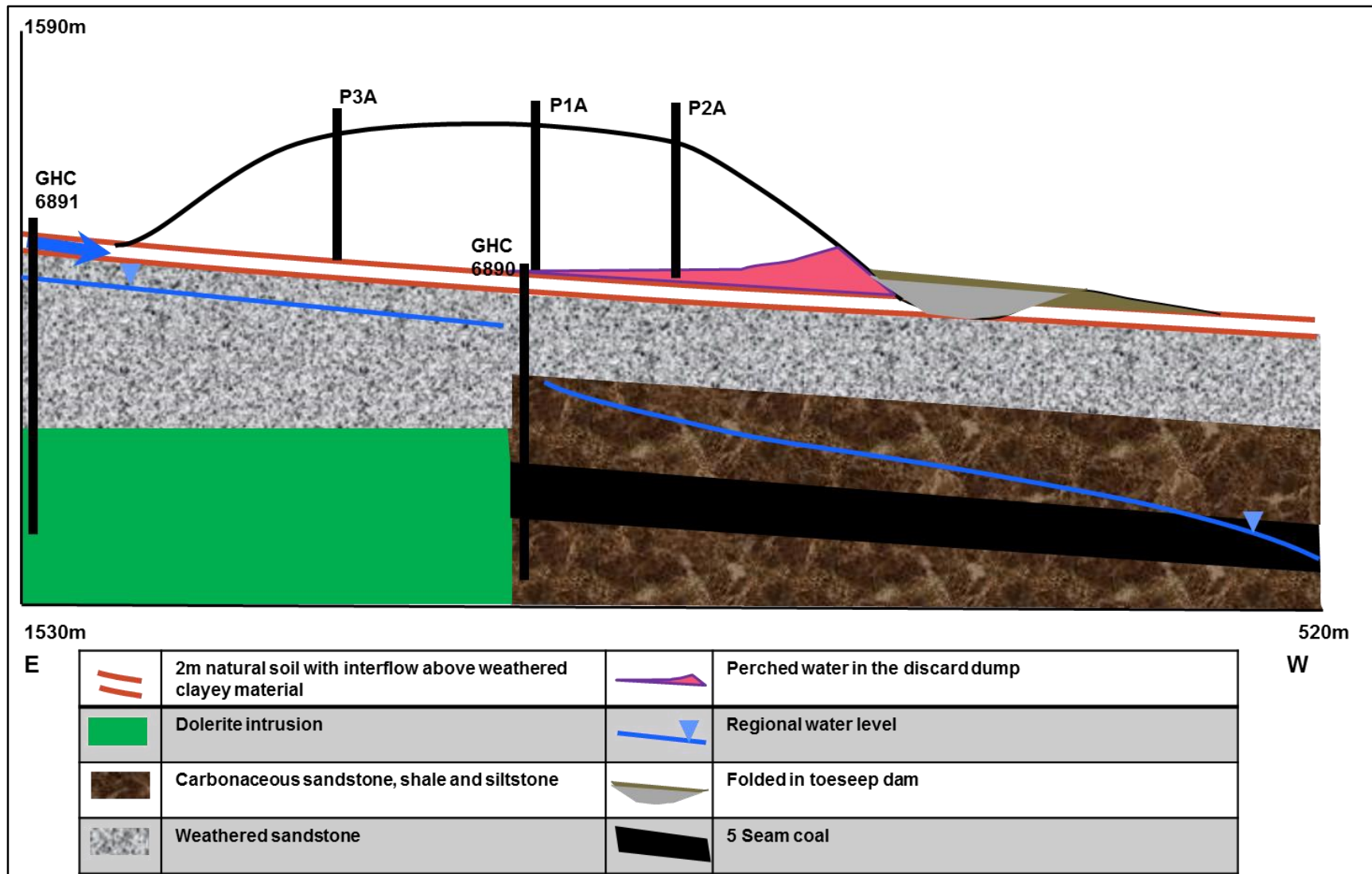


Figure 33: CSM based on site characterization. Section Line E-W is shown on figure 31.

Borehole GH6890 penetrates, 2 m of soil, underlain by a sequence of weathered sandstone (11.6 m), followed by carbonaceous mudstone, siltstone to a depth of approximately 19 m. Top seam 5 coal is intercepted (21.8 m to 24.3 m) in a sequence of unweathered carbonaceous sandstone and mudstone sequence from a depth of 19 m to 26.9 m. The log of borehole GH6891, approximately 100 m east of GH6890, indicates significant differences geological conditions. Two meters of soil is underlain by 14.9 m of weathered sandstone and mudstone, followed by a weathered (approximately 1 m) fractured dolerite sill to a depth of 26.8 m. The presence of the dolerite sill could control the groundwater movement beneath the dump, however, very little information on the geometry and configuration of the dolerite is available. Comparison of the final depth of piezometers drilled into Springbok 2 Dump, i.e. P2A, P1A and P3A reveal that they penetrate the unconsolidated soil below the dump (final piezometer depth in the sequence above is 1552.59; 1557.04 and 1560.13 metres above mean sea level (mamsl)). The approximately 2 m thick unconsolidated soil zone beneath the dump acts as an permeable layer transporting recently recharged water above the relatively impermeable weathered Bainsvlei soils.

Analysis of the piezometer water level elevations indicates the presence of a water mound above the soil layer towards the western perimeter of the dump (P2A). In P1A the water level is in the soil zone, which is seen as a seasonal perched aquifer, fed by rainfall recharge. P3A became dry towards the end of 2012 and it is suspected that the Northern interception trench has resulted in the drop in water level. The relationship between interflow in the soil zone and the dolerite is not known. Seepage from the saturation in the dump (perched layer) will express itself at surface as toe seep at the Dump perimeter. It is likely that the intrusion play a role in feeding the shallow groundwater zone beneath the dump. In all the piezometers, the water level has dropped over a period of approximately a year. An interception trench was installed in April 2012, which could have successfully drained the perched aquifer and reduced recharge.

A separate shallow perched water table is associated with the interflow zone in the shallow soil zone beneath the dump, which has not been removed prior to deposition of the discard. The perched water table has resulted in mounding towards the western pit perimeter as well as the northern perimeter. This perched water table, are fed partly by residual water in the dump as well as underflow in the soil zone. The sources, salt, and ARD seepage are twofold:

- (a) Hypersaline soils in the rehabilitated pollution control dam (PCD). The absence of a breaker layer result in the formation of the precipitation of salts due to capillary action associated with the infiltration of rainwater.

- (b) Toe seep of saline water around the western and northern perimeter as a result of water in the soil zone beneath the dump in the vicinity of the mound. This seepage can be controlled by interception trenches on the east and west.

In conclusion, to effectively deal with the pollution plume and associated risk, mitigation options have been developed and a best option has been proposed based on the site characterization, CSM and the best practice and industry practices which were identified in Chapter 4.

## 5.5. Mitigation options for consideration

Following the journey of a detailed site characterization which lead to the development of a CSM, the next steps comprise of applying the hierarchy of water management controls and the development of a comprehensive sampling programme. Pollution prevention, minimization and treatment were earmarked as the possible options to address the pollution from Springbok 2 discard facility.

### 5.5.1. Options Analysis

Options analysis (table 14) was done on the hierarchy of water management controls which took into account the site conditions at Springbok 2 discard facility, budget constraints and physical limitations. This was done to determine the best route to follow in addressing the pollution problem of the Springbok 2 discard facility.

**Table 14: Options analysis on water management hierarchy of controls.**

Category	Option	Advantage	Disadvantage
Pollution prevention	Reuse and reclamation of coal discard	Total removal of pollution source	Capital intensive
Pollution Minimization	Water volume reduction and diversion	Springbok 2 conforms to certain of these aspects. Most cost effective option.	Project dependent on several actions to address pollution.
	Encapsulation of coal discard facility	Prevention of infiltration.	Capital intensive.
	Detoxification	Cost effective option.	Not as effective as water diversion and reduction. Buffer capacity diminish after time.
Treatment	In-Situ Treatment	Installed system.	System maintenance.
	Passive treatment	Installed system.	System maintenance.
	Active treatment	Decreased liability and addressing symptoms.	Expensive, maintenance intensive.

From table 14 it is evident that water volume reduction and diversion was chosen as the preferred option. The steps one would investigate is as follow:

1. Discard dump surface rehabilitation and vegetation cover.
2. Discard needs to be compacted prior to rehabilitation.
3. Discard dump surface needs to be domed to promote surface runoff and reduce infiltration.

4. Surface and groundwater interception.
5. Construction of interception trenches upstream and downstream of pollution source informed by CSM.
6. Drilling of dewatering boreholes upstream and downstream of pollution source informed by CSM.
7. Planting of high consumption, salt tolerant trees, eg. Eucalyptus.
8. Injection of grout barriers.

Springbok 2 discard facility conforms to several of these points and will be driven to implement grout barriers and permanent groundwater and seepage interception measures.

The following options presented in Table 15 which falls under the heading of water volume reduction and diversion were rigorously investigated, options analysis conducted (Table 16) and the optimal option costed (Table 17) to determine the best strategy for managing groundwater, surface water and aesthetics at the Springbok 2 discard dump.

**Table 15: Mitigation options for consideration.**

OPTION	ADVANTAGE	DISADVANTAGE
Leave "as is"	<ul style="list-style-type: none"> <li>• No cost implications</li> </ul>	<ul style="list-style-type: none"> <li>• Pollution to surface and groundwater resource</li> <li>• Possible regulatory action</li> <li>• Possible charge under WDSCS</li> <li>• Aesthetics</li> </ul>
Northern drain installation & In-situ treatment of pc dam	<ul style="list-style-type: none"> <li>• Low cost implications</li> <li>• Temporary buffer capacity</li> <li>• Temporary improvement of aesthetics</li> <li>• Groundwater component reduced</li> </ul>	<ul style="list-style-type: none"> <li>• Method will be rendered ineffective within 1 year period</li> <li>• Continuous ingress and reaction of water with pollutants</li> <li>• Continuous maintenance</li> </ul>
<b>Northern drain installation &amp; geotextile (1.0mm HDPE liner) capped pc dam</b>	<ul style="list-style-type: none"> <li>• Pollutants isolated</li> <li>• No ingress and reaction of water with pollutants</li> <li>• No maintenance, effectively walkaway situation</li> </ul>	<ul style="list-style-type: none"> <li>• Large financial implications</li> <li>• Liner damage during installation</li> </ul>
<b>Northern drain installation &amp; geotextile (geoliner) capped pc dam</b>	<ul style="list-style-type: none"> <li>• Pollutants isolated</li> <li>• No ingress and reaction of water with pollutants</li> <li>• No maintenance, effectively walkaway situation</li> <li>• Liner can be repaired if damaged</li> <li>• Spray on application</li> </ul>	<ul style="list-style-type: none"> <li>• Larger financial implications than HDPE liner</li> </ul>

**Table 16: Options analysis for mitigation options under consideration.**

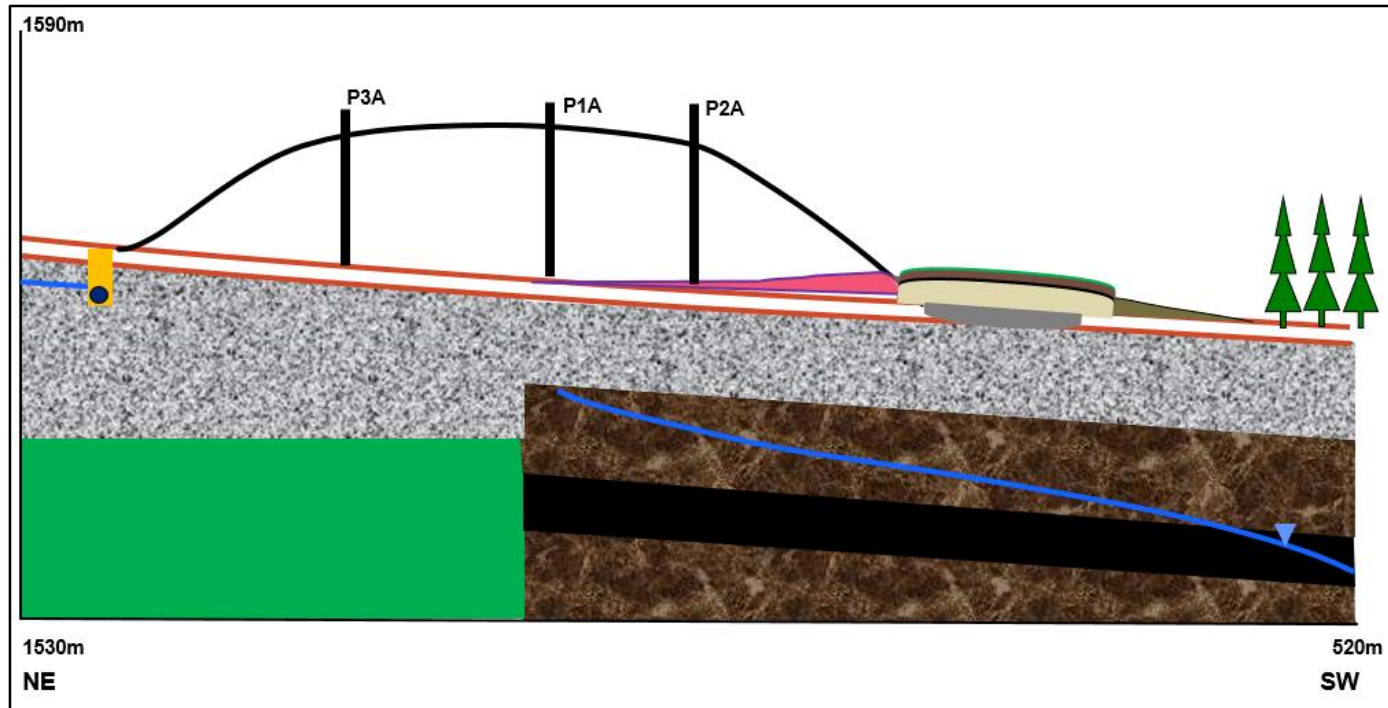
Mitigation	Leave "as is"	Northern drain installation & In-situ treatment of toeseep dam	Northern drain installation & geotextile (HDPE) capped toeseep dam	Northern drain installation & geotextile (geoliner) capped toeseep dam
Dump surface (R80,000)	X	X	X	X
Perimeter Aesthetics (R45,000)	X	X	X	X
Northern Interception Drain (R2,000,000)		X	X	X
Toeseep Dam in-situ rehab (R52,000)		X		
Geoliner with full toeseep rehab and topsoil (R2,000,000)				X
1.0mm HDPE Flexible Membrane Lining (R650,000)			X	
<b>Total Estimated (R)</b>	<b>125,000</b>	<b>2,177,000</b>	<b>2,771,870</b>	<b>4,123,769</b>

**Table 17: Cost breakdown for preferred option.**

Zone	Mitigation measure	Entails	Cost (R)
1	Interception drains	<ul style="list-style-type: none"> <li>Drain design</li> <li>Excavation and installation</li> </ul>	2,000,000
2	Dump surface rehabilitation	<ul style="list-style-type: none"> <li>Topsoil import for ~1 ha at R40 per m3 if stockpile is available</li> <li>Amelioration of 1 ha</li> </ul>	80,000
3	Toe seep dam rehabilitation	<ul style="list-style-type: none"> <li>In-situ rehabilitation (note this option is not recommended, continuous low pH seep and capillary movement will render this method non effective within a 1 year period.)                             <ul style="list-style-type: none"> <li>Lime application 30t/ha, Phosphate application (Super P) 0.3t/ha, Lime Ammonium Nitrate 0.35t/ha, ripping, disking, Seed mix application 20kg/ha, rolling)</li> </ul> </li> <li>Geoliner domed and cap, fully rehabilitated, assuming topsoil availability on site</li> <li>HDPE 1.0mm geomembrane</li> </ul>	52,000 1,998,769 646,870
4	Perimeter aesthetics	Eucalyptus tree screen (3 rows (450) at R100/tree)	45,000

### 5.3.7. Final desired overview of CSM

The final anticipated overview is shown in Figure 34 below. Figure 35 shows the image below in plan view.



**Figure 34: Cross section of final anticipated overview of Springbok 2 discard facility.**

- Discard dump surface: Rehabilitated where soil and vegetation burn was observed.
- Subsurface drain installed at 3m to divert clean groundwater away from the pollution source. Refer to figure 35 for a plan view.
- Toe seep dam graded, covered with building sand layer, covered with geotextile, topsoiled shaped and domed, ameliorated and vegetated.
- Eucalyptus tree screen around facility.

### 5.3.8. Conclusion

- 4 zones need to be managed individually in order to improve on the bigger picture (Figure 30)
- Priority should be given to installation of a subsurface drain where the current trench is north of the dump, installed at 3 metres deep to divert clean groundwater away from the pollution source. Subsurface drain covered with gravelpack and bidim.
- Toe seep dam to be graded, covered with building sand layer, covered with geotextile liner, topsoiled shaped and domed, ameliorated and vegetated.
- Further monitoring and site improvement should be carried out on a monthly basis to assess rehabilitation and mitigation efforts.

At its current status in 2016 the Springbok 2 discard dump has not had visible seepage from the toe of the dump and has shown a remarkable improvement in the overall aesthetics. The improvement of all aspects of the Springbok 2 discard dump is a key learning for Anglo American Coal SA which can be implemented at numerous other discard facilities.



Figure 35: Final anticipated overview of Springbok 2 Discard facility (plan view).



## 5.5. Summary: Chapter 5

The objective of Chapter 5 is to provide the reader with a case study as an example which was used in conjunction with Chapter 4 to develop a set of practical implementable guidelines in order to manage groundwater in and around a rehabilitated coal discard facility. The case study goes through a site characterization process which is graphically illustrated in Chapter 6. A number of investigations are showcased which feeds into the development of the CSM, the foundation for the management guideline. From there the hierarchy of water management controls are explored to identify the best fit option which is site specific and may conform to any number of the options listed, both in the case study as well as the graphic illustration that is unpacked in Chapter 6.

A summary of mitigation measures are explored, which were founded on the CSM and specialist studies, which feeds into the final desired overview of this facility. It must be emphasised that the mitigation measures implemented were restricted by budget availability from the mine and it needs to be stressed that this will be a key risk for any future implementations of this guideline presented in Chapter 6.

## CHAPTER 6: GUIDELINE FOR THE MANAGEMENT OF GROUNDWATER IN AND AROUND REHABILITATED COAL DISCARD FACILITIES

During each stage of the development of the guidelines for managing groundwater in and around rehabilitated coal discard facilities, cognisance had to be taken to stick to the hierarchy of controls for managing mine water (Department: Water Affairs and Forestry, 2008):

1. Pollution prevention
2. Reuse or recycle contaminated water (not applicable to this study)
3. Water treatment
4. Reuse of treated water (not applicable to this study)
5. Discharge or disposal

The guideline is represented as a practical document with a series of flow diagrams and steps which needs to be taken to produce the desired outcome. The guideline is an amalgamation of the literature study in Chapter 4 and the case study of Springbok 2 discard facility as discussed in Chapter 5.

### 6.1. Guideline Development

The main sections of the guideline document revolves around the importance of adequate site characterization which then informs the conceptual site model and in turn provides valuable input into the development of a monitoring programme and the evaluation of different initiatives which align with the hierarchy of controls for managing mine water.

Figure 36 represents the overarching guideline document. It is important to note the flow of actions from site characterization to the development of the CSM and the consequential steps which needs to be followed.

Figure 37 represents the first major part of the overarching guideline document and needs to be unpacked into smaller portions like it was done with the case study in Chapter 5.

Figure 38 represents the second major part of the overarching guideline document and needs to be unpacked into smaller portions like it was done with the case study in Chapter 5.

For adequate site characterization it is necessary to undertake the following activities:

1. Determine dump characteristics
2. Determine site geology
3. Determine site history
4. Determination of site hydrological parameters
5. Determination of site geochemical parameters
6. Intrusive studies
7. Produce conceptual site model

Each of the sections above has several input requirements (grey boxes) and results in the output of certain results (blue boxes).

Once the CSM has been developed, it is crucial to initiate 2 steps namely:

1. Hierarchy of controls for mine water management (figure 39) and;
2. Development of a comprehensive sampling programme (figure 40), taken from Barnes and Vermeulen, (2012).

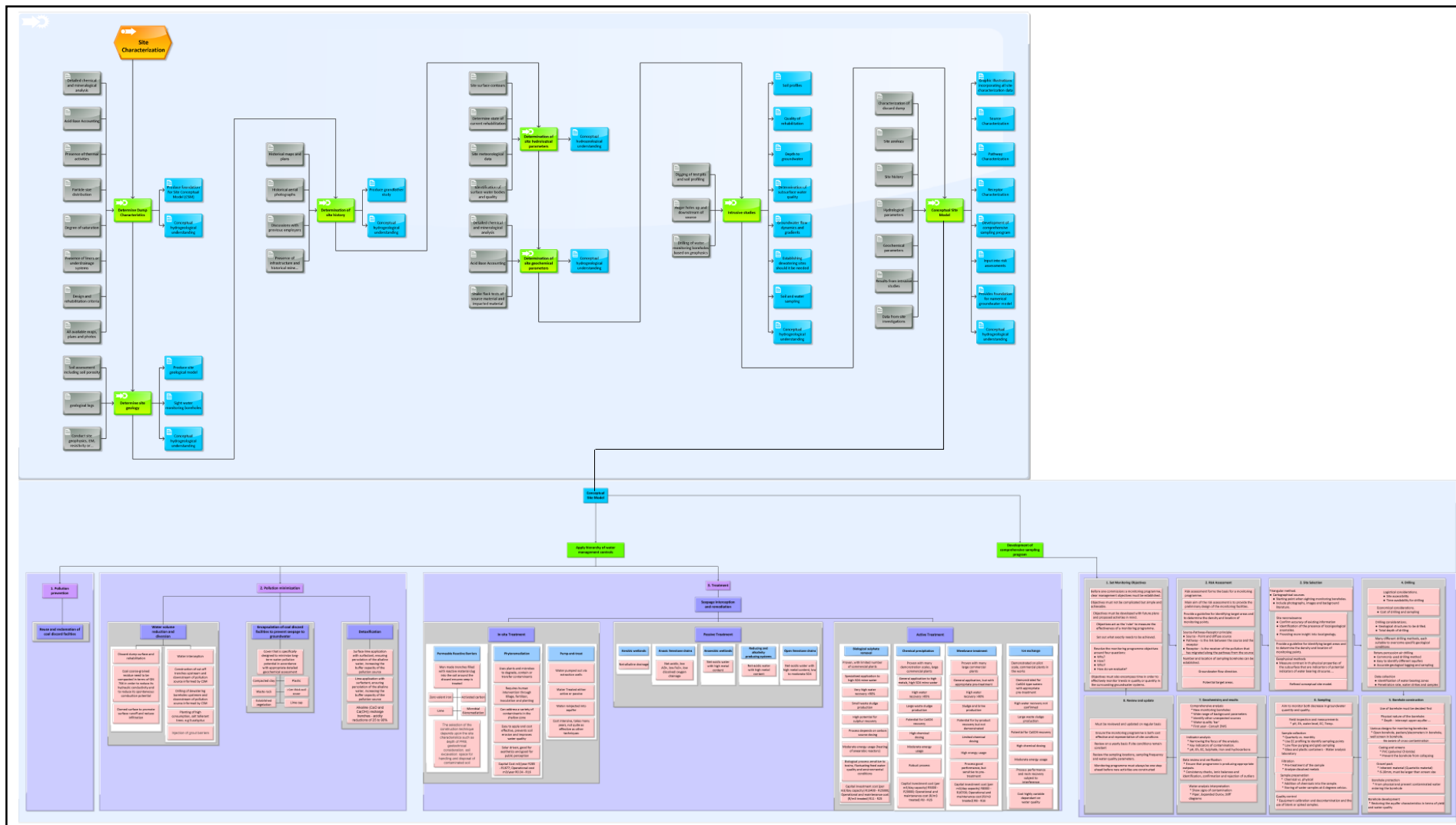


Figure 36: A guideline for the management of groundwater in and around rehabilitated coal discard facilities.

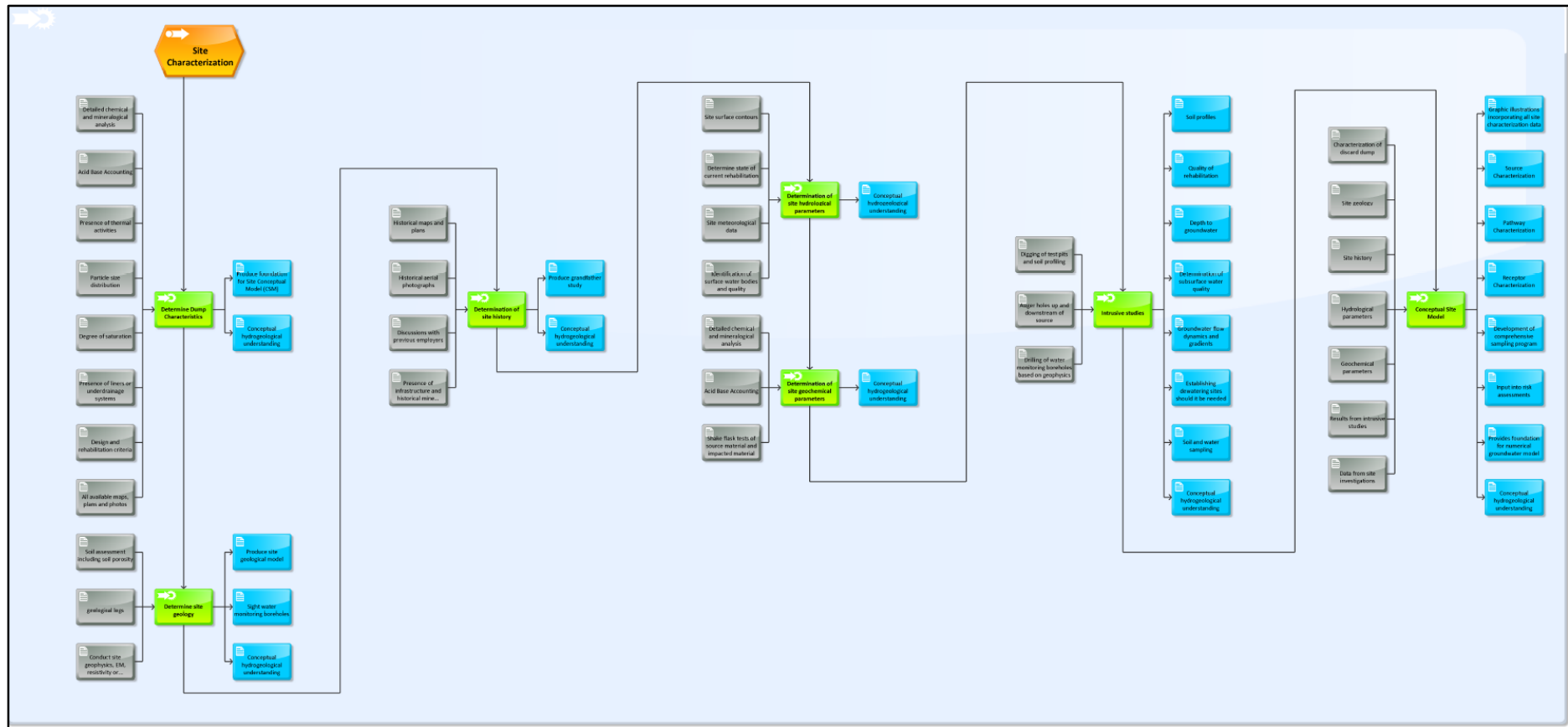


Figure 37: The first part of the overarching guideline entailing the initial process from site characterization to the development of a CSM for the management of groundwater in and around rehabilitated coal discard facilities.

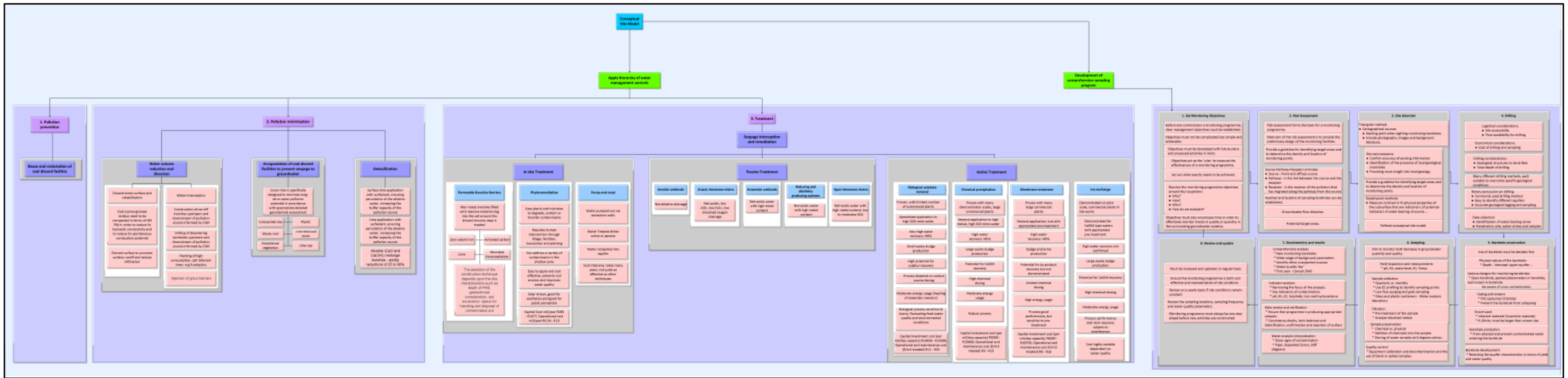
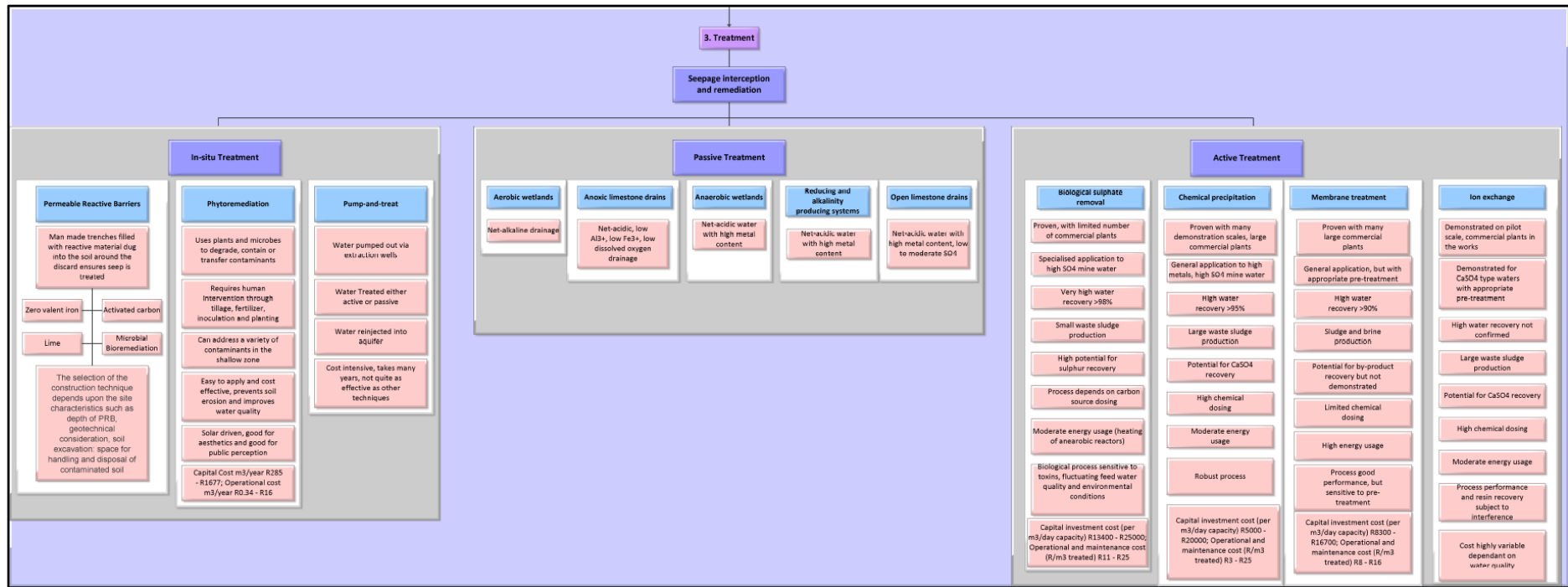


Figure 38: The second part of the overarching guideline entailing the process following site characterization through to the hierarchy of controls and the development of a sampling programme.



**Figure 39: Last step required for the hierarchy of controls which needs to be applied where possible for mine water management for a rehabilitated coal discard dump.**

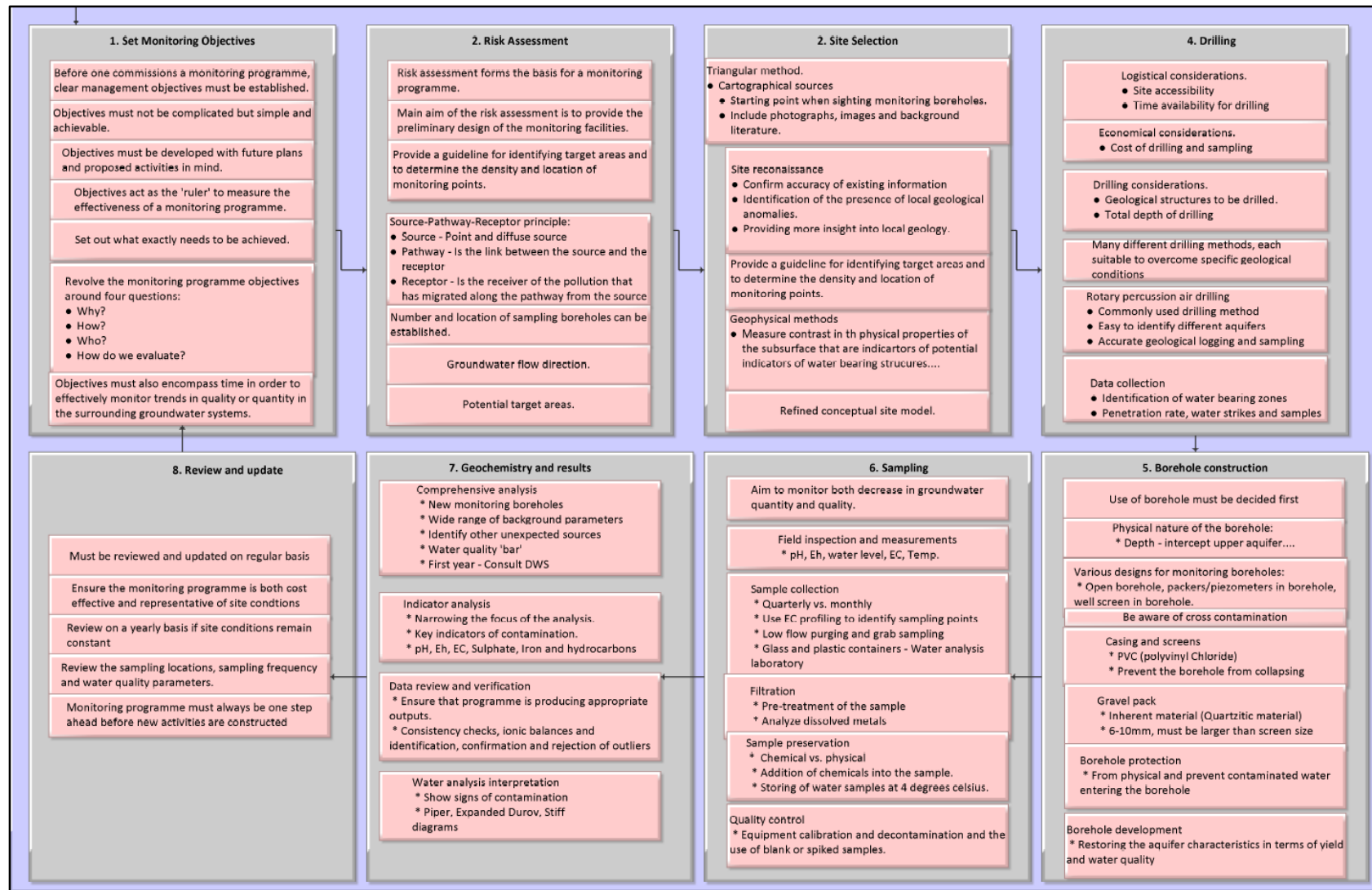


Figure 40: Steps required for the development of a comprehensive sampling programme for mine water management for a rehabilitated coal discard dump (taken from Barnes and Vermeulen, 2012).



## CHAPTER 7: FINDINGS AND CONCLUDING REMARKS

Chapter 7 provides a summary in bullet form of the guideline presented in Chapter 6. These steps are also in accordance with the steps taken with the discussion of the case study in Chapter 5. Specifics are provided on the input data and output deliverables from the main activities which forms the foundation of the guideline.

### 7.1. Guideline Specifics

In order to inform the CSM, a full site characterization has to be carried out and is summarised below:

#### **Activity – Determination of Dump Characteristics**

*Input documents and data:*

- Detailed chemical and mineralogical analysis
- Acid Base Accounting
- Presence of thermal activities
- Particle size distribution
- Degree of saturation
- Presence of liners or underdrainage systems
- Design and rehabilitation criteria
- All available maps, plans and photos

*Output Deliverables:*

- Produce foundation for Conceptual Site Model (CSM)
- Conceptual hydrogeological understanding

#### **Activity – Determination of Site Geology**

*Input documents and data:*

- Soil assessment including soil porosity
- Geological logs
- Conduct site geophysics, electromagnetics, resistivity or magnetics

*Output Deliverables:*

- Produce site geological model
- Sight water monitoring boreholes
- Conceptual hydrogeological understanding

**Activity – Determination of Site History**

*Input documents and data:*

- Historical maps and plans
- Historical aerial photographs
- Discussions with previous employers
- Presence of infrastructure and historical mine workings

*Output Deliverables:*

- Produce grandfather study
- Conceptual hydrogeological understanding

### **Activity – Determination of Site Hydrological Parameters**

#### *Input documents and data:*

- Site surface contours
- Determine state of current rehabilitation
- Site meteorological data
- Identification of surface water bodies and quality thereof

#### *Output Deliverables:*

- Conceptual hydrological understanding
- Conceptual hydrogeological understanding

### **Activity – Determination of Site Geochemical Parameters**

#### *Input documents and data:*

- Detailed chemical and mineralogical analysis
- Acid Base Accounting
- Shake flask tests of source material and impacted material

#### *Output Deliverables:*

- Conceptual hydrogeological understanding

### **Activity – Intrusive Studies**

#### *Input documents and data:*

- Digging of test pits and soil profiling
- Auger holes up and downstream of source
- Drilling of water monitoring boreholes based on geophysics

*Output Deliverables:*

- Soil profiles
- Quality of rehabilitation
- Depth to groundwater
- Determination of subsurface water quality
- Groundwater flow dynamics and gradients
- Establishing dewatering sites should it be needed
- Soil and water sampling
- Conceptual hydrogeological understanding

**Activity – Conceptual Site Model**

*Input documents and data:*

- Characterization of discard dump
- Site geology
- Site history
- Hydrological parameters
- Geochemical parameters
- Results from intrusive studies
- Data from site investigations

*Output Deliverables:*

- Graphic illustrations incorporating all site characterization data
- Source Characterization
- Pathway Characterization
- Receptor Characterization
- Development of comprehensive sampling program
- Input into risk assessments
- Provides foundation for numerical groundwater model
- Conceptual hydrogeological understanding

Once the CSM has been developed it can now be used to develop a comprehensive sampling programme (Figure 40) – for specifics these diagrams should be read together with the *Guide to groundwater monitoring for the coal industry* by Barnes and Vermeulen (2012). The CSM informs the

hierarchy of water management controls which is summarised below and refers back to the Chapter 6 flow diagrams:

**Activity – Pollution Prevention**

- Reuse and reclamation of coal discard facilities

**Activity – Pollution Minimization**

- Water volume reduction and diversion
- Encapsulation of coal discard facilities to prevent seepage to groundwater
- Detoxification

**Activity – Treatment**

- In-situ Treatment
  - Permeable Reactive Barriers
  - Phytoremediation
  - Pump-and-treat
- Passive Treatment
  - Aerobic wetlands
  - Anoxic limestone drains
  - Anaerobic wetlands
  - Reducing and alkalinity producing systems
  - Open limestone drains
- Active Treatment
  - Biological sulphate removal
  - Chemical precipitation
  - Membrane treatment
  - Ion exchange

## 7.2. Conclusion

The development of this guideline is aimed at providing a non-hydrogeologist with a set of tools, examples, costs and guidelines which can be practically implemented at any rehabilitated coal discard facility. It aims to support the reader with a step by step approach on what studies and information typically goes into the management of a rehabilitated coal discard facility, even if the facility is abandoned, lacks basic infrastructure, security and data.

Diverse approaches of remediation and recovery has been successfully realized in order to reduce the impact of rock drainage on the environment, in South Africa and abroad.

Legislatively, the disposal of mineral residue waste is governed by several acts, regulations as well as the Best Practice Guidelines published by the Department of Water and Sanitation (DWS). To ensure compliance to regulations, management of rehabilitated coal discard facilities needs to be conducted in a sustainable and cost effective way as to minimise and reduce pollution emanating from these facilities.

The guideline can be used in conjunction with other practices and will complement the investigation where current practices falls short.

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## APPENDIX A

### Acid Base Accounting Results

Acid – Base Accounting Modified Sobek (EPA-600)	Sample Identification		
	GHS 07 0.4m-0.8m	GHS 07 0.8m-2.0m	GHS 08 0.4m-1.7m
Sample Number	9984	9985	9987
Paste pH	2.8	3.2	2.4
Total Sulphur (%) (LECO)	1.21	2.03	2.89
Acid Potential (AP) (kg/t)	37.81	63.44	90.31
Neutralization Potential (NP)	0.00	0.00	0.00
Nett Neutralization Potential (NNP)	-37.81	-63.44	-90.31
Neutralising Potential Ratio (NPR) (NP : AP)	0.25	0.22	0.17
Rock Type	I	I	I

Acid – Base Accounting Modified Sobek (EPA-600)	Sample Identification	
	GHTP 1.1	GHTP 1.2
Sample Number	9989	9990
Paste pH	2.6	2.0
Total Sulphur (%) (LECO)	0.87	4.84
Acid Potential (AP) (kg/t)	27.19	152.19
Neutralization Potential (NP)	0.00	0.00
Nett Neutralization Potential (NNP)	-27.19	-152.19
Neutralising Potential Ratio (NPR) (NP : AP)	0.45	0.16
Rock Type	I	I

## Distilled Water Extractions

Analyses	Sample Identification			
	GHS 07 0.4m – 0.8m		GHS 07 0.8m – 1.15m	
Sample number	9984		9985	
TCLP / Acid Rain / Distilled Water / H <sub>2</sub> O <sub>2</sub>	-		-	
Mass Used (g)	-		-	
Volume Used (mℓ)	-		-	
pH Value at 25°C	-		-	
Units	mg/ℓ	mg/kg	mg/ℓ	mg/kg
Total Dissolved Solids at 180°C	-	-	-	-
Nitrate as N	-	-	-	-
Sulphate as SO <sub>4</sub>	-	-	-	-
TOC	-	-	-	-
ICP OES Scan	-		-	
Acid Base Accounting	See attached report #25072 ABA		See attached Report #25072 ABA	
Sulphur Speciation	-		-	
X-ray Diffraction	-		-	

Analyses	Sample Identification			
	GHS 07 1.15m – 2.0m		GHS 08 0.4m – 0.8m	
Sample number	9986		9987	
TCLP / Acid Rain / Distilled Water / H <sub>2</sub> O <sub>2</sub>	Distilled Water		-	
Mass Used (g)	500		-	
Volume Used (mℓ)	1000		-	
pH Value at 25°C	2.5		-	
Units	mg/ℓ	mg/ℓ	mg/ℓ	mg/kg
Total Dissolved Solids at 180°C	8680	17360	-	-
Nitrate as N	0.2	0.4	-	-
Sulphate as SO <sub>4</sub>	7024	14048	-	-
TOC	3.50		-	-
ICP OES Scan	See attached Spreadsheet #25702A		-	
Acid Base Accounting	See attached Report #25072 ABA		See attached Report #25072 ABA	
Sulphur Speciation	See attached Report #25072 S-Speciation		-	
X-ray Diffraction	-		-	

Analyses	Sample Identification			
	GHS 08 0.7m – 1.7m		GHTP 1.1	
Sample number	9988		9989	
TCLP / Acid Rain / Distilled Water / H <sub>2</sub> O <sub>2</sub>	-		-	
Mass Used (g)	-		-	
Volume Used (mℓ)	-		-	
pH Value at 25°C	-		-	
Units	mg/ℓ	mg/ℓ	mg/ℓ	mg/kg
Total Dissolved Solids at 180°C	-	-	-	-
Nitrate as N	-	-	-	-
Sulphate as SO <sub>4</sub>	-	-	-	-
TOC	-	-	-	-
ICP OES Scan	-		-	
Acid Base Accounting	See attached Report #25072 ABA		See attached Report #25072 ABA	
Sulphur Speciation	-		See attached Report #25072 S-Speciation	
X-ray Diffraction	-		-	

Analyses	Sample Identification	
	GHTP 1.2	
Sample number	9990	
TCLP / Acid Rain / Distilled Water / H <sub>2</sub> O <sub>2</sub>	Distilled Water	
Mass Used (g)	500	
Volume Used (mℓ)	1000	
pH Value at 25°C	2.2	
Units	mg/ℓ	mg/kg
Total Dissolved Solids at 180°C	10438	20876
Nitrate as N	0.3	0.6
Sulphate as SO <sub>4</sub>	7993	15986
TOC	12.0	
ICP OES Scan	See attached Spreadsheet #25702A	
Acid Base Accounting	See attached Report #25072 ABA	
Sulphur Speciation	See attached Report #25072 S-Speciation	
X-ray Diffraction	See attached Report #25072 XRD	



## Sulphur Speciation

Sulphur Speciation	Sample Identification		
	GHS 07 1.15m – 2.0m	GHTP 1.1	GHTP 1.2
Sample Number	9986	9989	9990
Total Sulphur (%) (LECO)	2.08	0.870	4.84
Sulphate (SO <sub>4</sub> <sup>2-</sup> ) Sulphur (%)	1.53	0.820	1.87
Sulphide (S <sup>2-</sup> ) Sulphur (%)	0.210	0.040	2.90

## X-Ray Diffraction

Mineral	Composition (%)
	GHTP 1.2
Sample	9990
Gypsum	17
Jarosite	48
Anatase	-
Hematite	-
Quartz	29
Kaolinite	6
Mica	-
I/S Interstratification	-

## ICP-OES

Extract	Sample Dry Mass	Volume	Mass (g)	Factor
Distilled Water	500	1000	500	2

Sample Id	Sample number	Ag	Ag	Al	Al	As	As
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<0.025	<0.050	<0.100	<0.200	<0.010	<0.020
GHS 07 1.15m - 2.0m	9986	0.170	0.340	208	416	<0.010	<0.020
GHTP 1.2	9990	3.08	6.18	351	702	<0.010	<0.020

Sample Id	Sample number	B	B	Ba	Ba	Be	Be
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<0.025	<0.050	<0.025	<0.050	<0.025	<0.050
GHS 07 1.15m - 2.0m	9986	<0.025	<0.050	<0.025	<0.050	0.047	0.094
GHTP 1.2	9990	<0.025	<0.050	<0.025	<0.050	0.074	0.148

Sample Id	Sample number	Bi	Bi	Ca	Ca	Cd	Cd
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<0.025	<0.050	<2	<4	<0.005	<0.010
GHS 07 1.15m - 2.0m	9986	<0.025	<0.050	492	984	<0.005	<0.010
GHTP 1.2	9990	<0.025	<0.050	492	984	<0.005	<0.010

Sample Id	Sample number	Co	Co	Cr	Cr	Cu	Cu
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<0.025	<0.050	<0.025	<0.050	<0.025	<0.050
GHS 07 1.15m - 2.0m	9986	0.267	0.634	0.185	0.370	0.327	0.654
GHT P 1.2	9990	4.21	8.42	0.148	0.296	0.207	0.414

Sample Id	Sample number	Fe	Fe	K	K	Li	Li
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<0.025	<0.050	<1.0	<2.0	<0.025	<0.050
GHS 07 1.15m - 2.0m	9986	350	700	<1.0	<2.0	0.315	0.630
GHT P 1.2	9990	267	534	<1.0	<2.0	0.193	0.386

Sample Id	Sample number	Mg	Mg	Mn	Mn	Mo	Mo
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<2	<4	<0.025	<0.050	<0.025	<0.050
GHS 07 1.15m - 2.0m	9986	579	1158	25	50	<0.025	<0.050
GHT P 1.2	9990	543	1086	149	298	<0.025	<0.050

Sample Id	Sample number	Na	Na	Ni	Ni	P	P
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<2	<4	<0.025	<0.050	<0.025	<0.050
GHS 07 1.15m - 2.0m	9986	3	6	0.323	0.646	0.260	0.520
GHT P 1.2	9990	4	8	1.37	2.74	<0.025	<0.050

Sample Id	Sample number	Pb	Pb	S	S	Sb	Sb
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<0.020	<0.040	<0.100	<0.200	<0.010	<0.020
GHS 07 1.15m - 2.0m	9986	0.055	0.110	1891	3782	<0.010	<0.020
GHT P 1.2	9990	0.064	0.128	2303	4606	<0.010	<0.020

Sample Id	Sample number	Se	Se	Si	Si	Sn	Sn
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<0.020	<0.040	<0.200	<0.400	<0.025	<0.050
GHS 07 1.15m - 2.0m	9986		0.00	18.3	37	<0.025	<0.050
GHT P 1.2	9990	0.063	0.126	25	50	<0.025	<0.050

Sample Id	Sample number	Sr	Sr	Ti	Ti	V	V
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<0.025	<0.050	<0.025	<0.050	<0.025	<0.050
GHS 07 1.15m - 2.0m	9986	0.709	1.42	<0.025	<0.050	0.203	0.406
GHT P 1.2	9990	0.139	0.278	<0.025	<0.050	0.203	0.406

Sample Id	Sample number	W	W	Zn	Zn	Zr	Zr
		mg/l	mg/kg	mg/l	mg/kg	mg/l	mg/kg
Det Limit		<0.025	<0.050	<0.025	<0.050	<0.025	<0.050
GHS 07 1.15m - 2.0m	9986	0.031	0.062	1.00	2.00	<0.025	<0.050
GHT P 1.2	9990	<0.025	<0.050	1.27	2.54	<0.025	<0.050

**Batch** A00001728  
**Sample** GHTP6  
**Sample Mass** A00001728001  
**Bottle** A00001728001  
**Request No.** 37246  
**Date Sampled** 10/06/2009  
**Date received** 10/07/2009  
**Date Completed** 10/09/2009  
**Turnaround Days** 14  
**Type** POL

Group	Description	Mnemonic	unit	
Other	Electrical Conductivity	EC	mS/m	2809.92
	pH	pH	pH	3.41
	Suspended Solids	SUS	mg/L	1840.00
	Temperature	Temp	°C	24.80
	Total Acidity endpoint at 8.3	TACl	mg/L	28515.00
	Total Alkalinity	TALK	mg/L CaCO3	0.00
	Total Dissolved Solids	TDS	mg/L	67650.00
Anions	Chloride	CL-	mg/L	4.05
	Sulphate	SO4	mg/L	44215.0000
Cations	Aluminium	Al	mg/L	936.8098
	Calcium	Ca	mg/L	286.11
	Iron	Fe	mg/L	0.0000
	Magnesium	Mg	mg/L	3923.10
	Manganese	Mn	mg/L	202.39
	Potassium	K	mg/L	8.0855
	Sodium	Na	mg/L	81.91

	<b>Batch Sample Bottle Request No. Date Sampled Result</b>	<b>A00001728 GHTP6 A00001728001 37246 10/06/2009 Result</b>
<b>Description</b>		
Total Cations		735.345
Total Anions		920.671
% Difference		-11.191
Anions - Cations		185.326
Calculated TDS		48518.254
Measured TDS		67650
Ratio		1.394
Measured TDS/Conductivity ratio		24.075
Calculated TDS/Conductivity ratio		17.267

# APPENDIX B

## Geological logs

### Borehole GHC6890

<p>LOCALITY PLAN</p>		<p>ANGLO COAL GEOLOGICAL SERVICES ANGLO COAL DIVISION a member of the Anglo American plc group</p>		<p>SHEET NO. 1 of 1</p> <p><b>BOREHOLE No. GHC6890</b></p>							
<p>PROJECT <b>GOEDEHOOP</b></p> <p>FARM <b>Vandyksdrift 019IS</b></p> <p>DISTRICT <b>Witbank</b></p> <p>PROVINCE <b>Lo Cape System</b></p> <p>TOPO SHEET</p>		<p>COORDINATES CAFE Y 2886596.00</p> <p>COORDINATES CAFE X 1568.79</p> <p>DRILLER Zoomen Exploration Drilling</p> <p>DATE COMMENCED 14/09/2012</p> <p>DIAMETER OF CORE 860 mm.</p> <p>LOGGED BY Surveyed</p> <p>F/S ANALYSIS BY Surveyed</p> <p>COAL ANALYSIS BY Surveyed</p> <p>SPECIAL ANALYSIS BY Logsheet generated</p> <p>APPROVED BY .....</p>		<p>COORDINATES WGS Y -33520.00</p> <p>COORDINATES WGS X 2886895.00</p> <p>DATE COMPLETED 15/09/2012</p> <p>CASING LEFT IN HOLE m</p> <p>DATE DATE DATE</p> <p>HEAD of GEOLOGY D.R.W. Dingemans</p>							
BOREHOLE SECTION				BOREHOLE SECTION				BOREHOLE SECTION			
DEPTH	SECTION	WIDTH	RECORD OF STRATA	DEPTH	SECTION	WIDTH	RECORD OF STRATA	DEPTH	SECTION	WIDTH	RECORD OF STRATA
1.05		1.05	SOIL, dark, orange, ferruginous								
1.52		0.47	SANDSTONE, light, orange, muddy, clayey, Highly_Weathered								
2.06		0.00	Base of Weathering								
		8.77	SANDSTONE, white, coarse_to_Medium_Grained, massive, micaceous, Weathered								
10.83		1.13	SANDSTONE/SILTSTONE, orange, laminated, Weathered								
11.96		1.65	SANDSTONE/CARBONACEOUS MUDSTONE, banded, laminated, Weathered								
13.61		0.00	Base of Weathering								
		4.18	CARBONACEOUS MUDSTONE/SANDSTONE, Weathered in parts								
17.79		1.06	CARBONACEOUS MUDSTONE/SILTSTONE, dark, grey, fissile, Banded sand, slightly weathered								
18.85		0.00	Base of Hard Weathering								
18.97		0.12	SANDSTONE/CARBONACEOUS MUDSTONE, banded, laminated, slightly weathered								
21.81		0.00	Base of Hard Weathering								
		2.84	SANDSTONE/CARBONACEOUS MUDSTONE, banded, laminated								
24.33		2.52	COAL, No. 5 Seam								
26.52		2.19	SANDSTONE/CARBONACEOUS MUDSTONE, banded, laminated								
28.79		0.27	CARBONACEOUS MUDSTONE/SILTSTONE, dark, grey, fissile, Banded sand								
EOH											

# Borehole GHC6891

