Management and Mitigation of Acid Mine Drainage in South Africa

Input for Mineral Beneficiation in Africa

Shingirirai S Mutanga and Munyaradzi Mujuru (eds)

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Preface

South Africa is facing the increasing challenge of acid mine drainage (AMD) whose genesis is the country's mining history, which paid limited attention to post-mining mine site management. In mineral resource-rich Africa, this has emerged as one of the most daunting challenges of our time.

South Africa has been bold in its approach to mitigating this problem, although the challenge is multi-faceted. On a positive note, substantial research has been conducted to confront the challenge. However, thus far, the research has been largely fragmented. This book builds on the work that has been done, but also provides a refreshing multi-disciplinary approach that is useful in addressing the AMD challenges that South Africa and the continent face. Whilst addressing the problem as a scientific and engineering challenge, the book also exposes the economic, policy and legal challenges involved in addressing the problem. The book concludes, quite uniquely, that AMD is an opportunity that can be used by South Africa and Africa to solve problems, such as acute water shortage, as well as mineral recovery operations.

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Foreword

The discovery of gold on the Witwatersrand in 1886 was a turning point in South African history. With gold deposits that far exceeded that of diamonds, this discovery changed South Africa from an agricultural society into the largest gold-producer in the world. This is a story that has been replicated around the world, on every continent and has shaped the modern global economy.

More than a century after this discovery, we are rapidly, and painfully, discovering the true meaning of full cycle cost. The flip side of the mining economic boom is the environmental costs – as we in the beginning of the 21st Century are realizing the full impact of two centuries of environmentally poor mining practices. Front and Centre is the phenomenon of Acid Rock Drainage, more commonly called Acid Mine Drainage or AMD. This has become one of the biggest environmental threats facing the mining industry and society at large.

This book addresses two specific issues. The first issue pertains to examining the technologies, technological capabilities, innovations, and financing technological capabilities and innovations in terms of contaminated mine water treatment in South Africa. The detailing of these technologies and the institutional and policy regimes that determined the development, adoption and disposal of these technologies and innovations is important, not only for South Africa, but also for other mineral rich sub-Saharan African (SSA) economies and elsewhere. It is particularly important, given the argument that China's entry into the labor intensive manufacturing scene has, for the time being, effectively blocked off one of the SSA industrialisation routes (Morris et al, 2012)[1]. The tenet of the argument is that the SSA economies could possibly be industrialised through production linkages into and out of their natural resources sector. In essence, this argument means that the mining sector is an important development sector for these economies. South Africa has had to deal with the remediation of water from contaminated mines and the South African experience with AMD is an important indicator of some of the negative externalities associated with the extractive industry.

The second part of the book addresses the question: What can other African countries that are going into the extractive sectors learn from SA and how can they finance these technologies and innovations innovatively? The question seeks to examine the transferability of South African AMD treatment technological capabilities and innovations and funding models to mining industries in other African countries. Acknowledging that the technology arena is a function of institutional and policy regimes, the question will also interrogate the transferability of the institutional and policy regimes governing these technologies and capabilities into these countries. Avoiding the post-operations management of negative externalities that characterise the AMD challenge in South Africa demands pro-active management to both eliminate and mitigate real and potential negative externalities from these industries.

AMD and acid mine water in general represents simultaneously on the biggest water quality challenges of our time on the one hand, and an important opportunity to plot a path to improved water security on the other. We have a chance, on the back of our AMD interventions, to introduce game-changing technological, regulatory and water governance platforms that could fundamentally shift our water fortunes from one of despair to prosperity.

Mr Dhesigen Naidoo
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CHAPTER 1

Introduction

Shingirirai S Mutanga and Munyaradzi Mujuru

INTRODUCTION

As early as 1987, the United States Environmental Protection Agency had recognised that '… problems related to mine waste may be ranked second only to global warming and stratospheric ozone depletion in terms of ecological risk. The release to the environment of mining waste can result in profound, generally irreversible destruction of ecosystems'.[1] This has become a painful reality for South Africa, and an emerging challenge for mineral-rich Africa.

For most African countries, successful exploitation of their mineral resources is considered key to national economic development and poverty alleviation. Realisation of benefits therefrom, however, has been and will be beset by many painful challenges – political, economic and technical. One of the technical challenges that have this far received little attention is policy development on mineral exploitation on the continent. This has been witnessed through poor waste water management and mitigation, resulting in the problem of acid mine drainage (AMD).[2] This book explains the genesis and composition of AMD as one of the technical challenges that most mining countries on the continent will have to face for some time.

Using the experience of South Africa, as the most developed mining country on the continent, the book presents an evaluation of management and mitigation of AMD. The book also details the legal, policy and technical interventions that have been developed in South Africa as lessons for other African countries that are starting out on the mining journey. The book concludes that since the AMD challenge will persist for centuries to come, there is a need for continuous policy, legal and technological interventions and improvements. The book also makes recommendations to other African countries that are new to the mining business on how to deal with the AMD challenge. Specifically, the book recommends that since mine waste water contains substances that are valuable to an economy, such as water and minerals, AMD should be viewed as an opportunity for the economy;

therefore funding for developing technologies that extract these valuable materials from AMD should be a priority.

The challenge of AMD is multi-faceted. The book acknowledges that there is a dearth of multi-disciplinary, multi-sectoral African empirically grounded studies on contaminated water purification technologies, technological capabilities and innovation, and how they can be financed sustainably. Most of the discussions to date tend to be disciplinary bound and do not encompass a multi-disciplinary approach that would enable cross-sectoral application of successful policies and practices to water purification in mine contaminated water in South Africa. As a result, in order to address this challenge comprehensively, a multi-disciplinary approach has been used in this book, with contributors from a wide range of disciplines and areas of expertise, including the natural sciences, engineering, economics, finance and the social sciences.

SOME KEY TERMINOLOGY

Mining activities inevitably result in the generation of AMD (also referred to as acid rock drainage (ARD)[3] by some scientists), which leads to environmental and water contamination. Hoffert[4] defines AMD in the context of mineral source, AMD from coal is considered an industrial waste that is peculiar in that it arises not from the processing of coal but as a result of the mere extraction of the mineral from the ground. Similarly, the AMD definition can make specific reference to the formation process, i.e. that acid water is created when sulphide minerals are exposed to air and water and produce sulphuric acid through a natural chemical reaction.[5] The chemical generation of AMD is described in detail in Chapter 3. This book adopts AMD instead of ARD as the standard term and defines AMD as highly acidic water, usually containing high concentrations of metals (such as iron, manganese and uranium), sulphides, free acid and salts as a consequence of mining activity.

In order to deal with the challenge of AMD, an array of intervention technologies and methods has been tried and applied, as described in depth in Section C of this book. The intervention technologies are grouped according to both ‘soft’ and ‘hard’ technology interventions. This is drawn from Arthur’s assertion that all technologies are assemblies that orchestrate phenomena for some purpose.[6] Such technologies may comprise of, use or embody tools that may be physical, conceptual or both. Bessant and

Francis,[7] consider hard technologies as being physical, while soft technologies are considered to be human-mediated processes. This is complemented by Zhouying's[8] assertion that soft technologies are the human factors that are the necessary adjuncts of hard tools. It is against this background that this book classifies soft interventions to include legal and policy frameworks that have been developed over the years and which provide pertinent lessons for other African countries that have not yet started to face the difficulties that result from AMD. Soft interventions also include various types of modelling that have been used, such as geographical information systems (GIS) and mathematical modelling, which have been used to determine the extent and severity of the AMD problem. The identified intervention technologies corroborate Jon Dron's assertion that soft technologies are flexible: they support creativity and change because the gaps inside them have to be filled with processes constructed by people.[9] Similarly, the aforementioned soft technologies are never complete in terms of their ability to confront the intractable AMD challenge – hence they are functionally incomplete. They can become many different technologies by aggregation or integration with other technologies, including physical/software tools and, more significantly, methods, norms, processes and patterns that are entirely embodied in human minds.[10]

On the other hand, hard technologies are those that are more complete and 'less needy'. The more they do what they do without the need to aggregate them with different technologies, the 'harder' they become.[11] In this context hard intervention technologies are mostly the remediation processes that have been used to treat AMD. There are biological and chemical remediation techniques that have been developed and used in South Africa and other countries. These techniques have been adapted from coal and gold mining to various types of AMD.

In South Africa, particularly in the Witwatersrand area, most mines have been abandoned, with an extensive network of underground tunnels having been left behind. Over the years since mining ceased, these tunnels have been filling with AMD, which has started to decant on the surface in some areas.[12] The proposed solution has been to pump and treat the AMD on the surface until the underground AMD levels reduce to 'environmental critical level' (ECL). The ECL level is the level of AMD underground, below which decanting of AMD on the surface does not happen.[13]

This book is fully cognisant of the fact that a plethora of studies on AMD have been undertaken in the past few decades; however, the literature is too fragmented and this book attempts to consolidate current research on AMD water treatment in South Africa. The book thus seeks to broaden the understanding of the AMD challenge through the multi-disciplinary lenses. The next section provides an outline of the book and the salient elements captured in each of the sections and chapters, in the order in which they appear.

BOOK AND CHAPTER OUTLINE

This book comes in 15 chapters that are organised in five sections. Section A is made up of three introductory chapters. The first chapter provides an overview of the broad AMD challenge, which has been the impetus for this book project. The second chapter details the legacy of mining and AMD. The chapter provides a historical overview of mining broadly, with emphasis on the South African context and the genesis of the intractable AMD challenge. The chapter briefly describes the legal and policy movements in the context of mine closure and how this precipitated and propelled the challenge of AMD, with identifiable hot spots across the country, the impacts of which are being felt across different sectors of the economy. The third chapter unpacks and broadens the understanding of the AMD challenge. The chapter defines and describes the origin and chemistry of the complex formation process of AMD and its occurrence.

Section B of the book focuses on impacts of AMD, comprising three distinctive chapters that look at water resources and social and economic impacts. The main thrust of Chapter 4 is a detailed description of the impacts of AMD on water resources in the South African context. This is followed by Chapter 5, which focuses on social impacts, with specific reference to the South African context. The chapter applies social impact assessment (SIA) as an over-arching framework that embodies the evaluation of all projects that impact on humans and on all the ways in which people and their communities interact with their socio-cultural, economic and bio-physical environments. Chapter 6 looks at the economic perspective and discusses the performance and contribution of the mining sector to the South African economy, taking into account the negative externality element of AMD.

Section C of the book consists of soft intervention measures for the AMD challenge. This section comprises five chapters. Chapter 7 of the book describes the role of strategic planning for sustainable management of AMD. Chapter 8 looks at legal interventions. The chapter interrogates and juxtaposes historical and current AMD intervention frameworks, including legal, policy and regulatory systems. It engages with the narrative of why such frameworks (if they exist) have not been practically translated into responses that address the issue. It also engages with the conundrum of who should ideally take responsibility for the current state of affairs.

Chapter 9 provides more insight on the role of finance in managing AMD. The chapter provides an overview of the funding mechanisms available, AMD remediation technologies in South Africa, running costs and funding mechanisms, and also explores some models that need to be considered in order to deal with contemporary and future AMD remediation challenges. The chapter discusses how AMD remediation can be linked to sustainable funding mechanisms that leverage downstream integration of AMD treatment process outputs with public, commercial, agricultural or industrial activities or business models.

The tenth chapter of the book describes the role of mathematical modelling and provides an overview of popular conceptual models used to simulate major elements of AMD generation, transport and treatment processes. The chapter acknowledges that, despite several years of research, there has been no single, independent and quick solution to remedy or treat AMD. However, over the years, it has been recognised that mathematical modelling and simulation can contribute to the understanding of AMD generation and the subsequent design of treatment processes. Mathematical models are useful tools that allow for rapid and varied evaluation of causes and effects, with the principal advantage being that they enable an analysis of even long-term actions with limited investment costs. This is complemented by the eleventh chapter, which focuses on the role of geospatial technologies in the form of GIS and remote sensing in providing location-based tools to monitor or predict the levels of pollution in the environment.

Section D of the book focuses on hard technological interventions related to the AMD challenge. This section consists of two main chapters, namely chemical treatment and bio-remediation. The twelfth chapter describes the chemical treatment technologies, with emphasis on remedial control systems involved in the treatment of AMD, which are classified into two major categories, namely: active treatment systems and passive treatment systems. The thirteenth chapter describes how biological remediation of acid mine drainage is applied as a mild environmentally-friendly method. The chapter details an array of innovative bio-remediation investigations that have been carried out in South Africa and elsewhere, to deal with the persistent environmental challenges posed by AMD caused by mining activity. The chapter also provides: an overview of the AMD bio-remediation process; organisms involved and process designs; and bio-remediation cases in South Africa. The section also indicates the strengths and weaknesses of the aforementioned treatment technologies.

The last section (E) of the book provides a conclusion to the book with two distinctive chapters. Chapter 14 focuses on deriving benefits from AMD remediation. The chapter reports on the possibility of recovering valuable products such as drinking water, metals, electricity, pigments and sulphur from AMD in South Africa. A lot of effort has been put into AMD remediation using different technologies; however, each of the proposed technologies has advantages and disadvantages that tend to limit their use. To compensate for the limitations of the proposed technologies, researchers should focus on AMD remediation with recovery of valuable products from such efforts. Chapter 15, apart from providing a summation of the book, suggests future directions and provides recommendations drawn from salient lessons for consideration by South Africa and other African countries. Essentially, the chapter unfolds in a manner that is based on the three schools of thought, that is:

(i) some current and future AMD impacts are inevitable because of the extent of the AMD challenge;
(ii) the nature and extent of the AMD challenge is such that it requires concerted effort by a divided stakeholder system; and
(iii) there are innovations that can be used to mediate the production, spread and impact of AMD.

CONCLUSION

This chapter provides a snapshot of AMD, which is considered to be one of the world's greatest challenges (second to climate change) and which is the impetus that has led to the production of this book project. The chapter describes the salient elements of the book and the rationale behind the sequence of the book, starting from the introductory section, which describes the legacy of AMD and broadening the understanding of the challenge, followed by four sections, namely: impacts; soft technological interventions and hard interventions technologies; and the concluding section, which maps the recommendations and the lessons drawn for Sub-Saharan Africa.

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CHAPTER 2

The Legacy of Acid Mine Drainage in South Africa

Vuyo Mjimba, Munyaradzi Mujuru and Shingirirai S Mutanga

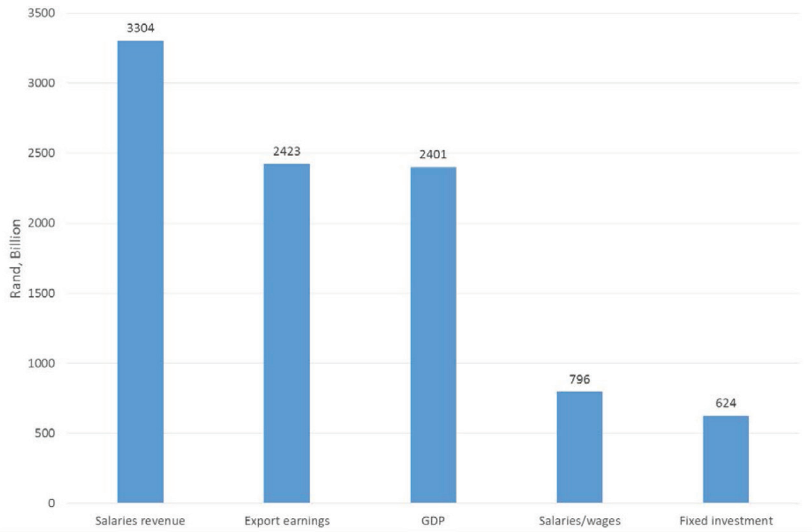
ABSTRACT

South Africa's mining sector plays a significant role in the country's economy. The Acid Mine Drainage (AMD) challenge can be traced back more than 100 years to the 1800s. While the source of AMD formation is largely abandoned mines and their associated waste dumps, the problem of acid water spreads far beyond the immediate surroundings of the mines and the mine dumps. The challenge of acid mine drainage has been described as a ticking time-bomb of the twenty-first century, given its effects on the environment. The lack of structured legal instruments and initiatives to deal with the AMD challenge during the early years of its formation aggravated the enormity of the challenge in South Africa. This chapter provides the historical background of the mining sector, which precipitated the AMD challenge; maps the spatial distribution of the challenge, by defining the hot-spots of the challenge; and describes the evolution of relevant legal instruments and how this contributed to the problem.

INTRODUCTION

South Africa is endowed with a variety of minerals that have been, and still are, a source of economic benefit to the country. The mining industry is a contributor to the country's aggregate economic output, generating direct and indirect employment, fiscal linkages through royalties, other taxes and as a foreign exchange earner. It has, in great part, contributed to South Africa's economic development and growth, leading to its current status as Africa's most sophisticated emerging economy. Figure 2.1 summarises the contribution of the mining sector to the South African economy in 2013.

Figure 2.1 Mining Sector contribution to South African economy over the past decade: Expressed in 2013 real money terms.[1]



Historically, South Africa has been the leading producer of gold. At its peak, (1970s), the country accounted for almost 60 per cent of the world's gold production.[2] Despite the history of gold mining industry dominance, South Africa is also endowed with an array of other mineral deposits. Among them it holds the world's largest reserves of manganese and platinum group metals (PGMs). In addition, it also has considerable deposits of diamonds, chromite ore, vanadium, iron ore and coal.[3] The importance of some of these minerals to the economy has surpassed that of gold. For example, in 2013, coal contributed R51 billion to South Africa's economy, compared to gold's R31 billion contribution.[4] While the different minerals jostle for prominence, an indisputable fact is that mining continues to play a significant role in the country's economy.

However, not all of the industry's outputs have been positive. The industry is associated with pre-democratic and democratic epoch violence and labour unrest. In addition, insufficient electricity supply and declining mineral prices have, both separately and jointly, dulled the sparkle of the industry. While these issues are cyclical and can be addressed with immediate benefits to the sector, the adverse environmental impacts present a different challenge. Climate change is perhaps the most discussed adverse environmental impact linked to mining. However, this chapter avoids this subject and instead looks at the ever-present challenge of AMD. The United

States of America's Environmental Protection Agency recognised AMD and the related mining-waste management challenge by stating:

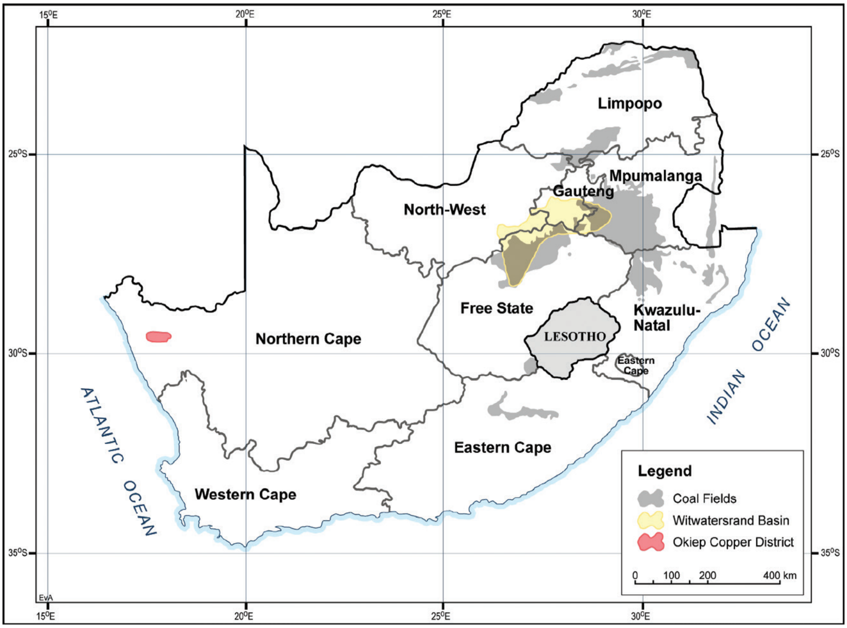
> … problems related to mining waste may be rated as second only to global warming and stratospheric ozone depletion in terms of ecological risk. The release to the environment of mining waste can result in profound, generally irreversible destruction of ecosystems.[5]

AMD forms when water flows over or through sulphur-bearing materials to form acidic wastewater. The acidic wastewater results from a variety of economic activities. Industrial operations, such as galvanic processing and the scrubbing of flue gases at power plants, contribute to AMD.[6] The largest contributor of AMD is the mining industry. This chapter is restricted to the latter source of AMD, because of the overwhelming contribution of the industry to the AMD challenge. Mining is a major ADM source when acidic water drains from both active and abandoned mines. The water causes adverse environmental impacts because it often contains high concentrations of metals, including iron, aluminium and manganese, and metalloids that include arsenic.[7] When this contaminated water flows into natural waterways, it elevates the acidity of the water and changes the metallic composition of the water, which has a negative impact on the flora and fauna of river systems and natural and artificial water reservoirs linked to catchment systems. The chemistry of water acidification is dealt with in the first chapter of this book. What is important for this chapter is that in South Africa, AMD is mainly related to gold mining and coal mining activities. Consequently, the country's major AMD challenge largely emanates from these two sub-sectors. This chapter thus traces the distribution and genesis of the AMD challenge impact, and provides a helicopter view of the impact, although the impact is discussed in-depth in subsequent chapters.

THE SPATIAL DISTRIBUTION OF THE AMD CHALLENGE IN SOUTH AFRICA

The distribution of South Africa's severe AMD challenges is linked to two economic minerals, namely gold and coal mining, and activities linked to the catchment areas of major inland fresh waterways. The AMD hot-spots shown in Map 2.1 will be discussed per mineral.

Map 2.1: Map showing AMD hot-spots in South Africa[8]

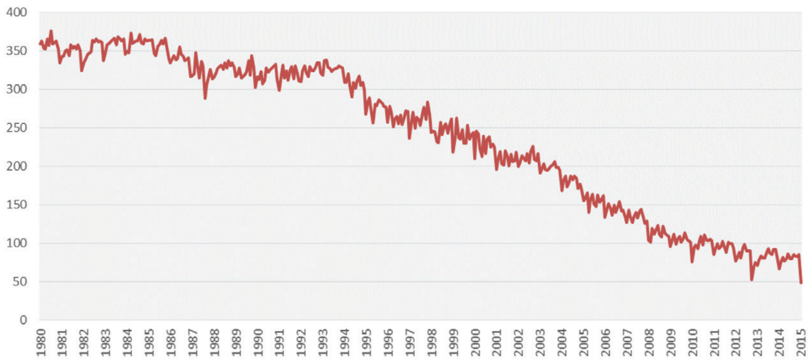


GOLD MINING AND AMD

The genesis of large-scale mining in South Africa was the discovery of gold in the Witwatersrand region in the 1880s. Initially, gold mining was confined to individual prospectors and diggers working for their own account or in small partnerships. This arrangement later changed, when individuals or small consortiums were replaced by larger ownerships, giving way to amalgamations and the listing of joint stock companies to raise adequate capital for the development of intensive operations.[9] Since then, large-scale gold mining dominated the mining industry (until recently). A critical development of the epoch was the discovery of the cyanidation process as a means to recovering gold from the refractory pyritic ore from deeper levels. Deeper mines boosted gold production but added to the AMD challenge. It was estimated that, by 2010, the Witwatersrand region had produced over 16 000 tonnes of refined gold.[10] This production was made possible through a combination of factors, including relatively good ore yields. Cheap labour under the then racially discriminatory laws up to 1994 led to innovations that enabled the exploitation of ore from as deep as three thousand metres underground. These and other factors propelled South Africa into being the world's leading gold producer in the 1980s.

Over the years, gold production in the area has declined and, in some cases, economically and technically exploitable ores have been exhausted and mining has ceased. In 2007, the country lost its global gold production leadership status to China, because of increasingly poor, deeper and declining deposits.[11] However, it remains Africa's biggest producer (Figure 2.2).

Figure 2.2: Declining gold production figures in SA from 1980 to 2015[12]

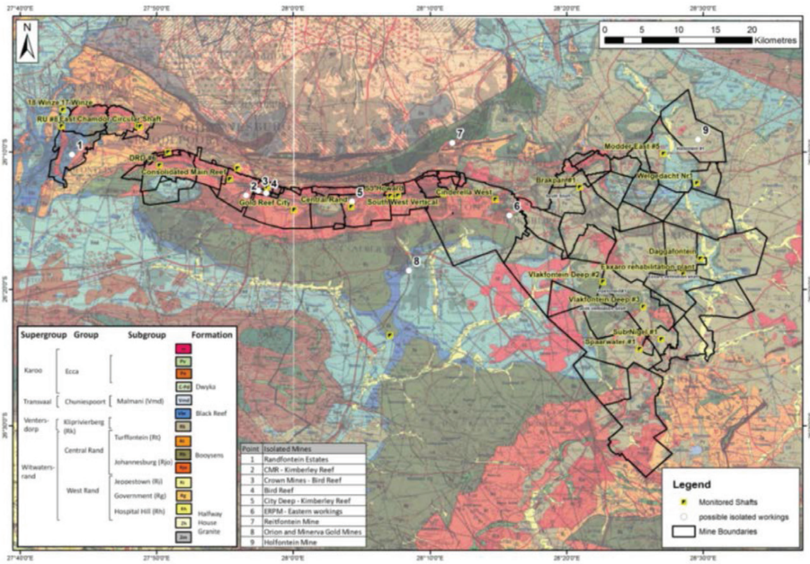


The next section provides an overview of the main areas where major mining activities have taken place and which are, coincidentally, problematic areas, in as far as the AMD challenge is concerned. Among these the Witwatersrand basin is key. It can be divided into three large gold-fields: the East Rand, Central Rand and West Rand basins, which are about 86 km long in a west-east direction as illustrated on Map 2.2. Some of the known problematic gold mining areas, in terms of AMD, are:

- Western Basin
- Central Basin
- Eastern Basin
- Free State Gold Field
- Klerksdorp-Orkney-Stilfontein-Hartbeesfontein (KOSH) Gold Field
- Far Western Basin
- Evander Gold Field

- South Rand Gold Field

Map 2.2: Map of the Western, Central and Eastern Basins and their shafts.[13]



The Western Basin covers mainly the Krugersdorp, Witpoortjie and Randfontein parts of Gauteng. This is considered the worst affected area in South Africa, as it started decanting in the Mogale City and Randfontein areas in 2002. Most of the mines are now defunct, although there is now some reprocessing of gold ores. The Far Western Basin is a gold field that geographically covers the Carletonville and Westonaria areas. Most of the mines in this area are operational.

The Central Basin spans the area from Durban Roodepoort Deep (DRD) in the West Rand to East Rand Proprietary Mines (ERPM) in the Germiston area. The Johannesburg Central area lies to the immediate north of this basin. The basin contains non-functional mines with water levels that are rising. The Central Basin is the largest of the three basins. The area was explored by several prospectors from 1875.[14]

The Eastern Basin is in the Ekurhuleni Metropolitan area. Formerly a farming region, the area's mining history can be traced back to the discovery of gold in Boksburg in 1887.[15] The Eastern Basin covers the East Rand area and includes areas like Springs, Brakpan, Boksburg and Nigel. The discovery was followed by an influx of people, as mining activities grew. The basin is characterised by some active mines, although some mines are no longer operational. The Evander Gold Field is the far eastern gold producing basin in South African and is located in Mpumalanga. The Evander mine is still operational. The South Rand Gold Field is in the area around the town of Balfour in Mpumalanga Province.

The Free State Gold Field is yet another hot-spot, extending through areas like Welkom, Bothaville, Odendaalsrus, Brandfort, Ventersburg and Virginia in Free State Province. Gold mining in this area contributes about 30 per cent of South Africa's gross domestic product.[16] The mines in this area are still functional, hence there is active pumping of mine water.

Another hot-spot is the KOSH Gold Field. This goldfield covers the four adjacent gold mining towns of Klerksdorp, Orkney, Stilfontein and Hartbees-fontein in North West Province. Most of the mines are functional, although others are no longer operational due to liquidation.

The mining activity in the region that has been ongoing for more than a century has left a number of cavities and waste rock dumps (mine dumps) that now characterise the terrain of a number of areas in the region.

Figure 2.3: A typical mine dump from gold mining on the West Rand, South Africa[17]

The abandoned mines and dumps are a source of AMD. In the abandoned mine pits, water has been accumulating, because the pumping that was practised during mine operations has stopped. The water in the pits reacts with chemicals in the exposed rocks to form AMD. At the same time, the dumps create AMD when rain water percolates into the dumps and reacts with the minerals in the waste rock. The result is AMD emerging from both underground and surface sources and flowing into and mixing with water in natural and artificial waterways. It is estimated that AMD flows from the Witwatersrand may reach a level of about 350 million litres a day if nothing is done to address the accumulation of water in the network of complex haulages, tunnels and ultra-deep vertical shafts/sub-vertical shafts in the abandoned mines and related mine dumps.[18] This is described in-depth in Chapter 3 of this book.

Gold mining in the Witwatersrand area contributes significantly to the AMD challenge, and is often the most cited, although it is not the only culpable party in this challenge. The coal mining sector has made a significant contribution to the mess.

COAL MINING

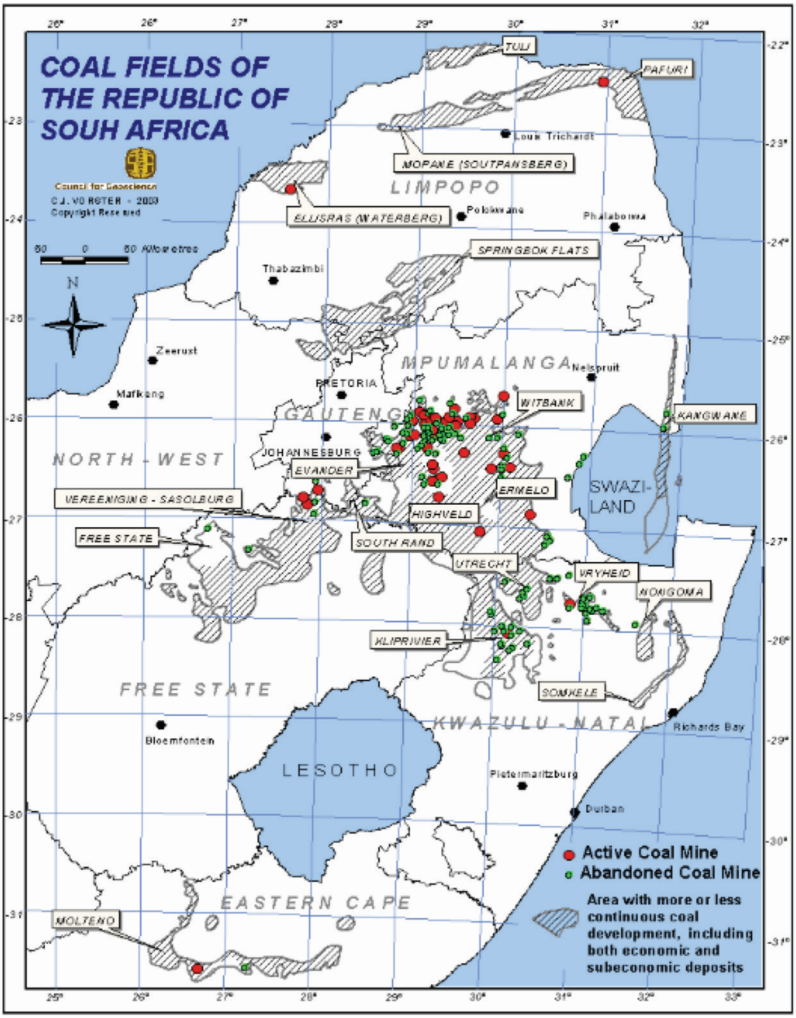
The history of coal mining can be traced back to 1894.[19] The industry grew to support the energy needs of the growing mining and manufacturing industries in the Witwatersrand area. South Africa's coal reserves lie in 18 coalfields. The largest coalfields are found in a continuous expanse from Mpumalanga into KwaZulu-Natal, as shown in Map 2.3. The seams are between 15 and 100 metres below the surface, and up to seven metres thick. Exploitation of other deposits, such as those in the north (Waterberg and Soutpansberg), has also started. As at October 2015, South Africa had 64 collieries, ranging from among the largest in the world to small scale mines.[20] However, only a few large-scale producers supply coal primarily to the electricity generation firm Eskom and the coal to liquid fuel firm Sasol.[21]

The Mpumalanga coalfields have been the most important suppliers of coal to both the local market and the export market. The Mpumalanga coalfields consist of the Witbank, Highveld and Ermelo coalfields. The Witbank coalfield is the country's oldest, with exploitation starting around 1895 in order to supply coal to the diamond industry in Kimberley. The three coalfields account for 74.8 per cent of South Africa's coal reserves, which indicates their importance.[22] The locations of these three coalfields have implications for the three main river systems in South Africa, namely the Olifants, the Vaal and the Komati.

The KwaZulu-Natal coalfields consist of the Utretch, Klip River, Vryheid and Nongoma fields, which produce mainly anthracite and coking coal. Production is small and has been declining over the years.

The Limpopo Province is home to the Waterberg coalfield. This is a relatively new coalfield that was developed in the 1970s. It has been producing mainly coal for the Matimba Power Station. However, with the Medupi Power Station near completion and the coal mining export market opportunities, it is set to increase significantly.

Map 2.3: Active and abandoned coal fields of the Republic of South Africa.[23]



These mining activities are exposing the rock to the AMD formation process and will result in an increase in the discharge of acid water when their ores are exhausted and the mines are abandoned.

As coal is one of the main minerals in South Africa that has sulphide constituents, this has resulted in hot spots of the AMD arising from coal mining covering mainly Mpumalanga, KwaZulu-Natal and Limpopo as described in the preceding section. The AMD challenge from the coal mining sector largely arises from defunct mines in the Witbank area. There are concerns that the numerous collieries will eventually contribute to the AMD challenge when they exhaust their ores and abandon the mines. Compounding this challenge is the fact that there are other mining activities alongside these coal-fields, most notable the platinum mining industry on the eastern and western limbs of the Bushveld Complex.

An AMD hot-spot has also been documented arising from copper mining in the O'kiep Copper District in the Northern Cape.[24] This is the oldest formal mining area in South Africa. Copper mining in this area started in the nineteenth century, but there are currently no major operational mines in this area.

AMD arising from gold mining has been the most commonly documented in South Africa, due to the volumes involved and the massive decanting of the AMD. However, there is an estimated 62 mega litres per day post-closure decant from coal mines in the Highveld Coalfield in Mpumalanga and around 50 mega litres per day of AMD discharging into the Olifants River catchment, which reduces the quality of water for irrigation and municipalities, and damages freshwater ecosystems and biodiversity. Further remediation is urgently required.

Figure 2.4: A pollution event by AMD from coal mining in Mpumalanga[25]

While the source of AMD formation is largely abandoned mines and their associated waste dumps, the problem of acid water spreads far beyond the immediate surroundings of the mines and mine dumps. Acid water flows on the surface or underground and eventually flows into natural waterways (streams and rivers). A cause of concern is that this water eventually reaches the country's major rivers, like the Olifants River. The adverse impact of the AMD phenomenon is contamination (sometimes lethally) of the water systems of the country (Figure 2.4). A question that begs an answer is: What is the nature and extent of the AMD challenge in South Africa? We address this question in the next section and Chapter 3.

HOW BAD IS THE SITUATION REALLY?

Acid mine drainage has been described as a ticking time-bomb. Its hazards are resident in the toxicity of high acidity and the chemical composition of AMD discharges as it accumulates in fresh water bodies and the surrounding land. These hazards have brought this challenge to the fore and it is receiving considerable attention.

The severity of the challenge is best demonstrated by the magnitude of the problem at source. Mining in South Africa has left a number of disused mines. The legacy of the intensive mining is a series of anthropogenic underground cavities with a total volume of one billion cubic metres. These cavities were not of major concern when the mines were in operation. However, they have become a cause for concern since mining ceased, because they are gradually filling with water. In addition, the abandoned mines have left numerous tailings dumps (mine dumps), which contain between four billion and six billion tonnes of waste. For example, the Witwatersrand region has approximately 244 mine dumps.[26] While the AMD contribution of an individual mine or mine dump may be manageable, the challenge becomes enormous when dealing with many more mines and dumps resulting from the more than 100 years of gold and coal mining in the region. This can be illustrated by the quantity of water discharged in the Witwatersrand region. It is estimated that the three basins in the region discharge about 15 million litres of AMD daily. A 2011 estimate stated that the West Rand was discharging 40 million litres of AMD into the Tweelopiespruit each day. The water discharged has had a number of deleterious effects. We outline three such effects. The first is that the toxic water discharged has destroyed life in the Tweelopiespruit and the Robinson Lake near Randfontein, as well as in other places.[27] The water has also contaminated the Blesbokspruit and the Marievale Bird Sanctuaries, upsetting the ecological balance. Second, the aesthetics of the dams and other waterways have been adversely affected.

Earth Life[28] stated that the waterways of the Tweelopiespruit had been coloured dark orange (Figure 2.5).

Figure 2.5: Dark orange water flow on the West Rand[29]

The orange deposit is a sign of the significant quantities of iron in the acidic mine water. Third, the waterways are characterised by the pervasive smell of sulphur in some places, in addition to high acidity, with pH values as low as 2.0.[30]

While these adverse effects are visible, there are also hidden, but long-term, adverse effects of contamination from radioactive materials and heavy metals. Taylor[31] reported the case of uranium contamination at the Robinson Dam. The contamination was measured at 40 000 times higher than the natural uranium levels in the area. These levels are higher than accepted standards for human exposure. Further to uranium contamination in the dam was the challenge of contamination from heavy metals, most commonly cadmium, zinc, arsenic, cobalt and copper. These and other contaminations have affected both the surface and underground water and the soil in the area.[32] As a result, there are reported cases of failed vegetable gardens in the area, and, where the gardens survive, there is a risk of contamination when water from the area is used to irrigate the crops.[33] A greater concern is that AMD has begun to affect horticulture on some farmlands that supply Johannesburg with fresh produce. There is reported contamination underground from river water used to irrigate fresh farm produce in Tarlton.[34] While we have only outlined the case of the West Rand, it is important to note that the Central and the Eastern basins of the

Witwatersrand region have also witnessed growing AMD discharges and also face similar devastating consequences.

A disturbing development is the application of new gold extraction technologies, which have spurred the mining industry to extract latent gold from the tailings of old mine dumps on the Witwatersrand.[35] This process generates even more acidic mine waste water, as previously buried rocks in the dump are exposed to conditions that are conducive to AMD formation. Further, some mining companies transport the reprocessed tailings to new super dumps in remote locations, where the mining waste is stored for processing in the future when advances in processing technology permit it.[36] This tacitly spread the sites of AMD formation to areas even outside the previous mining regions.

As stated earlier, the Witwatersrand is not the sole contributor to the AMD problem. A number of cases illustrate the presence of AMD discharge from coal mining areas. We will highlight three cases. The first is the level of pollution in the Olifants River (and its catchment area) which are referred to as one of most degraded and stressed river systems in South Africa.[37] The pollution largely emanates from coal mining in the Witbank area and is compounded by pollutants from agriculture, industry and sewage discharges from urban settlements in the catchment area. Coal mining in the Olifants catchment area started in the 1890s and by 2004 about 50 000 cubic metres of mine water was being discharged into the Olifants River daily, as well as 64 000 cubic metres /day from closed and abandoned mines.[38] In 2001, mine water use in the catchment area was estimated at an average 4.6 per cent of total water use in the area. However, mine water use contributed approximately 78 per cent of the total sulphate load in the river water. The Witbank and Middelburg Dams in the Olifants catchment area started showing increased sulphate and total dissolved solids (TDS) concentrations as early as 1986, mainly as a result of coal mining activity. Presently, the sulphate concentrations range between 120 and 160 mg/l.[39] This is much higher than the expected 20 to 40 mg/l had mining not occurred upstream of the dams. It is estimated that 62 mega litres/day post-closure decant from coal mines in the Highveld Coalfield in Mpumalanga. Around 50 mega litres/day of AMD is discharged into the Olifants River catchment, reducing the quality of water for irrigation and municipalities, as well as damaging freshwater ecosystems and biodiversity.

The high levels of pollution from mine water discharged have negatively affected the livelihood of farmers and urban and rural dwellers living in the catchment area. The case of Emalahleni illustrates the contribution of the coal mining sector to the AMD challenge. Schneider[40] reports a case of a landscape that is characterised by bright colours with layers of white and yellow covering former riverbeds and grasslands. She adds that the water flowing in some of the rivers is lifeless, bearing testimony to AMD pollution, which prevents the survival of flora and fauna that survived in the rivers prior to mining activity occurring. The adverse impacts of AMD have spread to the tourism sector as well, as tourists and wildlife in the Kruger National Park have been affected. In 2014, the South African National Parks reported that acid mine water had polluted a Kruger National Park river, killing a 'massive' number of fish.[41]

Against the background of the foregone, one of the concerns of the AMD challenge is its impact on water supplies to satisfy South Africa's commercial and social access to potable water, this is described in detail in Chapter 3 of this book.[42] Based on current economic and population growth projections, it is estimated that the country will have a water deficit of about 2.7 billion cubic metres by the year 2030. This implies that if the AMD challenge is not addressed, the water deficit challenge will be higher that this estimate. An interesting observation is that mining only consumes part of the eight per cent available fresh water resources used by large industries and power generation. Despite the relatively small consumption figure, the industry is a major contributor to contamination of waterways and both natural and artificial large water reservoirs in the country. This observation leads to two questions: How did we get here? and; What do we do to redress this threat? The former question is addressed in the next section and the latter is addressed in Section C of this book.

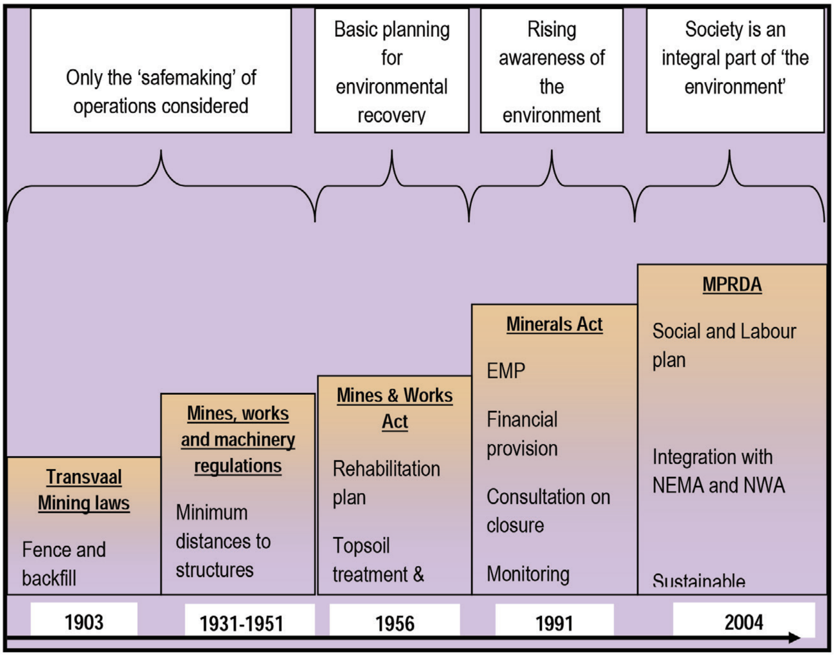
HOW DID WE GET HERE?

The enormity of the AMD challenge in South Africa can be attributed to two factors that have acted in tandem. The first factor pertains to be oblivious of the impacts of mining and the second to inertia when the AMD-mining relationship was established. The state of being unaware of the relationship between AMD formation and mining is reflected in the history of environmental legislation that has governed the mining industry. Whereas the current legal regime in South Africa holds polluters liable for the rehabilitation and remediation of polluted water, including historic pollution, history shows that this has not always been the case. An examination of the country's first attempts to regulate the industry shows that it only started in 1903, with the promulgation of Transvaal Mining Laws. Figure 2.6 highlights some of the key legislation enacted. A more detailed description of the policies and legal implications is described in Section D of this book.

Figure 2.6 shows that early mining regulations largely paid greater attention to safety aspects, with virtually no regard, or limited regard to environmental management. Between 1931 and 1951 mining was governed by the Mines, Works and Machinery Regulations. The first legislation to cover aspects of environmental management was the Mines and Works Act promulgated in 1956. Under this law, environmental management pertained to rehabilitation work that was limited to topsoil treatment and vegetation recovery. The first comprehensive piece of legislation that paid attention to environmental issues and also had a bearing on AMD management was the Minerals Act of 1991.[43] Under this Act, operating mines were required to provide funds for environmental and social rehabilitation and mine closure.

Post-1994, the laws have increasingly paid greater attention to the AMD challenge, both tacitly and explicitly. On a grand scale, managing the AMD challenge is expressed in Section 24 of the Constitution of the Republic of South Africa, 1996.[44] The section relates to the environment and the health and well-being of the people in the country.

Figure 2.6: A sample of mining related legislation in South Africa 1903-2004[45]



In this section, the Constitution guarantees the right to an environment that is not harmful to human health or well-being and to environmental protection for the benefit of present and future generations.[46] Section 24(b) directs the state to take reasonable legislative and other measures to prevent pollution, promote conservation, and secure the ecologically sustainable development and use of natural resources (including water and mineral resources), while promoting justifiable economic and social development.

This and other sections of the Constitution have been interpreted and translated into relevant sector acts and policies. For example, from the Minerals Act of 1991, the Minerals and Petroleum Resources Development Act (MPRDA) of 2002, together with General Notice Regulation 527 of 2004 and associated guidelines, a methodology which allows for the financial estimation of the closure quantum should be provided by the mining company. This estimation is to be revisited annually by the mine, in conjunction with relevant government departments, to ensure the sufficient provision of funds. However, despite these and other legal instruments, the AMD challenge persists. This is because 'polluter pays' principle is legal, but it is only applicable if its addressees are identifiable and still exist. This presents a challenge, since the majority of the mines have ceased operations and are not owned by a legal entity. Tracking down past owners of mines and holding them liable for AMD formation is a physically and legally insurmountable task. This leaves the government as the only body with the means to address the challenge, through employing public resources.[47]

While the legal regime has evolved to address AMD and other mining-related environmental challenges, a major drawback has been the inertia to initiative tangible efforts addressing these issues. Although knowledge of the link between the mining industry and AMD has been established, both the pre-democracy and democracy governments have not reacted rapidly to the problem. Indications are that the AMD challenge was identified as far back as the 1950s.[48] The response to AMD challenge has taken long. Notably, despite the identification during the 1950s and predictions by scientists in 1996, visible signs emerged around 2002 from an abandoned shaft in the Mogale City/Randfontein area of the Western Basin. One notable feature under threat is the tourist attraction Gold Reef City, which threat is caused by AMD should pumping operations in the Mogale City/Randfontein area not start or be discontinued.

CONCLUSION

In conclusion, an important consideration in the AMD discourse in South Africa is that AMD production is a challenge that is most likely to continue in perpetuity. With mining operations expanding outside the traditional mining areas, the AMD challenge will similarly expand – spatially, in magnitude and in potential severity. Given the fact that its origins date back to the 1880s, seeking to allocate blame is not a remedy. Instead, all stakeholders need to seek innovative ways to manage this challenge. This chapter has provided an overview of the historical context of the AMD challenge, a short glimpse of the spatial distribution of the AMD challenge, and a helicopter view of the impacts, and has described the legal and policy contexts, although detailed description and analysis are provided in the next sections of the book.

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CHAPTER 3

The Formation of Acid Mine Drainage

Munyaradzi Mujuru, Shingirirai S. Mutanga and Zolani Dyosi

ABSTRACT

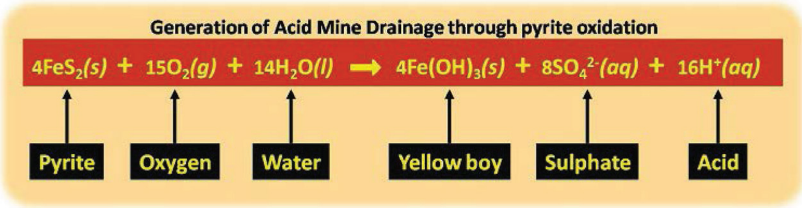
This chapter unpacks and broadens the understanding of the acid mine drainage (AMD) challenge. The chapter defines and describes the origin and chemistry of the complex formation processes of AMD, and its occurrence. The chapter describes the spatial variability in quality of AMD derived from both coal and gold mines in South Africa.

INTRODUCTION

AMD, which is also known as acid rock drainage (ARD), is one of the major polluting agents of water in many countries that have historic or existing mining and other related activities, including South Africa. The generation of AMD and its accumulation, release, mobility, spread and attenuation involves complicated processes that are dependent on a combination of biological, chemical and physical factors. In general, AMD is produced by the oxidation and dissolution of different types of sulphide minerals.[1]

The problems and challenges of sulphide oxidation and the resulting AMD generation has become a focus of research in the last 50 years or more. The term AMD is commonly used (rather than ARD) because this complicated process occurs mainly in current mining sites or abandoned mines. The acidic water formation process occurs in mining tunnels, mine workings, mineral processing sites, open pits, waste rock piles and mill tailings. The chemistry and processes of AMD formation result in acidic water. The acidic water is dependent on the local geology of the mining area, whether or not micro-organisms, oxygen and water are present, and the prevailing temperature. These parameters affect AMD formation and differ according to region; as a result, the prediction, prevention, composition, containment and treatment of the acidic water must be determined with extreme care and specifically for a particular type of AMD.[2,3]

Figure 3.1: The chemical generation of AMD (ARD)[4]



AMD is a strongly acidic wastewater with high levels of ferrous and other metal sulphates and salts in a solution. If AMD is left untreated, it contaminates ground and surface water resources and soils as it accumulates, negatively affecting the health of plants, humans, wildlife and aquatic life. The research, development and optimisation of cost-effective and sustainable remediation and treatment solutions for the acidic water problem have been described and detailed in this book in the subsequent chapters. Even though AMD has been highlighted as a looming problem since the 1970s, because of the many influential stakeholders with powerful conflicting interests and incentives regarding action, no single party has produced the required combination of scale, processes, resources and credibility to deal with the problem of AMD. Stakeholders include national government, local government, non-governmental organisations and mining companies.[5]

THE CHEMISTRY OF AMD FORMATION

As discussed in Chapter 2, South Africa has extensive coal and gold mining operations that have been running for several decades. Both of these mining activities result in the generation of AMD. Coal and gold-bearing rock contains several minerals that can result in AMD.[5]

The main cause of acidic mine water formation is the oxidation of several sulphide minerals (listed in Table 3.1 and including pyrite minerals (FeS_2)), due to exposure of these minerals to oxygen, water and micro-organisms. Although the AMD formation process is known to occur naturally, mining and related activities accelerate the process of AMD formation, because such activities increase the exposure of the sulphide-bearing rocks to air, water and micro-organisms. As a result, AMD formation and accumulation are prominent in operating and inactive or abandoned mining sites, and are common in both coal mines and gold mines in South Africa – in underground tunnels and shafts, open pits, waste rock piles and mill tailings. Even though acidic water is less critical when the mine is still running, since the underground water table levels are kept low by pumping processes, it is a huge challenge with closed mines and abandoned mines, where pumping has ceased, resulting in the increase in underground acidic water levels. The rebound of the water table is well illustrated in Randfontein, where AMD has begun to decant on the surface in huge quantities.[6]

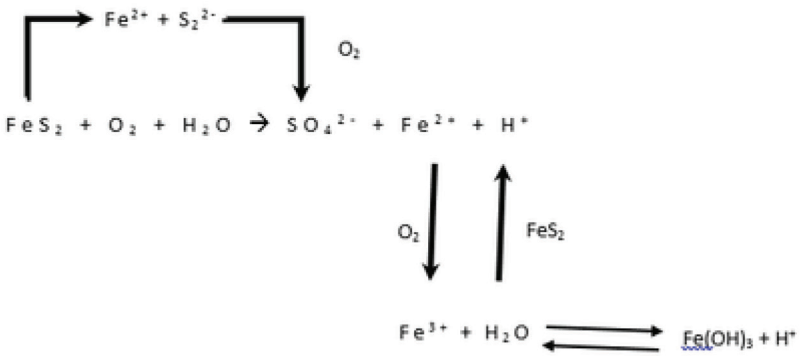
Table 3.1: Some important metal sulphides in AMD formation, with pyrite and marcasite being the predominant acid producers[7]

Metal sulphide	Chemical formula
Pyrite	FeS_2
Marcasite	FeS_2
Pyrrhotite	$Fe_{1-x}S$
Chalcocite	Cu_2S
Covelite	CuS
Chalcopyrite	$CuFeS_2$
Molybdenite	MoS_2
Millerite	NiS
Galena	PbS
Sphalerite	ZnS
Arsenopyrite	FeAsS

The process of acidic mine water formation is complicated, because it includes chemical, biological, electro-chemical and physical reaction processes that differ according to environmental and local geological conditions. Several sulphide minerals found in various ore bodies are formed in reducing environments in the absence of oxygen. Exposure of these various sulphide minerals to atmospheric oxygen or water with oxygen, due to mining, mineral processing, excavation, or other earthmoving processes (like road construction), causes these sulphide minerals to be unstable and they then oxidise.[8,9]

The reactions that take place during oxidation of FeS_2 clearly illustrate the process of AMD formation. Pyrite is one of the most commonly and well-known sulphide minerals. As illustrated in Figure 3.1, the oxidation of pyrite minerals occurs in terms of several reaction pathways, which have surface interaction processes with dissolved O_2, Fe^{3+} and other catalyst species, including MnO_2.[10,11]

Figure 3.2: The oxidation of pyrite leading to AMD formation[12,13]



The initial critical reaction in AMD generation is the process of oxidation of pyrite (or sulphide) into iron (II), sulphate and elemental hydrogen. The rate of this pyrite oxidation process and the resulting acid formation and accumulation are dependent on solid-phase compositional factors, microbial processes and the availability of elemental oxygen and water. The presence of sulphate ions in acidic mine waste water is the first indicator of sulphide mineral oxidation. In oxidising environmental conditions that depend on oxygen concentration, a pH above 3.5 and bacterial activity, iron (II) is released, which is oxidised to iron (III). If oxygen concentration is low, oxidation of iron (II) will not take place until the pH reaches about 8.5. In general, under varying conditions, oxidation of iron (II) is the rate-determining step in oxidation of various pyrites, because the conversion of iron (II) to iron (III) is slow at pH values below five under abiotic conditions with no micro-organisms present. At pH figures ranging between 2.3 and 3.5, iron (III) may undergo precipitation as $Fe(OH)_3$ and, to a lesser extent, as the mineral Jarosite, $H_3OFe_3(SO_4)_2(OH)_6$, leaving little concentration of Fe^{3+} in the solution, while lowering the pH values at the same time.[14,15]

When pH decreases below two, the products of ferric hydrolysis are not stable; as a result, iron (III) ions remain in the solution. An example of ferric hydrolysis products is $Fe(OH)_3$. Nevertheless, any unprecipitated Fe^{3+} that does not undergo precipitation into $Fe(OH)_3$ (or Jarosite) from the solution is usually used to oxidise additional pyrite minerals, making these processes form more and more AMD.[16]

The oxidation process of various pyrite minerals by ferric iron ions results in more acid formation. While elemental oxygen is the main oxidising agent, ferric iron (Fe^{3+}), resulting from the oxidation process of ferrous iron, is now accepted as a more potent oxidising agent than elemental oxygen, even at somewhat neutral pH conditions. In fact, at pH conditions of around 3.0 or so, the oxidation process of pyrite minerals by ions in a solution occurs at a fast rate — about 10–100 times faster than oxidation by elemental oxygen — making the oxidation of pyrites by iron (III) ions in a solution the dominant reaction process. This mechanism is attributed to more efficient electron transfer of Fe^{3+} ions compared to elemental oxygen.[17]

When iron (II) is produced and there is sufficient dissolved oxygen present, the oxidation of iron (II) and the precipitation of Fe^{3+} to $Fe(OH)_3$ continue until the supply of iron (III) or pyrites is diminished. However, even without dissolved elemental oxygen in the presence of Fe^{3+}, oxidation of sulphide minerals will continue to take place until completion and the water will have elevated levels of iron (II). Chemical modelling has shown that these reactions, which lead to AMD, will continue for centuries.[18,19]

In summary, from the above discussion, the processes leading to the formation of AMD may be considered to occur in three major steps:[20]

- The usual oxidation processes of iron sulphide minerals by elemental oxygen, accompanied by the enhanced oxidative processes of sulphide minerals by ferric iron.
- Oxidative processes of ferrous iron in a solution.
- The process of hydrolysis, followed by the precipitation of iron (III) and other associated minerals.

It is important to note that in naturally acidic systems, oxidation of iron (II) and pyrite can be significantly accelerated by the presence and activities of acidophilic bacteria such as *Thiobacillus ferroxidans*. These bacteria are thought to be involved in pyrites weathering and are known to be widespread in the environment. *Thiobacillus ferroxidans,* for example, has been shown to increase the rate of iron conversion to ferrous iron by factors of hundreds to as much as a million.[21]

The oxidation processes and leaching mechanisms of sulphide-bearing minerals by bacteria were initially thought to comprise two or three different mechanisms. The first was by the bacteria attaching onto the sulphide mineral particle surface, resulting in direct oxidation of iron and sulphur species in the minerals by biological means and release of metal ions in the solution. The second mechanism is not a direct one, and it is assumed to involve the bacteria in a solution that oxidises ferrous iron to iron (III) and elemental sulphur to sulphates, respectively, followed by the generated ferric iron leaching the sulphide mineral.[22,23]

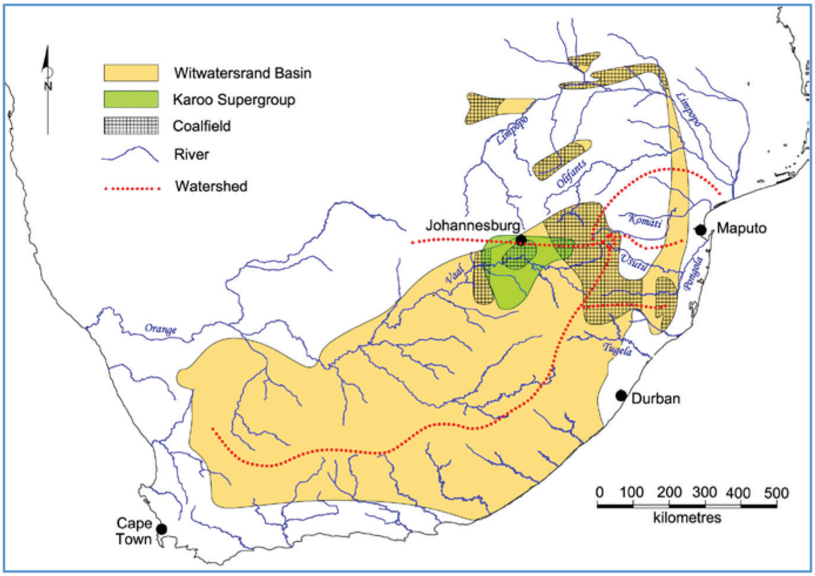
The last mechanism is indirect contact and is based on the assumption that the bacterial cells attach onto the sulphide mineral surface and produce polymers and form an exopolymeric layer. The bacteria concerned subsequently oxidise ferrous iron to ferric iron within this exopolymeric layer.[24]

THE OCCURRENCE OF ACIDIC MINE WATER IN SOUTH AFRICA

In South Africa, most acid mine water is associated with gold mining and coal mining. As described in Chapter 2 in this book, gold mining has been undertaken in South Africa for decades and includes current reworking of old mining waste. Coal mining has also been undertaken, but is now in a boom period, since there is a need for more coal for electricity generation locally and for export.[25]

As mentioned earlier in this chapter and elsewhere in the book, mining activities lead to increased exposure of pyrite-bearing rocks, water and oxygen. The water is mainly from rainfall and results in AMD generation. This process takes place via different mechanisms and processes in gold mining and coal mining. The acid mine water therefore primarily affects the environment where these two minerals are mined in South Africa, as shown in Map 3.1. Secondary effects occur in afar regions to which rivers coming from areas affected by coal mining and gold mining flow. This topic is discussed in detail in Chapter 4.

Map 3.1: The distribution of coal and gold deposits, where most of the AMD is generated[26]



ACID MINE WATER ASSOCIATED WITH GOLD MINING IN SOUTH AFRICA

In the Witwatersrand area in South Africa, gold exists in layers of complex conglomerate rock systems that are part of the approximately 7 000 m thick sequential sedimentary rocks known as the Witwatersrand Supergroup. These layers of rock are about a metre in thickness on average. These conglomerate rocks do not have uniform gold mineral content. It is only in certain localised rock areas where gold is present in economically viable and recoverable concentrations. These gold-bearing areas form the goldfields that have been mined over many years, but only a few of the conglomerate layers have been mined within any individual goldfield.[27]

The mining processes involve extracting the gold-bearing layer and transporting it to the surface for the ore to be crushed and for subsequent extraction of gold. Some conglomerate layers are left unmined to act as support to ensure the safety of workers still working underground. Some of the layers not mined have too poor a gold concentration to justify extraction. After extraction of gold and other useful products, the waste rock is dumped in waste heaps that are commonly known in the mining industry as slimes or tailings dumps. These are abundant in the Witwatersrand area. These gold-bearing rocks contain about three per cent pyrite minerals, which end up on the waste dumps. When rainwater falls on the mining waste dumps, it oxidises the pyrite minerals, forming sulphuric acid, which then percolates through the waste dump, dissolving toxic heavy metals such as uranium, cadmium, lead and iron as it transits through the mining waste. The acidic water usually flows from the base of the mining waste dump and pollutes the local groundwater as a plume. This acidic water (AMD) ultimately emerges on the surface, as is happening in Randfontein and in the streams and rivers draining the regions around the waste dumps. In most cases, streams that are draining areas with tailings dumps are acidic and have high concentrations of sulphates and heavy metals.[28]

Water Rhapsody puts it more clearly: 'A bitter paradox is unfolding in the economic heartland of South Africa: we're short of water to drink; we are also running out of gold. Yet, as the sun sets on the gold industry, the waters beneath her commercial capital are rising'.[29]

It is thought that millions of cubic metres of water are contained in the dolomitic aquifers (which are known to be spongy) that lie beneath the Witwatersrand area of South Africa. Before mining began in the eighteenth century, the water contained in these aquifers was pristine, but the only alternative way for mining to be done was to extract the water using large drainage pipes to pump the water to the surface. It has been confirmed that so much water has been left in these underground spongy aquifers and tunnels by mining that one estimate says the amount of water is equal to five times that of the water in Lake Kariba (approximately 25 000 square kilometres in area).[30]

The problem is that good water is now being poisoned by bad water (AMD), since it has now been proven that the acidic water is infiltrating and polluting these huge natural spongy aquifers. The AMD is coming from the abandoned mine voids underneath the Johannesburg area. The mine voids, which stretch from the west to the east of the city of Johannesburg, were dug out during mining activity carried out over a period of more than 120 years, and are estimated to have a volume of about 400 million cubic metres (now filled with acidic water). This extensive mining led to the formation of AMD by exposing sulphide rocks to air and bacteria and it has been accumulating over time.

THE QUALITY OF ACID MINE WATER ASSOCIATED WITH GOLD MINING

The quality of AMD generated in gold mining areas differs from area to area, depending on the local quality of the rocks carrying the pyrite minerals that leads to AMD formation. In the Witwatersrand area the AMD quality differs from the Western Basin, the Central Basin to the Eastern Basin. The AMD quality also differs with seasonal variations, especially with the rainfall pattern. The interconnection of unknown and abandoned underground tunnels has also been shown to affect the quality of AMD. In areas where mines are still active, it is possible that they may be dumping their waste water into the mining voids, which are already full of AMD. This has led to unexpected AMD quality variations – sometimes in one day. Table 3.2 below summarises the differing AMD quality according to the regions in the Witwatersrand area.[31]

Table 3.2: The varying AMD quality according to area in the Witwatersrand area[32]

Parameter	Western Basin	Central Basin	Eastern Basin	Guideline
pH	3.5	2.8	6.65	5-10
Electrical Conductivity (mS/m)	510	467	246	250
Sulphate (mg/L)	4 800	3 700	1 037	500
Fe (mg/L)	800	112	38	10
TDS (mg/L)	6 580	4 936	2 041	1 600
Source	Rand Uranium	Scott, 1995	Grootvlei Mine	DWAF

The data shows that: the Western Basin's AMD has the highest concentrations of sulphates, iron and total dissolved solids; the Central Basin's AMD has the lowest pH. Most of the quality parameters shown in the table for all three basins are far above the quality guidelines provided by the Department of Water and Sanitation, except for iron in the Central and Eastern Basins. The differing AMD quality also means that the treatment methods for the AMD in these basins will be different, as treatment must be adapted to each specific basin.

ACID MINE WATER ASSOCIATED WITH COAL MINING IN SOUTH AFRICA

South Africa is one country that boasts huge coal deposits and the country is the sixth largest producer in the world and the fifth largest exporter of different types of coal. Despite concerns about global warming, coal still plays a critical role in South Africa's domestic economy, with about 93 per cent of South Africa's electrical energy being generated by coal-fired thermal power stations. Most collieries are located in the Mpumalanga Province, and specifically in the vicinity of the towns of Ermelo, Middleburg, Witbank and Secunda.

Coal production, processing and use resulting a number of serious and negative environmental impacts, such as global warming caused by greenhouse gases emitted by coal combustion. Coal combustion produces gases such as carbon dioxide (CO_2), nitrous oxides and sulphur dioxide. CO_2 emissions from combustion of different fuels were around 340 mega tonnes in 2006, making South Africa the fifteenth largest emitter of carbon dioxide in the world. Eskom, which is South Africa's main power producer, has several coal-fired power stations. Sasol, which is a commercial producer of fuels and chemicals from coal (using the Fischer-Tropsch process), produces the majority of the emissions.[33] However, perhaps the most critical environmental concern is that of AMD associated with the mining, processing and use of coal.[34]

The coal found in South Africa is carried in several layers within sedimentary type rocks in the Karoo Supergroup region. It is known that both the coal and the host sedimentary rocks carry within them the pyrite minerals (FeS_2); when exposed to atmospheric oxygen and water, and with the presence of several bacterial types, these minerals are oxidised to form sulphuric acid. The oxidative process that forms AMD is known to also occur naturally in unperturbed rocks, but at a slower rate, such that it is normally and easily neutralised by different types of buffering minerals (such as carbonates and hydroxides), and by the process of hydrolysis of alumina silicate minerals. Mining activities carried out during the coal extraction process increase the exposed surface area of these sulphide-bearing and sulphur-bearing rocks, generating sulphuric acid that exceeds the buffering capacity and capabilities of the local natural environment. The resultant AMD increases the solubility of iron, aluminium and other heavy metals, thus making surface and groundwater toxic and unusable.[35]

The Karoo Supergroup in which coal is found is widespread in Southern Africa, but coal found in this supergroup is restricted and common to the regions shown in Map 3.1 in South Africa. In the regions shown in Map 3.1, coal is extracted by underground mining processes and by various opencast methods. Unlike the methods used to mine gold, the coal is usually transported from the site where it is mined and there is usually very little or no surface dumping of mining waste. As mentioned earlier, both coal and the coal-bearing host rock carry pyrites, but the pyrite minerals are usually more concentrated in the coal seams. Underground mining activity often results in the collapse of the overlying rock layers. When mining is terminated, the voids or tunnels in the fractured rock fill with mining wastewater, and decanting of acidic water occurs at the lowest opening. The water produced starts to decant on the surface and is acidic as a result of the reaction with different pyrite minerals in unmined coal seams and coal-bearing rocks.[36]

During the activities involved in opencast mining, blasting is done and the removal of overlying rocks follows. The fragmented overbearing rock is replaced (backfilled) and covered with ordinary soil material, so as to rehabilitate the terrain. Rainwater percolating through the soil cover into the backfill material of various minerals, including pyrites, becomes acidified in the process and ultimately decants on the surface as AMD. In most cases, decanting of AMD on the surface generally starts around a decade or more after mining has been stopped. Opencast mining alters and pollutes the usually good quality natural groundwater resources and radically and negatively changes the groundwater to surface water interaction processes.[37]

Oxidation of different sulphide minerals is the main cause of acid mine water generation. Minerals, such as various pyrites (FeS_2), form AMD when they get in contact with oxygen, water and micro-organisms. Although the AMD generation process is known to occur naturally, mining and related activities accelerate the process of acidic water formation, because such activities increase the exposure and interaction of different sulphide minerals with air, water and micro-organisms. As a result, AMD is a prominent environmental challenge in both operating and inactive or abandoned mining sites – in underground tunnels or voids and shafts, open pits, gullies, waste rock piles, and mill tailings or dumps. Although the environmental concerns about AMD are less critical and important when the coal mine or gold mine is in active operation, because water tables are kept low by pumping and treatment, it is a severe challenge in closed and abandoned mines, where pumping has ceased, resulting in rising water tables.[38] This is common in Mpumalanga, where some coal mines have been abandoned.

LESSONS FOR AFRICA

In many African countries, the mining industry is still in its infancy. Countries like Kenya, Uganda and Tanzania have recently discovered gold and are starting to exploit these resources. Mozambique and Botswana have started to mine coal for export and local utilisation. These countries, and others like Zimbabwe and Zambia, have still to experience the scourge of AMD which South Africa is experiencing. Zimbabwe has seen massive gold mine closures in recent years due to viability problems. Mine closure means that the pumping of wastewater has stopped and these mines are rapidly filling up with AMD and there are reports of this toxic water being a few metres from the surface. Such is the case in a study done on the Iron Duke mine in Mazowe Zimbabwe, where experiments revealed AMD traits in 1994.[39] Although the magnitude is not pronounced compared to South Africa, these countries could learn from South Africa and overcome this problem.

African counties embarking on the mining trajectory for decades need to assess the risks involved, as South Africa has done, to come up with comprehensive legal and policy frameworks so as to preserve water resources and the environment. Some of the intervention and prevention measures are discussed later in this book (Chapters 7 to 13). South Africa has invested much in terms of time, research and finances into the problem of AMD and could start to benefit from this investment by exporting some of the successfully tested technologies to other African countries.

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CHAPTER 4

Impact of Acid Mine Drainage on Water Resources in South Africa

Tichatonga Gonah

ABSTRACT

This chapter provides a detailed description on the impacts of acid mine drainage (AMD) on water resources from the South African context. A discussion is provided on the various mechanisms through which water resources are affected by AMD. The main mechanism through which AMD affects water resources has been found to be the contamination of freshwater resources and the associated consequences. The impact of AMD on water resources has been documented, mainly for the Witwatersrand basin and the Mpumalanga coalfields, which have all been under exploitation for over a century. Results from water quality analysis in these affected basins indicate that the water is unsuitable for any use without suitable treatment. The focus has also been on the implications of AMD on the water security situation in the South African context. AMD has been found to potentially affect water security negatively for both South Africa and its neighbouring states, which share both groundwater and surface water resources, if the situation is not dealt with. A suite of short-term to long-term lessons that can be learnt by other African countries from the South African AMD situation have been incorporated.

INTRODUCTION

The problem of AMD has affected both groundwater and surface water resources in South Africa. Continued gold mining has resulted in deep shafts and reefs which, when flooded, precipitated in AMD formation in the Witwatersrand basin as alluded to in Chapter 2 of this book. After the extraction of gold from the ore, the waste rock is heaped into waste rock dumps that form AMD upon oxidation in the presence of rainwater; this pollutes groundwater from the foot of the dump.[1] For this reason, groundwater has been the primary water resource that is polluted in such situations and surface water resources get polluted when the flooded shafts decant. However, coal has been mined primarily through opencast methods, but with underground methods also being used to a lesser extent. Both mining methods tend to affect groundwater, primarily because they alter the natural groundwater system. Surface water is affected when the AMD eventually decants.

The main drivers of the growing interest in the problem of AMD are the negative impact of the AMD on the water resources of South Africa and the fact that South Africa is a water scarce country. South Africa experiences huge disparities in the precipitation it receives and some areas are generally water scarce areas, for example, the western half of the country. The country has numerous inter-basin water transfer schemes that aim to alleviate this problem. In order to reduce the magnitude of the problem, there is a need for a good understanding of the impacts of AMD on the water resources.

WAYS IN WHICH AMD AFFECTS WATER RESOURCES

AMD is responsible for a wide array of effects on both groundwater and surface water resources; in most cases these are quite serious. Some of the ways in which AMD affects water resources include the following:

CONTAMINATION OF WATER RESOURCES

This is the most serious and problematic impact of AMD on the receiving waters. The contamination problem arises from the products of the chemical reactions that take place upon oxidation of a sulphide mineral in the presence of water. AMD can contaminate both surface and groundwater resources. The key mechanism of contamination is mainly acidic water that is rich in sulphates and metals like iron, manganese and zinc.

One of the key products of the reactions that form AMD is very acidic water that is often unsuitable for any use. The oxidation of the sulphide minerals (mostly pyrite) produces sulphate and ferrous iron. When ferrous iron is oxidised, ferric iron is produced, which forms an iron oxide and acid when it precipitates; the oxidation of the additional sulphide by the ferric iron produces further acid and sulphates. The net result is the highly acidified water exiting from the mineral, oxygen and water reaction front. In the

Western and Central Witwatersrand Basins, the pH of AMD was typically between two and three, making the water very acidic and unsuitable for any use.

One of the key characteristics of the AMD is the very high levels of sulphates. This is because one of the key ingredients in AMD formation is sulphide minerals, for example, pyrite, bornite or chalcopyrite. Oxidation of the sulphide in the presence of water will result in a breakdown of the sulphide into ferrous iron, sulphate and acid. An increase in the acidity of the water results in further production of sulphates, as the whole process is perpetuated.

The net result is water with very high sulphate levels, rendering it unfit for domestic, irrigation and livestock watering purposes and for disposal in aquatic habitats. Case studies conducted in the Witwatersrand Basin yielded sulphate results as high as 2 934 mg/l[2] and 2 080 mg/l,[3] whilst in the Witbank Coalfield, sulphate levels were as high as 2 352 mg/l and 3 522mg/l for water samples collected from a borehole and stream, respectively.[4] This is much higher than the legal limits for domestic use in South Africa, where the upper limit for long-term use (Class I) is 400 mg/l.[5]

Water with high levels of sulphates has been identified as causing catharsis, diarrhoea and dehydration in humans.[6] This therefore means that water with high levels of sulphates is unsuitable for human consumption.

The reaction of the acid produced from the AMD formation and the minerals, results in their solubility (heavy metals) in water. This leads to high levels of heavy metals, which are normally in minute concentrations in uncontaminated water resources. They are leached into surrounding water resources, like aquifers, or drain into adjacent rivers via flowing water. Examples of such metals include mercury, zinc, copper, nickel, lead, cobalt and arsenic. These are non-bio-degradable and can thus accumulate in living organisms that may have consumed them. Acute exposure to the heavy metals in large concentrations can result in the death of the living organisms: high concentrations of heavy metals are toxic to humans, animals and plants and can cause deformities in organisms.

An example in the Witwatersrand Basin is a borehole where iron and manganese levels were recorded as 197 mg/l and 18.9 mg/l, respectively.[7] In the Eastern Basin, raw water pumped at Grootvlei Mine had average concentrations of 135 mg/l and 4.1 mg/l for iron and manganese, respectively. These concentrations are hundreds of times above the Department of Water and Sanitation's upper limits for long-term use of water for domestic purposes (limits for Class I), which are set at 0.2 mg/l and 0.1 mg/l for iron and manganese, respectively — and according to the South African National

Standard (SANS 241) for drinking water, which specified limits of 2 000 μg/l (2 mg/l) and 500 μg/l (0.5 mg/l) for iron and manganese, respectively. Consumption of such water is unsuitable because of its toxicity.

The high concentrations of sulphates and, in some cases, calcium and magnesium, increase the level of dissolved salts, which provides an increased level of total dissolved solids (TDS) in water contaminated with AMD. This results in salty or brackish water that often causes secondary salinisation when the water evaporates (for example after irrigation), with this water resulting in an accumulation of these salts in the soil. A South African example is the increase in the salinity of the water in the Vaal River: it more than doubles between the Vaal Dam and the Vaal Barrage, due to the inflow from the Klipriver and the Blesbokspruit.[8] This necessitates periodic releases from the Vaal Dam to reduce the salinity of the water downstream of the dam, in order to ensure it is suitable for the different users.

A combination of the above factors (namely acidic water, with very high sulphate and heavy metal concentrations) results in the water being unsuitable for most, if not all, water uses. This is because the water becomes toxic to humans and other organisms (for example, livestock) and causing health problems or death.

The Department of Water and Sanitation's guidelines for drinking water (as outlined in Table 4.1) can be used in categorising the different classes in which the water falls:

Table 4.1: Drinking water guidelines[9]

Constituent	Unit	Class 0	Class I	Class II	Class III
Total dissolved solids	mg/l	< 450	450 – 1 000	1 000 – 2 450	> 2 450
Electrical conductivity	mS/m	< 70	70 – 150	150 – 370	> 370
Nitrate plus nitrite as N	mg/l	< 6	6 – 10	10 – 20	> 20
Fluoride	mg/l	< 1.0	1.0 – 1.5	1.5 – 3.5	> 3.5
Sulphate	mg/l	< 200	200 – 400	400 – 600	> 600
Magnesium	mg/l	< 30	30 – 70	70 – 100	> 100
Sodium	mg/l	< 100	100 – 200	200 – 400	> 400
Chloride	mg/l	< 100	100 – 200	200 – 400	> 600
pH	pH units	<6.0 – 9.0	5 – 6 or 9 – 9.5	4 – 5 or 9.5 – 10	< 4 or > 10
Iron	mg/l	< 0.1	0.1 – 0.2	0.2 – 2.0	> 2.0
Manganese	mg/l	< 0.05	0.05 – 0.1	0.1 – 1.0	> 1.0

Zinc	mg/l	< 3.0	3.0 – 5.0	5.0 – 10.0	> 10.0
Arsenic	mg/l	< 0.010	0.010 – 0.050	0.050 – 0.2	> 0.2
Cadmium	mg/l	< 0.005	0.005 – 0.010	0.010 – 0.020	> 0.02
Faecal coliforms	Counts/ 100ml	0	0 – 1	1 – 10	> 10
Ammonia	As N	< 1	1 – 2	2 – 10	> 10

Class 0 is ideal for drinking purposes, whilst Class I is suitable for lifetime use. Class II is suitable for short-term or emergency use and Class III is unfit for domestic use without suitable treatment. For purposes of determining whether the water is acceptable or not for drinking purposes, the SANS 241 standard can be used.

What is critical in terms of using water for drinking purposes is Class III, where water is not suitable for drinking purposes without suitable treatment. Such water has constituents at high concentrations which will cause serious health effects, especially in infants and elderly people. The concentrations of most parameters tested in the AMD of most South African hotspots fall in this class, making the water toxic and unsuitable for human consumption. Although the limits for other water uses are not discussed in this chapter a consideration of the concentrations of the different parameters in AMD is essential. It is known that water contaminated with AMD is not suitable for most uses like irrigation and livestock watering, though it needs to be addressed on a case to case basis. Based on the SANS 241 drinking water standards of 2011, it can be concluded that water contaminated with AMD is not suitable for drinking purposes.

TURBIDITY

AMD generation can greatly increase the turbidity of the receiving water, thus affecting plant and aquatic life.[10] This is triggered by the formation of iron (III) hydroxide that is a yellow–orange solid known as yellow boy. The suspended solids can be found at the AMD site or away from the AMD site, as they are transported with flowing water. These solids have the effect of reducing the amount of light in the water, thus adversely affecting biotic organisms as discussed under the section headed Biodiversity.

DESTRUCTION OF AQUIFERS, SINKHOLE FORMATION AND LOSING STREAMS

This physical effect on water resources occurs when the acidic water flows over carbonate aquifers (mainly dolomite and limestone aquifers), resulting in the dissolution of rock particles and thus opening up solution holes. This can result in the creation of huge cavities underground that eventually result in land subsidence and the formation of sinkholes – a phenomenon that destroys some of the best known productive aquifers. Losing streams is associated with karst topography when the carbonate rocks are exposed on the surface and a stream vanishes into the sub-surface with the water emerging (in some instances) kilometers away from where the water joined the sub-surface system. This can negatively affect the ecosystem of the stream, for example, a riverine ecosystem and the riparian zone. So both groundwater and surface water resources can be negatively affected in areas dominated by carbonate rocks. This can also promote further contamination of groundwater resources, as the large openings and sinkholes promote water entering and moving rapidly within the groundwater system.

This phenomenon has been observed in the Far Western Basin of South Africa. The formation of sinkholes in this area is prevalent due to the underlying dolomite. Slime dams that were sited above the dolomite area caused seepage of acidic water that accelerated sub-surface erosion, leading to the formation of sinkholes in several slimes dams. This was problematic to such an extent that, in one of the slimes dams, 52 sinkholes were formed in 12 years, resulting in the release of uranium-rich material in the aquifer and thus contaminating the aquifer.[11] Sinking streams were also observed in this case study, which eventually added contaminated water to the groundwater system. In the Eastern Basin, which is also underlain by dolomite, the risk of sinkhole formation due to AMD water flowing through the dolomite strata has been identified.[12]

SMOTHERING EFFECT

Turbidity also has a smothering effect wherever the water flows. The smothering effect is seen when the river- or stream bed is coated with fine sediment from the precipitates that settle. This affects the aquatic life that depends on the stream.

IMPACT OF AMD ON WATER RESOURCES IN SOUTH AFRICA

The impact of AMD on water is seen to be at different stages in different areas in South Africa. This section will unpack the different stages of development of AMD and the underlying reasons.

The Western Basin covers the area that has been worst affected by AMD. The mining shafts started decanting as far back as August 2002, polluting the Tweelopiespruit that drains into the Krugersdorp Game Reserve.[13] This has been exacerbated by the abandoned non-operational mines, mine residues acting as non-point sources of AMD and water ingress into the mine shafts. Although the then Department of Water Affairs issued a directive to the operational mines to pump and treat AMD, the main challenges have been the limited capacity of mines to treat AMD and the mines being defunct and ownerless, which has forced the government to mobilise funding for this purpose.

AMD decants through three old mine shafts, namely the Black Reef Incline, Number 17 and Number 18 Winzes.[14] The decant volume has been recorded at an average of 20 million litres per day (Ml/d), although there have been recorded peak volumes of up to 60 Ml/d during wet periods. Roughly 12 Ml/d is partially treated, with the rest flowing freely into the Tweelopiespruit. About 27 Ml/d of AMD need to be treated in this basin to maintain the water below the environmental critical level (ECL), which is the level that the water in the shafts and voids should not rise above if specific environmental features are to be protected, including groundwater.

The Tweelopiespruit had a number of water quality parameters that exceeded the guidelines for stock watering and aquatic ecosystems, and biomonitoring results indicated a shift from ecological category C (moderate modification and moderate levels of localised contamination) to category F (heavily modified and high levels of contamination that render the water resource unsustainable and unusable) between the years 2000 and 2004, thereby showing significant ecological degradation as a result of AMD decanting.[15] The long-term implications of decanting in this stream include the pollution of: the Hartbeespoort Dam and, to its downstream, the Crocodile River, on which the Hartbeespoort Dam is sited; and the transboundary Limpopo River, as will be discussed later in this chapter.

Very high sulphate concentrations of about 3500 mg/l and a pH ranging between two and three in water decanting from the Western Basin have been reported.[16] This is far above the upper limit for Class I (suitable for long-term domestic use) according to the Department of Water and Sanitation's water quality guidelines, which indicates a sulphate level maximum of 400 mg/l and a pH of between 5 and 6 or between 9 and 9.5. The water also has high levels of iron and other heavy metals. There is also an orange streak due to the oxidation of ferrous iron to ferric iron, which occurs after exposure to the air and causes precipitation of ferric hydroxide that leaves a bright orange streak (yellow boy) along river beds and banks. This shows that, besides the pollution of the spruit, the turbidity has been adversely affected by AMD.

The death of 27 animals (nine lions and 18 springbuck) recorded in the Krugersdorp Game Reserve a few months after the decanting, were possibly due to AMD.[17]

Figure 4.1: AMD in the Western Basin[18]

Figure 4.2: Uncontrolled decanting in the Western Basin[19]

The ECL for the Western Basin is 1 600 metres above mean sea level (mamsl), which will prevent water from entering the dolomite via the Black Reef Mine workings, thus also preventing groundwater from entering the compartment that hosts the Cradle of Humankind.[20] This could be lowered in the future should it be deemed to be insufficient so as to have a higher buffer.

The Central Basin has not recorded any decanting, although it is predicted that it will take a few years for the AMD to decant. Mine water was being pumped until October 2008, when the process was stopped because of safety issues. The issue of inadequate ventilation, owing to high carbon dioxide levels, resulted in two fatalities at the underground workings of East Rand Proprietary Mines (ERPM), which lead to pumping being stopped. The challenges arose from the lack of detection of the source of the carbon dioxide and how to clear CO2, resulting in the suspension of the pumping.

What is striking about the Central Basin is that the water levels in the mine shafts are rising at fast rates. As at 2013: the daily rate of water rising was 0.31 metres; the monthly rate was 9.39 meters.[21] The summer water rise rate has been estimated to be higher than the winter water rise rate because of rainfall. The water level was estimated to be about 334 meters below ground level in 2012. About 57 Ml/d of AMD needs to be treated in this basin to maintain the water below the ECL and ensure the environment is protected from pollution by AMD.

One study[22] showed the lowest recorded pH in the basin as being 2.3, indicating very acidic water levels, high electrical conductivity (EC) of between 2 and 4 mS/cm in general though streams near active slimes dumps had EC values of as high as 10.65 mS/cm. High sulphate and iron levels were recorded in the same study, which showed results as high as 7 571 mg/l and 1 010 mg/l, respectively. Overall, this indicates highly polluted water resources, as the levels are much higher than the allowable limits for domestic purposes, livestock watering and irrigation, based on the Department of Water and Sanitation guidelines. The water is toxic and hence unsuitable for any use.

The mine shafts with the lowest elevation in the Central Basin (namely Cinderella West, Cinderella East, Hercules, Angelo West, Angelo Deep and Central Vertical) are expected to decant first, should the water levels rise to ground level.[23] This is in line with findings that the pollution level, due to AMD contamination, along the Natalspruit River is high, as it is the western hot-spot of this basin.[24]

The ECL was set at 100 metres below ground level at the anticipated decanting points, for example, at ERPM and Cinderella West.[25] This will prevent the contamination of the aquifer and groundwater flow feeding the springs in the area. Groundwater from the contaminated aquifers is unsuitable for use. In instances of connection with other neighbouring aquifers, contamination of surface water resources is common where there is groundwater decant.

The Eastern Basin is still characterised by some active mines, while some mines have now ceased production. An example is the Grootvlei Mine which ceased operation in 2011 and pumping has been active for the continuation of mines. Since then, flooding of the shafts has been measured at a rate of 0.30 metres per day[26] and the water level was estimated to be about 560 metres below ground level in 2012. About 82 Ml/d of AMD needs to be treated in this basin, in order to maintain the water below the ECL.

This basin is critical, as the Blesbokspruit Ramsar site (which is important from ecological, tourism and economic perspectives) is located in this basin. A Ramsar site is recognised under the Ramsar Convention of 1971 as being a wetland with fundamental ecological, economic, cultural, scientific and recreational functions. The Ramsar wetlands are, therefore, supposed to be protected, as they are important and sensitive wetlands. The anticipated decanting points of this basin are in the Nigel area, which lies on the south eastern boundary of the basin. Compared to the other basins of the Witwatersrand Basin, the water in the Eastern Basin is more neutral, although it has higher manganese levels.

Figure 4.3: Water being pumped from the Eastern Basin to the treatment plant at Grootvlei Mine, before pumping ceased in 2011[27]

Table 4.2: Water quality of raw mine water pumped at Grootvlei Mine, as at 2002[28]

Parameter	Unit	Min	Max	Average	95th %
pH		6	6.8	6.4	6.7
Temperature	°C	25	28	26.7	28
DO	M	2	3.5	2.5	3.2
EC	mS/m	294	347	321.8	342.8
TDS	Mg/l	1 928	3 138	2 879	3 053
Cl	mg/l	170	198	183.8	193.8
F	mg/l	NA	NA	< 0.2 *	NA
SO4	mg/l	930	2 064	1 383	1 747
Na	mg/l	187	458	240	256
Ca	mg/l	385	493	422	435
Mg	mg/l	170	251	197	202
Al	mg/l	0.1	0.9	0.3	0.7
Fe	mg/l	82	210	135	206
Mn	mg/l	2.4	5.4	4.1	5
Zn	mg/l	NA	NA	0.01 *	NA
Ba	mg/l	NA	NA	< 0.001 *	NA

Ni	mg/l	NA	NA	< 0.003 *	NA
COD	mg/l	12	80	35.4	80
* Not measured NA = Not available					
Unsuitable for drinking purposes					

The raw mine water pumped at Grootvlei Mine shows elevated levels in terms of electrical conductivity, TDS, sulphates, sodium, calcium, magnesium, iron and manganese. Although the average pH of water is almost neutral, the very high levels of sulphate and the metals iron and manganese are consistent with AMD. The relatively high pH (compared to most AMD sites) is attributed to the dolomitic conditions in this area. When dolomite comes into contact with acidic water, the calcium magnesium carbonate is slowly dissolved, thus neutralising the pH of the water.

A study conducted to investigate the effect of pumping mine water from the Grootvlei Mine into the Blesbokspruit upstream of the Ramsar site (Blesbokspruit wetland) concluded that the water has elevated magnesium, sulphate, iron and electrical conductivity levels and that it contributes to the deterioration of the quality of the Blesbokspruit.[29]

The ECL for this basin has been set at 80 m below the surface to prevent the contamination of the dolomite aquifer.[30]

In the Free State Goldfield, pumping of mine water in this basin continues, as most of the mines are still operational. This means that the risk of mines flooding – and hence decanting occurring — is still low, though it needs to be monitored to maintain water levels. However, the waste disposal facilities (like tailings facilities and pollution control dams) need to be monitored to ensure any pollution is contained, as some boreholes have been found to be polluted by the tailings facilities in this area.[31]

The Klerksdorp-Orkney-Stilfontein-Hartbeesfontein (KOSH) Goldfield has some operational mines in the area, so the risk of flooding and decanting is still relatively low. The point of concern in this basin is the liquidation of one of the mining companies that was pumping the mine water from one of the key shafts, in order that it could continue operating. This resulted in pumping stopping, as the previous owner was not prepared to pump and treat mine water before disposal. This has serious implications in terms of maintaining the water level below the ECL and could result in pollution of groundwater resources and subsequently decanting, with its associated catastrophic effects.[32] This can be achieved through continuous monitoring.

The risk of AMD in the Far Western Basin is still regarded as low, because most of the mines are still operational and the mines de-water to access the ores; therefore the possibility of decanting is still low. The potential risks that have been identified include AMD occurring in the post closure era, contamination of the dolomite by the waste from the tailings facilities and the use of tailings waste to fill sinkholes in the dolomitic area.[33] In this case AMD from the tailings facilities will rapidly move in the dolomites, thus accelerating the pollution of the groundwater resources. Associated effects as discussed under the mechanisms of AMD affecting water resources are bound to occur.

In the Evander Gold Field, one shaft is currently operational in the basin, while the other two shafts are being used for pumping (about 4 Ml/d).[34] The bulk of the water is stored in evaporation dams and the rest is re-used in mining processes. The risk of flooding and decanting is low due to the pumping being done. However, localised contamination has been reported as a result of the evaporation dams and tailings facilities. At the South Rand Gold Field, although the goldfield was dormant, the resumption of production means that there will be pumping of groundwater in order to ensure safe continuation of mining. Therefore the risk of AMD is low.

The Mpumalanga Coalfields produce 80 per cent of South Africa's coal. The long period of mining in the Witbank and Middleburg areas, which started in 1894, illustrates the long-term impacts that are being experienced in this coalfield. Coal mining still occurs in this coalfield, although many of the mines are abandoned and some have collapsed. This is one of the major mining areas in which decanting of mines is active compared to the Witwatersrand Basin.

Pyrite is present both in coal and in the host rock. Although there is no pre-mining background water quality data, as water quality monitoring started after mining began in this area, the background water quality was extrapolated from the streams in the same catchment area where the sources are outside the mining area. The extrapolation concluded that: the TDS has increased ten-fold in the Witbank and Middleburg dams; and the sulphate level in the Middleburg dam is still rising and is now above the limits for domestic water use.

A study carried out on groundwater from six collieries in the Witbank Coalfield revealed mine water with very high TDS, very acidic, ranging between 2.65 and 2.9, and very high sulphate concentrations, ranging between 910 mg/l and 3 840mg/l.[35] This shows very acidic water that has not been neutralised. Highly acidic water with high levels of salts and sulphates, which is consistent with AMD pollution, has been recorded in the Blesbokspruit in the same area. Many of the streams originating in the coalfield that are tributaries of the Olifants River were cited as being affected by AMD to such an extent that they drain into the Loskop Dam.

In the KwaZulu-Natal (KZN) Coal Fields, most of the coal mines are now abandoned and defunct and the majority of the abandoned mines are decanting. Some of the mines and waste facilities have already started producing AMD and contaminating surface- and groundwater resources.

In the Waterberg Coal Fields, based on the acid base accounting (ABA) analysis conducted on core samples extracted from this coalfield, it can be concluded that coal mining in this area has enough pyrite to generate acid if oxidised in the presence of water.[36] Of the 20 samples analysed: 12 indicated a higher risk of acid generation; six indicated a medium risk; whilst two samples resulted in a lower risk of acid generation due to some calcite that can create a buffer that would neutralise acid production – hence limiting the amount of acid produced.[37] Although the area that was investigated is not yet being mined, there is a need to implement some mitigatory measures, especially in terms of disposal facilities when coal is mined in the area, in order to minimise the harmful effects of AMD.

In the O'Kiep Copper District, there are no major operational mines. A number of localised AMD sites have been identified in this area. The major risk is the potential for long-term impact and the contamination of water resources in this area, since it experiences extreme water scarcity.

Figure 4.4: Decanting of AMD in the O'Kiep Copper District[38]

IMPLICATIONS FOR WATER SECURITY

Water security is the capacity of a population to protect access to the desired quantities and quality of water in order to sustain human well-being and development whilst preventing pollution and disasters.[39] Therefore water security talks to the assurance of having the desired quantity and quality of water at the right time. Water security addresses three main aspects, namely water quantity, water quality and the issue of timing to sustain the livelihoods, socio-economic development, etc. In the South African context, all three aspects that relate to water security are already under pressure due to different factors.

Looking at water security from the perspective of South African AMD hotspots, the basins that are already affected include the Olifants River, the Crocodile River (draining from the Western Basin via the Tweelopiespruit and eventually draining into the Limpopo River) and the Vaal River draining from the Eastern Basin (via the Blesbokspruit) and the Central Witwatersrand Basins, whilst the Komati River could be affected. If not properly dealt with, AMD can have far reaching effects on the water resources of South Africa. In order to unpack the implications of AMD on water security, the effects will be discussed as per the aspects identified above.

WATER QUANTITY

South Africa is a water scarce country. There is heterogeneity in the distribution of water resources in South Africa, which is shaped by the distribution of precipitation in the country. The eastern half of the country is wetter than the western half.

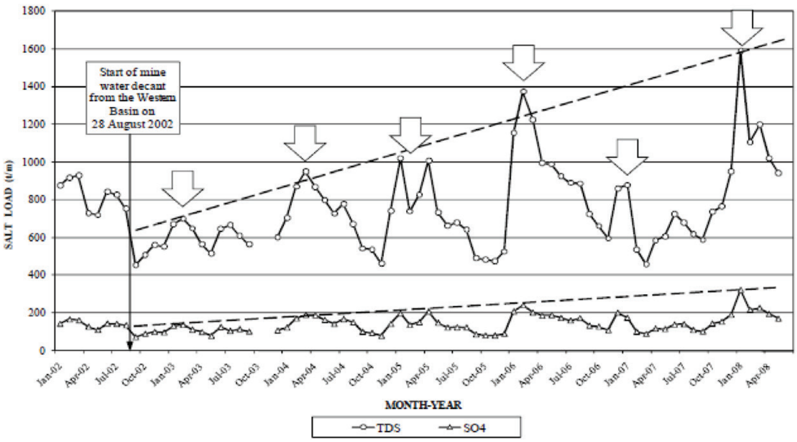
As such the pollution of the water resources by AMD greatly reduces the availability of the desired amount of water needed to unlock economic development in the country. Once the rivers and groundwater resources are polluted, the water will become unsuitable for most uses without suitable treatment. As such, there will be immense pressure on making decisions regarding allocation of the reduced usable quantity available for all water users. Some users will end up being worse off in terms of access to a sufficient quantity of water than before AMD pollution began. A major drawback is that desalinisation of AMD is an expensive process, making it an uneconomic option that could increase the price of water if treatment costs have to be recovered. An increase in pressure on the limited water resources available, coupled with the high cost of treating AMD, reduces the assurance of supply of water for the different users and reduces the water security of an area.

WATER QUALITY

Compromised water quality is one of the major concerns of AMD on water security. As discussed earlier, AMD is responsible for acidic water, with high metal and salt concentrations (mainly sulphate). As such, this negatively affects the water security of the receiving areas. As discussed in earlier, AMD is unsuitable for any use in the Western, Central and Eastern basins without suitable treatment. AMD has the potential to contaminate both groundwater and surface water resources in a number of major river basins and aquifers. Major reservoirs, like the Vaal Dam, which supplies the bulk of the water required by Gauteng Province, are at risk of contamination from AMD emanating from the Central and Eastern basins as well as the Highveld coalfields.

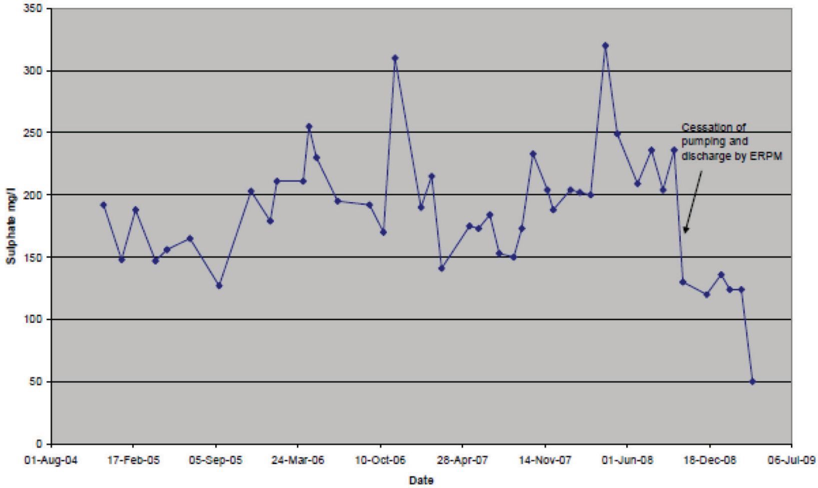
Figure 4.5 illustrates the overall increase in sulphate concentrations in the Bloubankspruit after the first decant in 2002. This illustrates the level of sulphate contamination experienced downstream of the Bloubankspruit.

Figure 4.5: Sulphate concentrations of the water leaving the Bloubank-spruit in the Western Basin before and after decanting[40]



As shown in Figure 4.6, since the cessation of pumping in the Central Basin, the sulphate levels in the Elsburgspruit, downstream of the ERPM mine, have dropped significantly, showing that the water that was being pumped from the Central Basin was contaminating the spruit.

Figure 4.6: Sulphate concentrations before and after cessation of pumping in the Central Basin[41]



It is widely argued that dilution of polluted water helps in reducing the effects of pollution. The pressure on the freshwater resources due to pollution means that the dilution capacity of rivers, for example, is reduced, thus making the polluted waters flowing in them less suitable for some uses. The dilution therefore improves water security. As such, processes like decanting of AMD means that rivers have low levels of dilution capacity and that the toxic effluent will have a more detrimental effect than water with lower concentrations of these constituents.[42] This means that AMD has a net negative impact on the water security of any region, due to the need to dilute water should other users downstream need to use it. As explained earlier, there are always dilutions from the Vaal Dam to neutralise the salinity of the water downstream. This can be problematic under drought conditions, where such releases for dilutions cannot be made and thus negatively impacting on the water security of the downstream users.

TRANSBOUNDARY WATER RESOURCES

South Africa shares water resources with a number of countries. From a surface water perspective, the major rivers that South Africa shares with other countries that are vulnerable to pollution by AMD are indicated in Table 4.3:

Table 4.3: Characteristics of transboundary rivers that are vulnerable to pollution by AMD

Transboundary river	Tributaries affected by AMD	Countries sharing the river
Orange	Blesbokspruit, Vaal	South Africa and Namibia
Limpopo	Tweelopiespruit, Bloubankspruit, Crocodile (West)	South Africa, Botswana, Zimbabwe and Mozambique
Komati	N/A	South Africa, Swaziland and Mozambique

The pollution of these rivers by AMD emanating from South Africa can have serious consequences in terms of the suitability of water use in countries downstream of South Africa that share the water resource.

Another critical point of concern with transboundary rivers is the legal implication of the Southern African Development Community (SADC) Protocol on Shared Watercourses, which has been ratified by South Africa and all the other riparian states in terms of the above transboundary rivers. In essence, the protocol states that member countries should take measures to prevent, minimise and control pollution of the shared rivers that could potentially harm users in the riparian states.[43] This means that measures should be taken to make sure that the water security of the downstream countries is not compromised. As such the pollution of transboundary rivers by AMD water will inevitably end up affecting the downstream countries that rely on the same water resource, thereby adversely impacting the region's water security.

From a groundwater perspective, should water transfers commence from the Witwatersrand Basin, the transboundary aquifers that lie in the affected areas are: the Limpopo Basin aquifer that is shared between South Africa and Zimbabwe; and the Tuli Karoo sub-basin aquifer shared by South Africa, Zimbabwe and Botswana. The aquifers are mainly alluvial and as such there is strong interaction between the surface and groundwater resources.

Any polluted water flowing through the rivers in the area can potentially contaminate the aquifer, thus negatively affecting water security.

WATER TRANSFERS

Due to the fact that South Africa is a water scarce country, the country has been relying on water transfers to unlock economic opportunities in areas where the demand for water is higher than supply, for example, the Lesotho Highlands Water Project (LHWP), where water is pumped from The Kingdom of Lesotho and discharged near Bethlehem in Free State Province where it flows and is abstracted for use downstream in Gauteng Province. The proposed Mokolo and Crocodile (West) Augmentation scheme will involve transferring surplus water from the Crocodile (West) River to Lephalale in Limpopo Province. If AMD is not managed properly in the Western Witwatersrand Basin, contaminated water will end up reaching the new economic hub of Lephalale, making the region a receiving area of the metals, salts and acids coming from the Witwatersrand Basin. It could be argued that although the augmentation scheme will seek to improve the water security of the receiving area by supplying the water quantities needed for the economic activities on time, from a quality perspective, the issue of water security in the receiving area might be worsened with time.

LESSONS FOR AFRICAN COUNTRIES ENGAGED IN MINING

As a result of the wide array of factors under which the problem of AMD has developed in South Africa, a number of lessons can be drawn for other countries whose mining sectors are growing and which could experience the problem of AMD.

One of the major lessons learnt from the South African AMD situation is the adoption of the polluter pays principle (PPP) when the environmental authorities are evaluating applications for economic activities that might have a negative impact on the environment, for example mining. Although the latest legislation (for example the National Water Act (Number 36 of 1998) and the National Environmental Management Act (Number 107 of 1998)) does address this, the environmental legislation in place during the mining of the Witwatersrand Basin in the 1880s did not address this problem. This is one of the negative legacies of early mining of gold and coal in

South Africa. This has left mainly the government to bear the costs of AMD and other environmental problems. As such, one of the conditions that need to be tied to environmental authorisation (for instance water use licences and permits) is the fact that polluters should bear the costs of any pollution arising from their activities, for instance the cost of treating water and any other damage caused by water contaminated with AMD. Punitive jail terms for offenders could also be used.

When assessing applications for mining, especially where there is the risk of AMD, countries could make it compulsory to undertake acid base accounting, i.e. specialist studies such as geohydrological studies. By so doing, the risk of AMD during the mining and post mining eras is ascertained well in advance so that mitigatory measures are incorporated in the planning and design phases. An example is the Waterberg Coalfield, where core sample analysis revealed that there is enough pyrite to generate acid if it is oxidised in the presence of water. Where the risk is high, more stringent measures need to be implemented than where the risk is lower.

Another lesson that could be learnt from the South African context is the need to undertake risk mapping of the AMD hotspots. This would entail identifying all the hotspots and ranking them in terms of their hazards. The major hotspots of South Africa have been mapped and research is continuing in terms of identifying areas that could be problematic in the future, for example, the geophysics studies being done by the Council for Geoscience (CGS) in identifying tailings facilities that have the potential to contribute to or are already contributing to AMD. Once such areas have been identified, authorities and other stakeholders would be better empowered to deal with the problem of AMD in those areas.

The issue of better design of waste disposal facilities is another area from which lessons can be drawn. Uncontrolled and poorly designed facilities, like tailings facilities and waste rock dumps, can accelerate AMD formation. Cases in point are the West and Central basins, where the tailings facilities have been undisturbed for close to a century, resulting in the facilities being exposed to oxygenated rainwater that forms AMD, which percolates through the facilities into the groundwater system. From this perspective, better design of such waste disposal facilities is vital in minimising seepage from such facilities into groundwater or via the toe of such facilities into surface water resources. Where the risk of AMD formation is high, design could be enhanced through compulsory lining of such facilities, for example high density polyethylene (HDPE), polyvinyl chloride (PVC) or clay, coupled with best management practices so that the contaminated water emanating from such facilities does not mix with clean water systems before it is treated.

Pumping is one of the measures that can be employed in order to prevent decanting of AMD or to manage this process, for example, the pumping that is being done in the voids and shafts in the Witwatersrand Basin. This is necessary in order to avoid the water levels rising above the ECL. If water levels were allowed to rise above the ECL, detrimental environmental impacts would occur if the uncontaminated water mixed with the AMD, for example the contamination of aquifers. By constantly making sure that water levels are below the ECL, negative environmental impacts can be avoided. This option can be financially taxing, in the sense that robust pumps that need to pump water for extended periods of time may be needed and the pumps and pipes are often corroded by the acidic water. The pumping cost may also escalate, because of the high static head that the pumps need to overcome. This has been one of the challenges of pumping in South Africa, to such an extent that the government had to intervene by subsidising the pumping cost to avoid mining companies going bankrupt. This should therefore be one of the last options, because of the high cost of pumping and treating the AMD. Before the East Rand Proprietary Mine (ERPM) ceased pumping in the Central Basin in 2008, its monthly pumping cost was estimated to be about R40 million, with R8 million of the cost being paid by a government subsidy. This translates to significant pumping costs, which can have a significant bearing on the operational costs and viability of any mining company operating in such an environment.

One of the preventative measures that could be used is the control of ingress into the shafts and voids. As identified in the chapter on AMD formation, one of the key requirements for AMD formation is the presence of water that can come from several sources. It is vital to prevent/minimise this water reaching the mineral front, where the chemical reactions take place, resulting in the formation of AMD. This is part of the Best Practice Guidelines of the DWS in the context of mine water management. Examples include minimising water seeping from disposal facilities and minimising precipitation getting into mine workings and any other clean water in the mine workings.

The treatment of AMD and research in this area is one of the key areas in which South Africa is playing a pivotal role. In South Africa, different players, for example universities and research institutions, have been part of experts that have developed some of the treatment options for AMD. (Please refer to the chapter on AMD Treatment Technologies.) Other African countries could learn from some of the treatment options used to deal with the South African AMD issues. A good example is the development of the SAVMIN technology developed by the Council for Mineral Technology (Mintek) for the treatment of AMD.

Proper coordination of the institutional framework is another area in which other countries could emulate South Africa. There are a number of actors that are involved and have different roles in the monitoring, management, treatment, funding and research on AMD in South Africa. These include government departments (for example, the Department of Water & Sanitation and the Department of Mineral Resources), technical partners (for example, the Trans-Caledon Tunnel Authority), research institutions (for example, the Council for Geoscience (CGS), the Council for Scientific and Industrial Research (CSIR), the Water Research Commission (WRC)) and funding partners such as the National Research Foundation (NRF). Coordinated functioning of the different stakeholders minimises duplication of roles and functions, thus improving efficiency in dealing with the AMD problem.

One of the key lessons that can be drawn from the South African context is the comprehensive water quantity and quality monitoring programme. The Department of Water and Sanitation is involved in monthly monitoring of water levels in the shafts, voids and boreholes of the three different basins that comprise the Witwatersrand Basin. The water levels are compared with the ECL and concerns if any are raised promptly. Some of the boreholes have data loggers that enable real time measurement of the levels in the boreholes. Likewise, water quality samples are collected on a monthly basis for analysis so that a temporal analysis can be performed for each constituent. This can serve as an early warning system for action where concentrations could, for example, show a continuous increase.

CONCLUSION

In a nutshell, AMD has negative impacts on the water security of any region due to the fact that it: reduces the quantity of water that can be used for some or all uses; contaminates water resources, making them unsuitable for use; and reduces the frequency that water of a suitable quantity and quality is available for use. This chapter details an array of important lessons that other countries can learn from South Africa. These lessons can be applied from pre-feasibility, design and operational stages of mining projects. The earlier the stage of implementing some of the lessons during the project life cycle, the less the cumulative costs of dealing with the problem of AMD arising from such projects. This recommendation is alluded to in-depth in Chapter 7 of this book.

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CHAPTER 5

An Assessment of the Social Impact of Acid Mining Drainage on the West Rand, South Africa

Towards Responsive Mining and Sustainable Cities on the African Continent

Lawrence Matenga and Trynos Gumbo

ABSTRACT

Mining activity in South Africa creates a potentially dangerous situation for communities. Almost 40 per cent of the country's working mines have inadequate environmental rehabilitation, which leaves a negative impact on the communities. For more than a century West Rand region allowed South Africa to become a leading economic bloc on the continent. However the mining activities left behind numerous toxic footprints such as Acid Mine Drainage (AMD). To understand the social effects of AMD social impact assessment processes offer a plausible solution. Social Impact Assessment (SIA) is an over-arching framework that embodies the evaluation of all projects that impact on humans and on all the ways in which people and communities interact with the socio-cultural, economic and bio-physical environment. SIA minimises negative impacts due to a mismatch between people and projects by indicating the social impact of projects prior to implementation and facilitating project modification and mitigation through public input. In this case, the idea of SIA is being put across to assess the social impact of AMD on the West Rand. This chapter demonstrates that AMD on the West Rand is a result of mining companies abandoning mine shafts once they are no longer viable and failing to rehabilitate the mines by pumping water out of inactive shafts and discharging it safely into the environment. On the West Rand, and particularly at Mogale Gold Processing Plant 18 Winze shaft, AMD is spilling out onto the surface at a rate of about 30 million liters per month, leaving decimated ecosystems in its wake and posing a critical danger to the future drinking water supply of the nation. This chapter recommends that the South African government and other African governments need to consider mandating mining companies to

assess the social impacts when issuing a mining license and doing follow-up studies after the mines have closed. SIA can be used as a key in impact management processes.

INTRODUCTION AND BACKGROUND

Mining activities, particularly of minerals such as diamonds and gold, in the Republic of South Africa dates back several decades. The discovery of gold, in 1886, led to the creation of the present day Johannesburg which expanded east- and westwards, as mining activities increased.[1] This led to the formation of Westrand Consolidated Company that intensified and extended mining operations on the West Rand and led to the development of small towns and administrative centres such as Krugersdorp and other residential centres.[2,3,4] The expansion of mining activities also led to the establishment of Randfontein to accommodate the large workforce.[5] Economic migrants joined mining companies from neighboring countries to provide the much-needed general labour, leading to the rapid growth of the West Rand.[6]

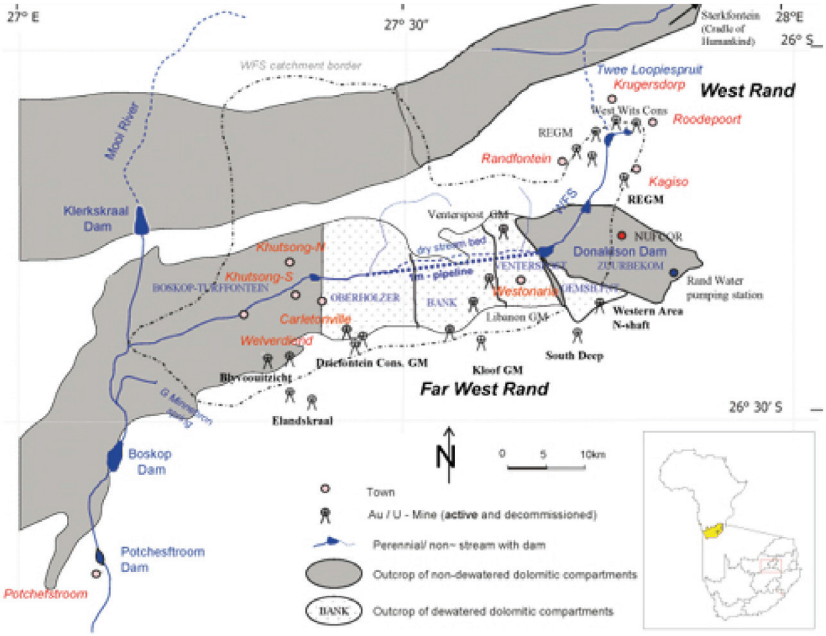
The mining activities led to the transformation of rural and under-developed areas into densely-populated regions, thus giving rise to concentrated physical and economic development. Following the huge investment in gold mining and spillover effects, several towns (such as Randfontein, Westonaria and Carletonville) witnessed massive improvement of infrastructure, including improvement of the roads, railways, water and electricity systems, schools, hospitals and commercial infrastructure. Historically, although the huge investment in gold mining activities directly and indirectly led to infrastructure development and massive employment creation, it also gave rise to negative social effects emanating from the mining practices and processes, particularly from AMD.[7] As has been extensively described and argued in this book (see Chapters 2 and 3), AMD is a result of oxidation of sulphide minerals in mine ore bodies, such as pyrite, when they are exposed by mining activities, which gives rise to acid water that dissolves heavy metals.

This chapter focuses on the social impact of gold mining and post-mining activities in the West Rand. As has been alluded to, although mining activities create wealth for the economy at all levels – nationally, provincially and locally – as well as for big corporations that are involved in the mining activities, they also have negative environmental and socio-economic impacts. AMD is therefore responsible for the most costly environmental and socio-economic problems in the West Rand area of Gauteng – hence the assessment of the extent of the impact in this chapter. The South African government has also registered strong concerns about the severity of the impact of AMD in the West Rand area – hence several interventions have been proposed to mitigate the environmental and economic impacts, as well as the social impacts of the phenomenon.[8,9] However, appropriate action to reverse the social impact of AMD can only be taken if adequate knowledge is generated – hence the inclusion of this chapter in this book. SIA techniques were applied in this work to demonstrate the generation and effects of AMD as a result of mining activities in the vicinity of Johannesburg. In this chapter, SIA is applied to comprehend and present a clear picture of the impact of mining development in the West Rand area of Gauteng.

STUDY AREA: WEST RAND, GAUTENG

This chapter specifically focuses on the areas that were left exposed to the negative social effects of mining activities on the West Rand (see Figure 5.1), including the Mohlakeng, Toekomsrus and Bekkersdal areas. The social impact of AMD on the West Rand can be traced back to the early years of mining. Of great concern is the practice of mining companies abandoning mine shafts once they are no longer viable and failing to rehabilitate the mines by pumping water out of inactive shafts and discharging it safely. AMD spills out on the surface at a rate of around 30 million liters per month at Mogale Gold Processing Plant 18 Winze shaft. This has led to negative environmental, economic and social impacts which are clearly presented in this chapter.[10]

Figure 5.1: Map of the West Rand, Johannesburg, South Africa[11,12,13]



The potential harmful effects of AMD on the West Rand was brought to the fore through the assistance of Chinese economic migrants, who worked in the mines as skilled underground personnel and who noticed one of the shafts first discharging water that was highly polluted. Unfortunately, during the early years of gold mining in the area under study, there was no formal process of SIA – hence no studies were conducted prior, during and after mining activities within the West Rand, leading to the huge social impacts of AMD. Although efforts were made by the Chinese, through the development of a social labour programme to deal with the impact of mining activity, unfortunately no serious and coordinated measures have been taken to date to redress the problems. The social labour programme is akin to the process of SIA which aids mining activities in dealing with the social impacts, emanating from the so called 'Black Reef Incline Shaft', and stop the impacts of the chemical process that leads to release of AMD[14] and expose it to the populace.

OPERATIONALISING THE STUDY

This chapter adopted a qualitative research approach within a case study phenomenological research design, with the West Rand chosen as the area of study. The work applied both content and document analysis, with relevant sources carefully selected for consideration and analysis, thus yielding a thick description of the events, processes and effects of AMD in the West Rand. Since AMD in the West Rand is a classic example of an inter-generational and intra-generational problem, trend analysis was also applied to understand the historical processes, so as to propose possible ways of solving the social problems emanating from AMD. Given the severity of the AMD problem, numerous stakeholders have emerged with varying solutions and concerns and the younger generations are seeking solutions to the historical issue of AMD.[15]

CONCEPTUALISING SOCIAL IMPACT ASSESSMENT AND ITS RATIONALE IN MINING PROJECTS

Social impact includes the real or perceived experiences of individuals or groups due to action or a lack of action that could either be positive or negative. Similarly, SIA can best be defined as a process for understanding and responding to the social issues associated with any form of development.[16] The process of assessing the social impact of any development initiative assists in ensuring the orderly and sustainable development of communities. It has also been observed that SIA is most effective as an iterative process across the life cycle of developments, rather than as a one-off activity at the outset of developments such as mining activities.[17,18] In the majority of cases, SIA helps to encourage communities to participate in the decision-making process in projects that affect their development. SIA assists with the identification, avoidance, mitigation and enhancement of outcomes of developmental initiatives for communities.[19]

There have been developments to improve the application of SIA in mining projects; for instance, the South African government enacted the Mineral and Petroleum Resources Development Act (MPRDA), which requires mining companies to assess the social impact of mining activities from start to closure and beyond. To support these initiatives, the Department of Minerals and Energy (DME) only issues approval of a mining right if social impacts are documented and considered as part of the mining operations. Mining companies in the country are requested to compile and implement a social labour plan (SPL) that should support the socio-economic development of surrounding communities, as a measure to reduce or prevent negative social impact. Also, international financial organisations, such as the World Bank, have taken a stance that they will not fund any mining project unless clear and detailed social studies are undertaken for the purpose of contributing positively to the development of communities. As recent as 2009, the South African government compiled an AMD report[20] as a way of raising awareness of SIA's potential role in mining projects. There is, however, a need for active community engagement with such initiatives, since the community is affected by mining projects and is a key pillar of SIA processes. There have also been efforts to introduce social and labour plans and, in some instances, water has been pumped from dumps to deal with challenges of AMD.

All stakeholders, including mining corporations and governments, benefit from the application of SIA – hence it is not only communities and individuals that stand to benefit from the process. The SIA process produces a legal register, starting from the initiation of the mining project and including the operation and closure phases. Such a register assists communities in the West Rand region to enjoy a sustainable life. A good social impact study predicts the closure impact of AMD. Predicting the impact allows mining corporations and communities to prepare closure plans which might be sustainable to the community and are cost effective to the company. Social impact assessment fosters a process of open consultation with the community, which helps with identifying problems of AMD in a timely manner and with addressing them early enough.

RESEARCH FINDINGS – SOCIAL IMPACTS OF AMD IN THE WEST RAND

The operation and closure of West Rand mines had a strong impact on population dynamics, the rate of employment and infrastructure development, which were historically contributed to by the mines. Access to clean water is commonly regarded as a universal human right that is also a precondition for social development.[21] However, in West Rand communities, the AMD has exposed residents to health hazards such as radon exhalation, radiation, dust and other tailings-related hazards from the old slimes dams.[22] The underground mine shafts are still filled with water, which is being discharged into sub-surface or surface water resources. There are many dumps, which have caused extensive soil and water pollution in the region and further afield. The AMD passes though a decanting stream known as Tweelopiespruit, which empties into the Indian Ocean – hence it has the potential to pollute massive volumes of water and give rise to serious social problems. Research has revealed that AMD has become a serious problem in the West Rand. Long term exposure to AMD has resulted in increased rates of cancer, decreased cognitive function, skin lesions, health problems in pregnant women, neural problems and possible mental retardation.[23] In addition, an estimated 15 to 30 Ml/d of polluted water passes though the Krugersdorp Game Reserve, which has health implications for the animals.[24]

There are also sink-holes that develop due to the acidic AMD that fills tunnels and reacts in the Khutsong area. One of the social impacts of AMD is the displacement of residents in Khutsong in the West Rand, an area with communities that necessitates the relocation of about 10 000 households at a huge cost. There has also been an impact on farms, which have become unproductive due to land pollution by AMD dumping its salts on the land as it floods the mines in the area. Also, these farms cannot be sold for urban expansion purposes, as the underground tunnels mean the land cannot support urban development.

Additionally, one of the social problems on the West Rand is unemployment. Although many towns, for example, Carletonville and Westonaria, and the adjacent townships used to benefit from mining activities in terms of employment creation, residents are currently facing serious social problems due to a lack of opportunities.[25] The area is largely dependent on mining and considered unsuitable for agriculture.[26]

The leaking AMD in the West Rand has largely disturbed human settlements. Since 2002, AMD has been flowing uncontrollably from underground and entering surface watercourses of the West Rand. Mining authorities suggest that 60 million litres of AMD is decanting per day around Shaft 18 in the West Rand. The acidic water then flows into Tweelopiespruit and the surrounding farming land. Most of the settlements have been built on radioactive land and people living close to Tudor dam, for example, need to deal with polluted water and affected soil. This means that more than 10 000 households in Khutsong North need to be relocated due to sinkholes that have formed over the years due to mining activity.[27] In a nutshell, the broad social impacts that emanate from challenges related to AMD include social exclusion, deteriorating social infrastructure, health complications, crime and social disorder.[28]

LESSONS FOR THE MINERAL RICH AFRICAN CONTINENT AND THE WAY FORWARD

This chapter has raised a number of issues that need to be considered by all stakeholders when conceiving, implementing and decommissioning mining projects. Lessons learnt should be shared with other African countries that are rich in mineral wealth, as they help to inform proper procedures in mining. It has been noted that more attention has been given to environmental aspects of mining activities, but not socio-cultural and economic impacts. It is therefore paramount for authorities to seriously consider the management of social impacts and the risks involved with mining activities. This can only be achieved if SIA is considered in all planning processes for mining activities.

More importantly, is the need for community engagement in finding remedies for the AMD problem. If mines can look for public participation or community involvement it gives the communities power to deal with problems like AMD as they will have been involved in the solutions and implementation of the closing process. Mining closure often results in ghost towns and impoverished people. It is also noted that unskilled personnel are left stranded, as only more skilled personnel are reabsorbed into other mining activities.

The problem of AMD demands change in terms of the current solution of just pumping acid water using submersible pumps, in order to maintain acid water levels below environmental critical levels and neutralise AMD. This is believed to be providing a temporary solution, but a more sustainable long-term solution is required. There is, therefore, a need for the enactment of laws and precautionary principles that stipulate and enforce the 'polluter pays' principle in the mining sector on the African continent. The adoption of SIA by mining companies will help a great deal to either eliminate or significantly reduce social problems associated with AMD. The application of SIA at an early stage of mining project development would also help in off-setting social impacts emanating from decommissioning. Sustainability is measured when a mine has managed a successful closure plan and the community is not affected by AMD problems. The mining closure process must show respect for ecosystem management and should not have a negative social impact on society. Mining companies usually lack proper planning and rehabilitation in terms of waste dumps, which results in socio-economic impacts on communities.

Governments should consider mandating mining companies to assess social impacts as part of the process of issuing a mining license and it could be followed after the mines have closed with follow-up studies. The roles and responsibilities of government departments and bodies should be specified and streamlined, so that duplication and overlaps are eliminated, thereby promoting orderliness in the mining industry. For example, clearly distinguishing the responsibilities of the departments for mining and the environment will result in clear roles in terms of the management of the activities of mining and how they impact communities, particularly mining waste. Equally, the government organs responsible for economic and socio-cultural development and preservation should be part of the mining operations, particularly monitoring the impact of such activities within their domain. For instance, in the case of South Africa, the Department of Social Development should be involved, so that it can develop policies that deal with the social impacts of mining, for example, the impact of AMD.

Since most of the people who are affected by AMD problems in the West Rand are the socially disadvantaged and the poorest in society, the third sector (NGOs, advocacy groups and civil society) has an obligation to ensure that policies and legislation that seek to promote social development in mining communities are adhered to by the mines. Furthermore, the emotional impact is also seen amongst the most affected people who are of the view that they cannot defend themselves from big multi-corporations who cause AMD and other forms of pollution. People affected by mining activities are represented by civil organisations and are also educated through awareness campaigns, workshops, and presentations by NGOs at school and community meetings. Due to the persistent problem of AMD, the government should emphasise research and the development of policies and ways to deal with the social sustainability of all water resources.

CONCLUSION

This chapter presented the social impacts of AMD in the West Rand, South Africa. It also highlighted what needs to be done by African governments before, during and after mining activities, so as to avert the serious consequences of mining companies disregarding the social impact of their activities.

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CHAPTER 6

AMD and the Mining Sector's Contribution to the South African Economy

Martin Kaggwa

ABSTRACT

Debate on how to make the mining sector in South Africa benefit more people and enhance the sector's contribution to national development has tended to ignore that mining activities have negative effects on society. These negative effects, which economists broadly refer to as negative externalities of production, are important in assessing the short-term and long-term benefits of mining. Without taking into account the externalities, the sector's contribution to the country's economy is likely to be exaggerated. This chapter discusses the performance and contribution of the mining sector to the South African economy, taking into account the negative externality element of acid mine drainage (AMD). It makes the case that profit and production levels for the sector have been kept higher without taking AMD into account. It suggests that this aspect needs to be acknowledged in national policy debates and in policy formulation aimed at sustaining the country's benefit from mining activities. Otherwise the current and future contribution of mining to the local economy will remain distorted.

INTRODUCTION

The contribution of the mining sector to the South African economy, while taking into account the effects of AMD, is part of the wider subject of how to increase the benefits to the country from exploitation of natural resources. Many countries on the African continent that are endowed with natural resources have not been able to leverage their resources for purposes of national development. In fact, the existence of natural resources is often considered a curse to a number of natural-resource rich countries like Nigeria, Sierra Leone and the Democratic Republic of Congo (DRC).[1]

There is renewed interest about how Africa should exploit its resources in ways that benefit more Africans. The African Union (AU) established a special division responsible for mineral beneficiation on the continent. The division undertakes research and provide knowledge on development options from harnessing the continent's natural resources.[2] The desire to increase the benefits from natural resources further led to the formation of Africa Mining Visions (AMV) in 2008.[3] At the centre of AMV is the triggering of development on the continent and the eradication of poverty using natural resources.

Specifically in South Africa, organised labour and some political parties continue to claim that the country is not getting the best dividends from its national resources. Despite the mining sector contributing almost five per cent to the country's Gross Domestic Product (GDP),[4] there is a general feeling that the distribution of benefits from mining is skewed in favour of the mining houses. As a result, recent policy debates have focussed on how to increase the mining sector's contribution to the country's economy and make sure that more South Africans benefit from this sector.

The pre-occupation with the mining sector's contribution to the economy has tended to focus on short-term performance. Current performance parameters, such as the sector's production, employment, productivity and wage levels, have dominated policy debates on the sector. Little attention has been paid to the fact that maximising current performance and benefits therefrom does have a trade-off in terms of the sector's future contribution to the country's economy and benefits to society.

Inequality and high levels of unemployment remain prevalent in South Africa, despite its transition to democratic governance in 1994 and the commitment of the democratic government to address the socio-economic imbalances of the past. The country needs to come up with creative, yet practical, ways to help more people out of poverty. Using its natural resources to create jobs for its citizens, thereby enabling them to earn an income, is one way the country can ease the plight of many disenfranchised poor people. Otherwise there is a risk that the continued economic exclusion of many South Africans from active and beneficial participation in local economic activities may result in political unrest.

Natural resources are exhaustible and in the process of their exploitation they often have an adverse effect on the environment. Mining, in particular, pollutes the air and the ground during the active years of mining. Further, mines have a specific life span, after which they close. This leaves mining communities with no employment opportunities, but carrying the environmental burden of the ceased mining activity. It is prudent that in assessing the contribution of the mining sector to the country's economy, and in coming up with ways through which this contribution could be enhanced in future, the adverse effects of mining on the environment are taken into account.

The focus of this chapter is the issue of AMD emanating from mining activities and the implications for the mining sector's contribution to the South African economy in the short and long-term. The next section discusses AMD in the context of production externalities and their subsequent effect on production and employment levels, in general. The third section analyses the mining sector's contribution to the economy without considering AMD, and later while taking the AMD problem into account. Contemporary challenges of the South African mining sector in the context of the AMD problem are discussed in the fourth section. The fifth section concludes the chapter and makes recommendations regarding managing the problem of AMD, while considering the country's need to enhance the mining sector's contribution to its short-term and long-term socio-economic development needs.

AMD IN THE CONTEXT OF PRODUCTION EXTERNALITIES

Production is central to realising economic growth and benefits. For a long time, economists have devoted time and effort to understanding what drives production and its effects on the economy where it takes place.

In analysing the consequences of production, it is important to identify both its positive and negative effects on society. Often, the tendency is to focus on the positive outcomes that are directly realisable by parties engaged in the production process. The undesirable and indirect consequences of production are seldom acknowledged. This lack of acknowledgment may be intentional or unintentional; nonetheless, it has fundamental implications for production decisions and the impact of production on society. The indirect effects of production are generally referred to as externalities of production.

The existence of production externalities creates a situation wherein societal interests are not fully taken into account when making production decisions. The externalities distort the costs and benefits of production, as perceived by the producing agent.

Positive externalities occur when there are positive, but indirect, benefits to society emanating from production. With positive production externalities, the monetary benefit realised by producers will be less than optimal, as part of it goes indirectly to society. Despite creating this benefit for society, the producers cannot charge for it because it is indirect and, in most cases, it takes the form of public goods or service.

A profit maximising producer makes production decisions based on the actual benefit realisable from undertaking production. With the existence of positive externalities of production, producers will under-estimate the benefits of production and subsequently produce at levels that are lower than optimal.

Following the same logic, the existence of negative externalities of production will lead to over-production. Producers will tend to under-estimate the cost of production and consequently over-estimating profits. The private cost of production experienced by the agent will be lower than the social cost of production, as the latter includes both the private cost of production and the cost to society. Motivated by higher profits, producers will produce more than what is desirable to society.

The existence of production externalities creates a classic case of market failure. Essentially if markets are left to operate without any external influence, they fail to simultaneously maximise the interest of the producers and that of the consumers. The ability of markets to lead to optimal production and consumption outcomes is one of the fundamental reasons put forward by free-market advocates to discourage state and external interventions in production and consumption decisions.

AMD constitutes a negative production externality of mining. Its impact is not directly realised by the mining houses, yet it affects society negatively. To make matters worse, the AMD effect on society is deferred to a future date. So, apart from mining houses not incurring the full cost of AMD, society takes time to recognise that it was being affected by the mining activity. This creates a situation in which the mining houses and society do not give the problem of AMD the necessary attention in the short-term.

At policy level, though, there is partial recognition of AMD as a negative externality of mining. This is reflected in polices and legislation that include clauses on safeguarding the environment, in general, during and after the mining period.

Under the new legislation, for example, mining houses have to submit an Environment Management Programme Report (EMPR) to government, in order to receive a mining licence. It is a requirement of EMPR that mines clearly state the impact of their activities on the environment and the resources they are committing, in advance, to address the adverse impact of their activity on the environment.[5]

It should be noted though that the South African government has not been effective in using legislation to achieve the desired socio-economic objective in the mining sector. Alder et al.[6] attribute the inability of government to implement well-intended legislation in the mining sector to insufficient specificity and intergovernmental disagreement about which policies are primary. In some cases, legislation cuts across departments, creating uncertainty regarding which department is the custodian and enforcer of a particular legislation. The Department of Mineral Resources, the Department of Water Affairs, the Department of Environmental Affairs and the Department of Trade and Industry are at the centre of this confusion. The situation is exacerbated by the national and provincial governments' formulation and enforcement roles. Whereas the national government is empowered to regulate issues pertaining to the environment, local governments are tasked with enforcement of environmental legislation. This has created a disjoint in the interpretation, implementation and enforcing of legislation pertaining to mining and the environment.[7]

Specific to AMD, three aspects have made it hard to use legislation to limit its occurrence and forcing mining houses to internalise its mitigation costs. The three factors are:

a) information asymmetry between mining houses and government;
b) incomplete contracts which do not take into account aspects that may only manifest themselves at a future date: and
c) methodological limitations in estimating the cost of AMD.

The legislation broadly requires that mining houses commit themselves to protecting the environment, including guarding against AMD. Mining houses are obliged to budget and put aside resources that will cover the cost of predicted environmental rehabilitation required as a result of mining activity. Although a good initiative, government, as the enforcer of the legislation, cannot predict with accuracy the extent of damage to the environment that is likely to emanate from specific mining undertakings. It has to depend on the mining houses to provide it with such information. The situation gives the mining houses a choice to decide what type of information to provide to government and in what form. Since government adjudicates the request for a mining licence based on this information, it is unlikely that mining houses will provide information that escalates their liability in terms of environmental protection and rehabilitation costs. The information asymmetry between government and mining houses on the generation of AMD and its mitigation cost favours the mining houses. It puts government in a very weak position in enforcing the applicable legislation.

The commitments that are made between the mining houses and government, as per the legislation, are future-based. A characteristic of future contracting is that a number of assumptions have to be made about the future. For example, it is often assumed that the mining practices adopted at the start of the mining undertaking will be maintained. However, mining processes can be changed by the mining houses in due course, in an attempt to minimise production costs. If this happens, the extent of AMD generation, as a result of a particular mining undertaking, will change. Government cannot anticipate such changes at the time of issuing a mining licence.

Sometimes, the full extent of AMD pollution can only be ascertained many years after the culpable mine has closed. In such cases, it is impractical to compel a closed mine to undertake remedial action for mitigating the cost of the AMD pollution.

It is probable that efforts to force mines, through legislation, to internalise AMD costs in their production decisions may not achieve the desired objective in its entirety, due to the legislation-enforcing challenges explained above. Both production and employment levels are likely to continue to be at sub-optimal levels. While the existence of the legislation cannot completely eliminate the AMD effect on mining houses production, it reduces the level of distortion when making the production decisions.

THE MINING SECTOR'S CONTRIBUTION TO THE SA ECONOMY IN THE CONTEXT OF AMD

First, this section assesses the contribution of the mining sector to the South African economy in isolation of AMD and any other negative production externalities. Thereafter, it discusses the implications of introducing concerns pertaining to AMD to the sector's contribution to the national economy.

THE MINING SECTOR'S CONTRIBUTION TO THE SA ECONOMY IN ISOLATION OF AMD

South Africa is rich in mineral resources and a major player in mineral trading globally. The mining sector has played a pivotal role in the country's socio-economic development path, through job creation and corporate social responsibility projects. The sector has also contributed to the transformation of the country into the most industrialised country on the African continent.[8]

The following discussions are based on secondary data from the South African Reserve Bank (SARB), Statistics South Africa (Stats SA), the Chamber of Mines (COM) and the Department of Mineral Resources (DMR). Data was triangulated between the four sources to minimise bias and increase the credibility of conclusions made therefrom.

SARB monitors and keeps track of economic performance at sectoral levels through periodic surveys. Its database is an important source of secondary data on sector contribution to the country's GDP. DMR keeps record of employment levels in the mining sector on a year-to-year basis.

COM collects data from employers in the mining sector and compiles the sector's financial performance facts and figures. COM analyses the mining sector's contribution to the country's economy from the perspective of employers. Stats SA also conducts quarterly sector-performance surveys. The National Treasury, on the other hand, keeps record of estimates of revenue from different sectors of the economy. These four sources combined, provided good secondary data to assess how the mining sector has been contributing to the South African economy. The ensuing sections provide details on the specific contributions.

CONTRIBUTION TO GROSS DOMESTIC PRODUCT

GDP is an important indicator of the performance of any economy. It presents the sum total of all goods and services produced within a country in a particular year. As such, it is indicative of revenues received by participants engaged in economic activity. In a perfect economy, therefore, GDP is correlated with the well-being of the citizens of a particular country.

The overall contribution of the sector to the country's GDP, in absolute terms, between 2003 and 2013, was estimated at over R2.1 trillion.[9] In rand terms, the sector contributed R330,090 million, R331,080 million and R288,702 million to national GDP in the 2010, 2011 and 2012 financial years respectively. Considered in percentage contribution terms, the mining sector contributed 4.9 per cent to South Africa's GDP in 2012.[10] Overall, the sector's contributions to the country's GDP remain reasonable, although they have fluctuated over time. For example, the sector contributed 2.7 per cent and 11.5 per cent to national GDP in 2002 and 2005 respectively.[11]

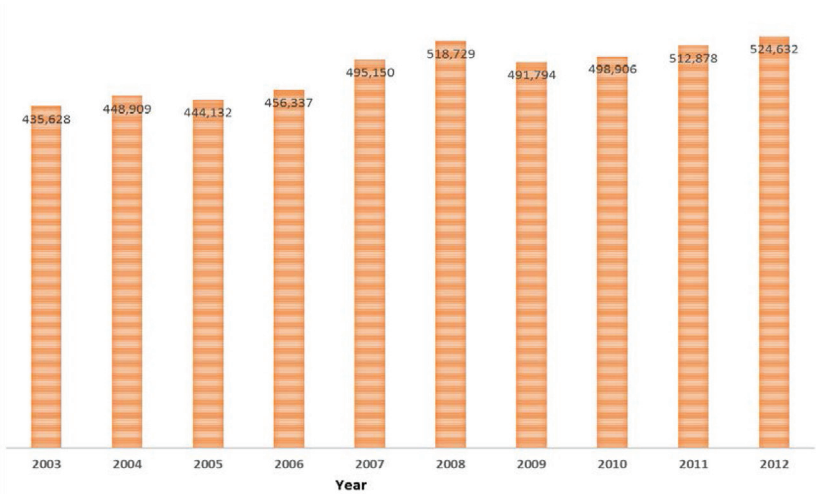
The slow recovery from the global recession experienced in the mid-2000s, falling commodity prices, unstable foreign exchange rates and labour unrest domestically are some of the reasons to which instability of the sector's contribution to national GDP is attributed. Nevertheless, the mining sector remains one of the ten most important sectors of the South African economy.

EMPLOYMENT

One of the direct ways through which an economic sector can improve the livelihood of the citizens of a country is through employment. Employment enables a section of society to receive income that it can use to improve the well-being of the recipient and the recipient's dependants. Employment is therefore an important parameter in assessing a particular sector's contribution to the socio-economic needs of a country.

The mining sector has been an important employer in South Africa for a long period of time. In isolation of the gold mining sub-sector, sector employment has been growing, although slowly, for the last 10 years.[12] In 2011, sector employment passed the 500,000 head count threshold (Figure 6.1).

Figure 6.1: Employment in the South Africa Mining Sector: 2003-2012[12]



Employment in the sector has been lower than that of the trade and the manufacturing sectors,[13] but the sector remains important in terms of job creation potential.

The sector employment figures do not capture the nature or quality of employment. Delving into the details of the nature of employment created by the sector may unearth interesting findings and could change opinion regarding the extent to which the sector contributed to job creation in the country. This analysis, however, is outside the scope of this section.

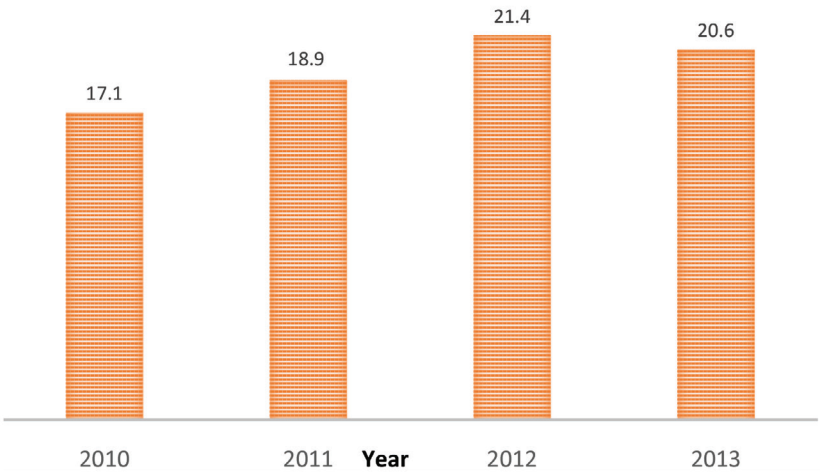
DIRECT TAX

Tax provides a way to redistribute a country's wealth to citizens who may not be directly involved in a particular economic activity that generates wealth. The redistributive role of government is particularly relevant to South Africa, given the number of people who were deliberately denied the ability to participate in economic activities during the apartheid era.

The developmental state model, which is advocated in the country's National Development Plan (NDP), requires that the country has enough resources at its disposal to influence the provision of goods and services that are critical for improving the welfare of those disadvantaged by market forces in society. Through its contribution to the country's revenue pool, via taxes and royalties, the mining sector enables the government, to some extent, to implement its developmental state agenda.

Average corporate taxes paid to the national coffers was Rand 19.5 billion per annum in the period 2010 to 2013. Corporate tax paid by the mining sector in billion rands per year between 2010 and 2013 is presented in Figure 6.2.

Figure 6.2: Corporate tax contribution of the South African mining sector: 2010 -2013 (Rand billion)[14]



It terms of royalties, the sector contributed R4.4 billion, R5.6 billion and R5 billion in the 2011, 2012 and 2013 financial years respectively.[15] The corporate tax sector contribution to national revenue pool has been significant. With careful planning and proper utilisation of the contributions, the country could make substantial positive change in the lives of many South Africans.

FOREIGN EXCHANGE EARNINGS

Trading with the external world allows a country to access resources outside its territorial borders for the benefit of its citizens. Foreign exchange earnings are one of the indicators of the extent to which a trading country is benefiting from external trade.

Between 2003 and 2013, foreign exchange earnings from mining sector trading activities were estimated at R2.16 trillion.[16] The sector contributed 50 per cent of the country's foreign exchange earnings in 2012.[17]

The South African mining sector, in isolation of AMD concerns, continues to contribute positively to the local economy. Through job creation, forex earnings and general contribution to government revenue, mining is a source of livelihood for a number of South Africans. The Chamber of Mines summarises the sector's contribution to the local economy between 2003 and 2013 as follows: sales revenue – R2.9 trillion; export earnings – R2.2 trillion; GDP – R2.1 trillion; employee remuneration – R706 billion; and fixed investment – R548 billion.[18]

The extent of its future contribution is uncertain though, given the fluctuation in commodity prices, instability in the local labour market and mine closures. New mining legislation to be introduced soon may also have a bearing on the sector's contribution to the domestic economy in the future, but this is undeterminable at moment.

IMPLICATIONS OF AMD FOR MINING SECTOR: CONTRIBUTION TO SA ECONOMY

Assessing the extent to which the AMD problem has and can affect mining output and job creation in the country can be a useful way to adjudicate the impact of AMD on the South African economy. Mining output has a direct impact on the country's GDP, while employment in the sector increases disposable income in the local economy. When disposable income increases, the country's GDP increases through the multiplier process.

In economic terms, AMD is a negative externality of production. Negative production externalities results in over-production or producing goods or services beyond optimal levels. The existence of negative production externalities leads economic agents to under-estimate the real cost of production, as alluded to previously. In the mining sector, this translates into over-exploitation of mineral resources in the short-term, while ignoring future costs. Although over-exploitation may have a positive effect on employment in the short-term, it does not guarantee that these jobs will be maintained in the future.

The direct effect of the AMD problem to the contribution of the mining sector to the country's economy has been to keep sector profit and production levels higher than the optimal levels. The status quo is not sustainable in the long term. With internalisation of the mitigation costs of AMD, profit margins will reduce, which will, in turn, affect sector production negatively and subsequently employment in the sector.

BALANCING THE IMMEDIATE AND FUTURE BENEFITS OF THE MINING SECTOR

South Africa should be clear about the mining development model it wants to adopt. Mining, by default, has an adverse effect on the environment, but that does not mean that mining needs to be stopped. Conscious decisions have to be made about how to get the right balance between engaging in mining as a means of national development and protecting the environment. In inter-temporal terms, a decision has to be made on how much pollution will be acceptable now against pollution that will be acceptable in future.

China was propelled to a faster rate of economic growth by ignoring some of the environmental concerns of mining in the short term. Although China developed environmental protection laws as far back as 1979, effective implementation started in 2003.[19] Within this period, the implicit policy stance followed by the country seemed to be 'development first and environmental concerns later'. The Chinese government pursued economic growth, with little concern for environmental issues across the board.

What is not disputable regarding China's experience, is that the country was able to achieve its economic growth objective. In the later years China started putting visible effort into minimising the adverse effects of mining to the environment and cleaning up pollution of past mining activities.

A key difference between South Africa and China, in terms of the 'development first and environmental concerns later' approach, relates to ownership of the mines. For a long time, most of the mining firms in China were state owned.[20] Even after restructuring of the mining sector in 1980s allowed foreign firms a stake in the local mining sector, joint ventures between the state and private companies remained prevalent.[21]

The state remains an active participant in mining sector, and should create an enabling environment for planned future mitigation of AMD. When the mining activities cease the state is and remains a provider of public goods and services. With the private sector being in control of mining, as is the case in South Africa, there is a risk that by the time remedial measures are taken to clean the environment, the mining activity could have stopped and the private actors could have closed the businesses. This has remained one of the key challenges to hold the private mining firms accountable for environmental degradation that emanated from their mining activities.

CONTEMPORARY CHALLENGES FOR THE SOUTH AFRICAN MINING SECTOR IN THE CONTEXT OF THE AMD PROBLEM

Despite its contribution to the national economy and its role in shaping the country's development path over time, the South African mining sector still faces a number of challenges, some of which may be exacerbated by the AMD problem.

LEVEL AND QUALITY OF SECTOR EMPLOYMENT

Organised labour and government still share the sentiment that the level and quality of employment in the sector can be improved upon. Through the adoption of technology that does not replace people, but rather supplements individual productivity, increasing the sector's growth. Sector growth accompanied by an increase in labour productivity, would enable the sector to employ more people and pay them better.

Currently, many people employed in the sector are low-skilled workers who receive very low wages. Very few people are employed in technical positions in high wage brackets. Employment figures reflecting the number of people employed in the sector masks the fact that many receive a bare living wage.

Wage disparity between senior managers and lower employment categories in the sector remain the highest in the country. For example, whereas the average starting basic wage of an underground miner was less than R5,000 per month in 2014, one mining executive was earning R2 million per month, with an additional R2 million per month from shares. The income of the executive was equivalent to the total monthly take home salary of 800 lower level employees at the same company.[22]

The combination of low pay for most of the people employed in the sector, the wage gap between high and low level employees, and the less than optimal working environment, promotes the belief that more can be done to increase the level and quality of employment in the mining sector.

The potential effect of AMD to increase the level and quality of employment is two-fold. If the mining houses are aggressively forced to account for AMD emanating from their activities and to adequately mitigate the effects of AMD, this will increase their production costs in the short term. Motivated by the desire to maintain high profits, they are likely to resort to cost-cutting measures, which normally include retrenchments. So in terms of employment levels, the goal of internalising AMD in production decisions is likely to result in job losses or maintaining the same levels of employment.

The aggressive pursuit of mitigating AMD effects to the environment through the budget provision requirement for mining houses, may weaken the position of labour in pushing for higher wages. The mining houses will have another reason to justify why they cannot increase wages. They are likely to claim that their production costs have increased, as a result of measures to control AMD, which has subsequently reduced their profit margins. With declared low profits, labour will find it harder to justify wage increases.

On the positive side, taking AMD into account is likely to create a safer working environment for workers. It is unlikely that a mining house will take measures to mitigate the AMD problem in isolation of other negative production externalities and safety issues. Recognition of the AMD challenge and efforts to minimise its effects to the environment during and after mining can contribute the overall safety and quality of work environment for miners.

LOW LOCAL BENEFICIATION

Low or a complete lack of mineral beneficiation has been identified as the main reason why the impact of mining activities has not permeated to other sectors of the economy. The disjoint between the mining sector and other sectors of the economy has limited the extent to which the country's mineral wealth has benefited South Africans. In addition, it has limited the revenue earned for the local economy, due to unprocessed minerals being exported.

With mineral beneficiation taking place in the local economy, it is expected that more people outside the mainstream mining business will get jobs and become indirect beneficiaries of mining activities. External revenue from the export of processed or semi-processed minerals will also increase, as a result of value addition that takes place in the local economy. Part of this revenue can be channelled to government's social welfare programmes, making it possible for more vulnerable people in the country to benefit from the country's resources.

Successful beneficiation has a highly likelihood of increasing the AMD problem and negative production externalities, through additional mineral processing and increasing water abstraction. It is important therefore, that planning for mineral beneficiation should include an assessment of AMD effects that will result from the undertaking and that remedial measures are put in place to minimise its occurrence.

DRIVE TO INCREASE LABOUR PRODUCTIVITY

There have been renewed calls by mining houses to increase labour productivity. Mining houses argue that this will improve sector competitiveness and possibly ensure higher wages.

The mining houses and labour agree that improved productivity is important and potentially beneficial to each party. Essentially productivity increases output per each unit of factor employed, thus reduce the average production cost and provide a competitive edge to the producer in the market. The ability to compete in markets enables firms to sustain their business and reduces the likelihood of job losses.

There are no guarantees that labour will always benefit from increased productivity. Its benefit is conditional, based on the willingness of the employer to rightfully quantify the realised increase in productivity and a willingness to pass on a portion of the increase to the workers.

There are, however, practical complications in apportioning the value of productivity gains. First, there needs to be a generally acceptable definition of productivity and detailed data on production processes. The production data should be accessible and understandable by all concerned parties. Most important, the data should be devoid of mistakes.

South Africa's experience in the mining sector reveals that the process of determining productivity and productivity related matters has not been transparent. The process lies in the hands of mining houses, as the custodians of production information. They decide at their own discretion what information to put in the public domain or share with other stakeholders. The information asymmetry in favour of the mining houses makes it impossible for other stakeholders, especially labour, to rightfully claim a fair share of its contribution to productivity gains. Hence the reluctance of organised labour to participate actively in productivity improvement initiatives proposed by employers.

The introduction of the AMD aspect in productivity improvement initiatives exacerbates information asymmetry between mining houses, on one hand, and organised labour and government, on the other, regarding contribution to productivity gains. Labour and government are put in a weaker position in terms of agitating for better sharing of productivity gains. Business can use the AMD concern and cost of AMD mitigation to discount productivity gain benefits that would have otherwise accrued to labour.

Ultimately, concerns about AMD are more likely to serve the interests of mining houses, rather than those of labour, in the short term. Unless labour is empowered to technically quantify its contribution to productivity gains and the mining houses are compelled to disclose all their production information in its entirety, labour will not have a factual basis on which to claim its contribution to increased productivity. Moreover, even though higher productivity may be achieved, there is no mechanism to ensure that the resultant increased profits are channelled to dealing with the negative externalities of mining, one of them being AMD.

BLACK ECONOMIC EMPOWERMENT

Black Economic Empowerment (BEE) for the mining sector is based on the Broad Based Socio-Economic Empowerment Charter for the South African mining industry, which was promulgated in 2004. The establishment of the Charter is a requirement of the Minerals and Petroleum Resources Development Act (MPRDA) of 2002. Better known as the Mining Charter, it was aimed at empowering previously disadvantaged South Africans to share in the ownership of the country's minerals wealth.

One of the challenges experienced in implementing BEE in the sector has been the sourcing of capital by previously disadvantaged black people to buy shares. Some of the black entrepreneurs who ventured into mining BEE deals had to borrow money at unfair terms from banks in order to buy shares. Some of the shares bought could not yield sufficient dividends to service the interest on the borrowed money. These entrepreneurs became bankrupt or had to sell their shares at a loss, but still had to meet their loan obligations using alternative sources of income. So, one of the risks of participating in BEE, which is an encumbrance, has been financing of BEE deals.

AMD creates yet another risk for entrepreneurs wishing to take advantage of BEE in the mining sector. With regulation in place that hold a mining house accountable for its adverse effects to the environment over its mining activity life time and post-mining period, a BEE partner can end up being liable to AMD mitigation costs for the previous mine owners.

It must be emphasised that the impact of AMD and other negative externalities of mining on the viability of BEE business in the mining sector is still a new subject that requires further investigation.

CONFORMING WITH SECTOR POLICIES AND REGULATIONS

South Africa has a number of policies and pieces of legislation in place; these are aimed at ensuring that mining business is carried in an ethical way and that it promotes national development imperatives. Regulation pertaining to protecting the environment from the adverse effects of mining existed prior to the country's democratic transition of 1994.

The Minerals Act of 1991 (Act 50 of 1991) was specifically aimed at safeguarding communities in mining areas from the long term effects of environmental pollution emanating from the mines. The Minerals and Petroleum Resources Development Act (MPRDA) of 2002 went a step further: it mandated the internalisation of the social and environmental cost of mining. The MPRDA 'further stipulated that, funds should be allocated for future mitigation of anticipated adverse effects on the environment as a result of starting the process of mineral extraction before the mining starts'.[22] Neither the Mineral Act of 1991 nor the MPRDA explicitly mentioned the problem of AMD. The problem was included with other environmental pollution problems. AMD thus receive little attention in the mitigation plans of mining houses, given the lack of acknowledgment in the legislation.

The failure to mention AMD in the legislation creates opportunities for mining houses to consider and focus on other types of pollution that are likely to cost them less in mitigation when they submit their operation plans to government. The impact of AMD on mining communities, when acknowledged, is more likely to be under-estimated by mining houses, due to the high cost of mitigation, both during mining and in the post-mining period.

In all, the renewed interest and explicit recognition of the need to internalise AMD mitigation cost into the cost function of mining houses is likely to motivate policy makers to include AMD mitigation specifics in legislation.

LABOUR UNREST

The mining sector in South Africa has been characterised by labour unrest in recent years. In 2014, one of the longest and most costly strikes, in terms of human life, took place in the North West province platinum belt. It lasted for five months, costing mining houses approximately R20 billion in lost revenue, and loss of income to workers was estimated at R2 billion.[23]

The experience of the 2014 platinum belt strike showed that if a strike drags on, it becomes a 'lose-lose' situation for all parties involved. As such, creating stability in the sector is one of the priorities for government and, to some extent, mining houses and organised labour.

Internalising AMD on the part of mining business can possibly fuel labour unrest in short term. This may be used as another reason for employers to continue paying lower wages citing increased cost of doing business. In extreme cases, it could mean some mining business are not viable, forcing them to close the business or drastically reduce the number of employees. The result would be more labour unrest – contrary to current intentions to stabilise the sector.

It is important therefore that enforcement of AMD mitigating measures within the sector should be carefully planned and executed, so as to minimise the potential negative effect on sector employment. Otherwise such measures may trigger labour unrest.

CONCLUSION AND RECOMMENDATIONS

The mining sector has been an important contributor to the South African economy, through revenue generated for the country and employment creation. In assessing the extent to which the sector has contributed and should contribute to the local economy, mining houses, government and labour have tended to focus on current performance parameters. Stakeholders have been more concerned about production levels, profitability, external revenue generated, and the number of people employed in the sector.

The assessment of the contribution has, to a large, extent, not taken into consideration the effects of mining on the environment; one of these is the generation of AMD. For a realistic assessment of the contribution of the mining sector to the South African economy in the short term and the long term, adverse effects of mining activities (such the AMD) have to be acknowledged and quantified. The current contribution should be discounted with future mitigation costs of rehabilitating the environment.

The discounting of the mining sector requires explicit relevant policies and legislations that guide the environmental rehabilitation process taking into account the mitigation costs. Otherwise the sector's contribution to the sustainable development of the country will continue to be over-estimated in the short-term. This observation does not apply only to South Africa, but to all African countries that are rich in natural resources and wish to use their natural resources to support their long-term development aspirations.

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CHAPTER 7

Strategic Planning and Sustainable Management of Acid Mine Drainage

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ABSTRACT

The majority of the gold mines in Gauteng have reached the end of their productive lives and a significant portion of these mines are now ownerless, as the original companies have closed over the years. Hence, the State has no choice but to take full responsibility for maintaining these defunct mines, as they are flooding with acidic water, which poses a threat to ground and surface water resources, as well as to human health and the environment. This chapter provides an overview of some strategic plans and sustainable management practices, with a specific focus on South Africa's institutional and regulatory frameworks. Major interest revolves around the role of the civil society and the government of South Africa, which has socio-economic and governance undertones. The chapter discusses the sustainability of current approaches.

INTRODUCTION

South Africa has a legacy of intensive gold mining, which started following the discovery of a rocky outcrop of the main gold-bearing reef in 1886 by George Harrison. What followed was the 'Witwatersrand Gold Rush', which led to the establishment of the 'City of Gold', Johannesburg, the commercial capital of South Africa. However, the fortunes of gold-mining in the then Transvaal Province, from which Gauteng was carved out in 1994, spans more than one and a quarter century. The majority of the gold mines in Gauteng have reached the end of their productive lives and a significant portion of these mines are now ownerless, due to the original companies closing over the years. Hence, the State has no choice but to take full responsibility for maintaining these defunct mines, as they are flooding with acidic water, which is posing a threat to ground and surface water resources, as well as to human health and the environment.

Acid mine drainage (AMD) has started posing environmental and industrial challenges in a number of former and current mining areas in South Africa, including the Witwatersrand goldfields, the Mpumalanga and KwaZulu-Natal coal fields, and the O'Kiep copper district. The Western, Central and Eastern Basins (Witwatersrand) have become priority areas, due to acid mine decanting, which has been observed in recent years.

The Department of Water and Sanitation (DWS) has proposed a raft of remediation measures to deal with the problem of AMD in the Western, Central and Eastern basins, after receiving recommendations from technical experts.[1,2,3,4] The DWS has come up with a strategy aimed at finding short and long-term solutions for the AMD problem in Gauteng. Implementation of the short-term solution was given the green light in April 2011 by Mrs Edna Molewa, Minister of Environmental and Water Affairs. Trans-Caledon Tunnel Authority (TCTA) was given a mandate and budgetary support by the Minister to implement the project, which provided a short-term solution. So far, the government of South Africa has made two attempts to support AMD remediation: R6,9 million in 2009 for AMD decanting into the Tweelopiespruit; and R400 million in 2011 for the short-term intervention solution. However, by mid-2014, the short-term solution was still tethered by a host of problems which range from financial constraints to technical capacity. The first DWS-supported project failed to treat AMD in the Western Basin to meet the set standards of the Department of Environmental Affairs (DEA).

TCTA floated tenders for the design, construction and commissioning of AMD treatment plants based on high density sludge (HDS) technology – one each at the Western and Central basins.[5] However, the contractors have since indicated that the allocated funds were insufficient and that a ball-park price of around R2 billion was needed to complete the short-term solution phase. The government has indicated that it does not have such financial resources.

Studies done in Canada and the United Kingdom (UK) have shown that the life-span of a decanting mine is between 60 to 110 years from the year of its first decant. Hence, the AMD in South Africa is anticipated to remain a challenge for the next 40 to 100 years.[6,7,8,9] This means sustainable funding and treatment strategies need to be considered, otherwise the AMD challenges will remain a burden to Gauteng Province, the heartland of South Africa's economy.

The theme of this study is of major interest to civil society and the government of South Africa, as it has socio-economic and governance undertones. The AMD remediation process is a costly exercise which requires strategic planning for DWS to achieve a sustainable future. Poor planning could further result in huge financial resources being channeled to AMD treatment and remediation projects. This will evidently put further financial constraints on the government's budgetary support for social programmes, such as old-age and other social-related pensions that are being paid to financially constrained citizens. Bearing in mind that the AMD remediation project could take 40 years or more before the contaminating pyritic rock outcrops in disused mine shafts are exhausted, any long-term AMD treatment solution should be as cost effective as possible.[10]

Another school of thought is to introduce an environmental levy to business and residents of Gauteng. However, this is not a likely option, as residents of Gauteng are the most heavily taxed South Africans, due to the introduction of toll roads on Gauteng's major freeways. The involvement of the State in AMD remediation is unavoidable, but the level of involvement needs to be leveraged in such a way that the risk is shared among all stakeholders. The major stakeholders are government, mining houses and AMD technology providers.

Another interesting aspect of the subject of AMD remediation is that South Africa, through its research councils, universities and, to some extent, private companies, has, for the past 10 years or so, invested quite a lot in research into and the development of technologies meant to allow cost-effective treatment of AMD. However, it seems there is little interest by the designated implementing agency, TCTA, to utilise locally developed AMD treatment technologies. There is another school of thought whose proponents are arguing that the traditional HDS process, if just taken as per its developers' prescript, is not likely to treat AMD to the required local standards for release into the environment. This argument is strengthened by results from the Western Basin short-term AMD treatment which, by 2014, showed that the HDS process is failing to produce water of a quality acceptable to conditions set out in the DEA's Waste Authorisation Permit given to the plant in Randfontein.

A lot of preliminary work was done by DWS before the onset of the short term intervention strategy. However, historically, AMD challenges in America, the United Kingdom and Canada were dealt with using a large number of participants, including technology providers, researchers, mines and state institutions.[11,12,13] The implementation was decentralised and this allowed the testing of a variety of technologies using funds from government and mines.[14,15] Hence, most of the so-called approved or conventional methods of AMD treatment originate from these countries. The huge divergence between what was recommended by South Africa's report to the Inter-Ministerial Committee (IMC) in 2010 and the due diligence studies carried out by consulting companies contracted by TCTA in 2011 should serve as an alarm bell. The Due Diligence Report left little space for the participation of companies using any of the locally developed technologies, as anticipated by the IMC report. Hence, in view of the preceding observation, the government, which needs to start with implementation urgently, appears to have put itself in a tricky position, which could result in the country spending more financial resources unnecessarily. Above all, sole dependence on the HDS technology in order to deal with AMD may not achieve the anticipated outcomes. The IMC report listed 10 locally developed technologies that DWS was supposed to consider as part of AMD treatment for the short-term and long-term solutions. However, none of these technologies is now likely to be utilised as part of either the short-term or long-term solution.

Another reason why this subject of strategic planning of AMD treatment in South Africa should be further interrogated is the procurement models and technology selection criteria that DWS seems to be pursuing. There is no one-size-fits-all approach in the field of technology implementation. Projects carried out in the USA, the UK and Canada in dealing with AMD challenges are unlikely to suffice in the South African situation, as there is a huge difference in terms of South African geology and AMD composition. Hence, in a field where there is no standard reference technology and only the preferred outcomes are known, a variety of procurement models need to be considered.

The problem of AMD in South Africa is mainly found in Gauteng Province, with its three metropolises, which are the most industrialised in Africa. If the four basins are allowed to start decanting, most of the raw water sources in Gauteng will be contaminated with heavy metals, acidity and radionuclides. This would pose a serious threat to the environment and health of Gauteng's ever increasing population. However, despite the significant threat that the AMD problem is posing to the people of Gauteng and the negative effect it will have on the economy, the South African government is apparently not prepared to tackle this problem, which is associated with a lack of strategic planning by preceding governments and other non-controllable historical events.

Several white papers were published by DWS on the way forward as far as AMD challenges are concerned.[16] All the publications and policy documents from the Department of Water Affairs (DWA) seem to assume that the challenges of AMD can be solved by the government following a normal business approach. The business approach used by the South African government resulted in the first tender for a short-term solution for AMD being awarded to TCTA, a state enterprise with no knowledge of treatment processes required to deal with the different kinds of AMD found in the four major basins of the Witwatersrand. This chapter suggests that AMD challenges in South Africa is not a technological issue, as projected by the DWS, but rather a mirror of non-aligned management policies. The current approach to the problem of AMD saw the budgeted funds being exhausted before the first short-term AMD treatment plant was commissioned. Hence, this study was focused on a sustainable strategic plan that the DWS needs to consider if the treatment of AMD is to be achieved cost-effectively. The locally based research community holds that the role of DWS should be to solicit service providers that can set up AMD treatment facilities at designated sites and produce water to specification. DWS should refrain from involving itself in technology selection, as that should be the risk taken by the service provider. In essence, this study was meant to unbundle a number of issues or challenges that DWS seems to have overlooked in awarding the short-term solution contract.

The filling of mine voids and subsequent decanting of acid mine water into the environment is a potential human and economic tragedy for Gauteng, the economic heartland of South Africa. The government of South Africa, after a review of all pertinent legislation, realised that the legacy of AMD was lying squarely in its own hands, as most of the decanting shafts are now ownerless. The present government has spent significant financial resources supporting social programmes, mostly in impoverished black communities. The special challenges posed by AMD in Gauteng mean that the government will have to realign its budget. The problems of AMD will probably be with us for the next 40 to 60 years, before the pyritic rocks in mine voids close to the surface are exhausted. During this period, the government needs to provide annual budgetary support for AMD treatment projects proposed for the Western, Central and Eastern basins. Therefore the government should cautiously enter into contracts with service providers after seriously considering sustainable strategies that will enable it to achieve the most viable procurement deals.

In 2011, the South African government budgeted R400 million for the short-to-medium-term phase of AMD treatment. These funds were reportedly exhausted by the end of 2013, before the short-term phase was completed. One of the engineering companies contracted to design and construct the short-term-phase wastewater treatment plants in Randfontein and in Boksburg was quoted in the print media as saying that about R2 billion was needed to complete the short-term phase. The government indicated that it did not have such financial resources and a variation to scope of work was implemented. The government, through its implementing agency, TCTA, decided to invest in the Rand Uranium Mine Wastewater Treatment plant. The agreement cited the government as taking the responsibility to meet the cost of running this wastewater treatment plant, and Rand Uranium (now operating as Sibanye Gold Ltd) assumed the role of operator of the plant. In essence, government is now taking responsibility for treating mine wastewater, both from ownerless shafts and from Sibanye Gold Ltd.

While the design, construction and operation of the wastewater treatment plant have met their own share of challenges, especially the Western Basin, by mid-2014 the plant was still failing to produce treated water of the desired quality and suitable for release into the Tweelopiespruit. The current situation weighs heavily on the government, as there seems to be no sharing of risk with its contractors. The government, in the current state of affairs, is responsible for financing, sourcing the projects and ensuring that the plants produce water of the desired quality. This appears to be a major hurdle.

The expected annual cost of AMD treatment was modelled on an ideal HDS process. However, the make-up of AMD in South Africa, especially in the Western Basin, is quite different from that found in Canada, where the HDS process was developed and used successfully. That means that the process on which the short-term plant was designed might need some tailoring. Reconfiguration of the plant will mean extra cost to government, but should be the responsibility of the contractor.

STEPS BEING TAKEN TO MANAGE ACID MINE WATER IN SOUTH AFRICA

THE SUSTAINABLE APPROACH = BY MINING COMPANIES

While the management of wastewater, such as sewage, is well developed in South Africa, the scenario is different when it comes to industrial wastewater, especially that from the mining sector. The treatment of sewage is well regulated, to the extent that the Department of Public Works (DPW) has published standard designs that should be used by engineering companies when constructing sewage treatment facilities.[17] The design and construction of such a facilities should be carried out after complying with other regulations, namely completing an acceptable environmental impact assessment (EIA), as anticipated by the National Environmental Management

Act No. 107 of 1998, and lodging a successful application for waste authorisation, according to the National Environmental Management: Waste Act 59 of 2008.

The lack of specific treatment procedures applied by regulators is propelled by the diverse mining operations, which produce waste water of varying quality levels. Mines have traditionally been releasing two forms of water. The first is processed water, which is heavily contaminated and requires treatment before being released into the environment. The second form is generally clean water from the dewatering of adjacent dolomite aquifers, especially in the Witwatersrand goldfields. Dewatering was practised in the Witwatersrand Basins until 2008.[18] Operating mines were carrying out dewatering in order to contain the flooding of mine shafts and allow safe mining. However, dewatering has led to surface subsidence and sinkhole formation at several sites in the Witwatersrand Basin.[19] The decision to stop dewatering of dolomitic aquifers, especially at non-operating mines, as a way of minimising sinkhole formation, created a new problem that manifested itself as the first AMD decant, which took place at Harmony Gold's BRI. Pre-1998, the water coming from the dolomitic aquifers was non-acidic, since this water was coming from rocks not exposed to oxygen. The stoppage of dewatering caused the flooding of most non-operational mine shafts. The exposed pyritic rock outcrops were then exposed to water and oxygen, which resulted in oxidation of pyrite to sulphuric acid.

By 2005, the then Department of Water Affairs and Forestry (DWAF) realised that a new environmental catastrophe was in the making (in the form of decanting acid mine water), with the potential to destabilise large parts of Gauteng Province. In response to the acid mine water threat, DWAF issued a directive enforcing cooperative agreement between mines to find a solution to acid mine drainage, especially in the Western Basin. In the Western Basin there is a mixed situation, with operating mines and non-operational ones. DWAF therefore had to resort to issuing a directive, as there was no existing regulation that could be used to apportion responsibility to the owners of prospecting licences or those who owned the mines, as anticipated in the Mineral and Petroleum Resources Development Act (MPRDA) of 2002. The decanting of acid mine water started in ownerless mines and non-operational mines where dewatering had been stopped in response to the problem of land subsidence and sinkhole formation.

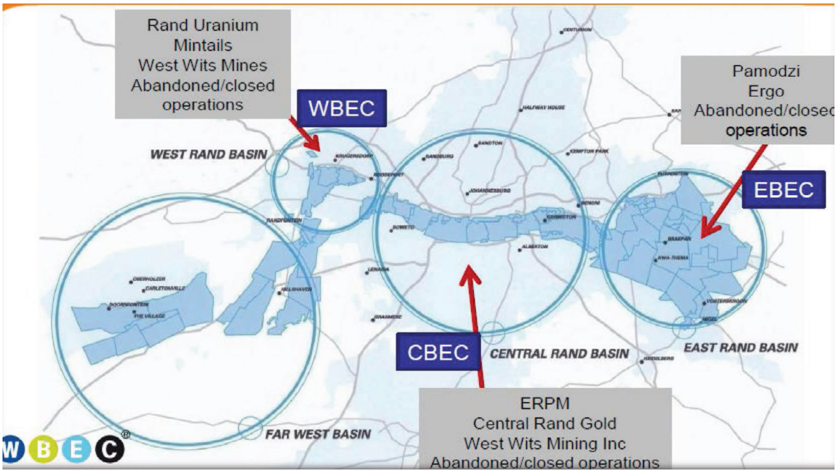
In response to the directive from DWAF, mining houses started to form Section 21 companies, which were intended to work in partnership with the government to solve the problem of decanting acid mine water. Initially, three Section 21 companies were formed, namely: Western Basin

Environmental Corporation (WBEC), Central Basin Environmental Corporation (CBEC) and Eastern Basin Environmental Corporation (EBEC). In 2006, DWAF gave mines the directive to form a Water Service Provider company, as anticipated in Section 19 (3) of the National Water Act of 1998, Act No. 36 of 1998. The mines operating in the Western, Central and the Eastern Basins responded by forming a water service company, which they named Western Utility Corporation (WUC). Figure 7.1 shows a relationship map for the three basins near Johannesburg.

Companies involved were given to understand that there would be private-public participation. DWAF wanted mine companies with limited liabilities to participate in the treatment of AMD, especially in the Western Basin, where decanting had started in 2002. The WUC proposal was to treat AMD to potable quality and then sell the water to water service providers, such as the municipalities or Rand Water. The company that was formed by the operating mines then embarked on feasibility studies for the Council for Scientific and Industrial Research (CSIR) Alkali-Barium-Calcium (ABC) process, until they had a bankable project in 2009. Their understanding, according to the directives and other communication from DWAF, was that these mines were going to be allowed to participate in AMD treatment, since they had huge infrastructure to pump water from the voids. In 2010, DWA issued a 'request for expression of interest' to companies that were interested in participating in the treatment of AMD. High interest was shown by more than 40 companies that were keen to use their technologies to treat AMD.

By the year 2010, WUC had spent more than R60 million on research and development in preparation for roll-out of AMD treatment plants in the three critical basins, which have the potential to provide 10 per cent of the water currently being supplied by Rand Water, mainly to the population of Gauteng. However, the project could not go ahead as the South African Government escalated the challenges of AMD to be dealt with at presidium level. An Inter-Ministerial Committee (IMC) was formed in 2010 and mandated to organise a team of experts who were to generate a report on the way forward. The report was to be used as a guide to the DWA in its plan of action for a sustainable long-term solution to AMD challenges in SA.

Figure 7.1: Wits Basin, showing the three basins initially targeted for AMD treatment by WUC[17]



THE APPROACH TO AMD TREATMENT TAKEN BY THE GOVERNMENT AFTER 2010

The formation of IMC on acid mine drainage by the South African government resulted in National Treasury putting forward a budget for AMD treatment. Unfortunately, the budget was put forward without clear direction of how the project was going to be implemented. The goal was clear, but the strategy to achieve it was not in place.

The first major step taken by the South African government to deal with AMD was the appointment of TCTA (by the Minister for Water and Environmental Affairs) to treat AMD. TCTA was appointed through a directive in terms of the National Water Act, (Act No. 36 of 1998), Section 103 (2). The TCTA is a state entity that was established in terms of Government Notice No 2631 in Government Gazette No 10545, dated 12 December 1986.

The TCTA was directed to implement the following recommendations as emergency works:

- Installation of pumps to extract water from the mines to on-site treatment plants;
- Construction of an on-site water treatment plant in each basin, with the option of refurbishing and upgrading the existing ones owned by the mines; and
- Installation of infrastructure to convey treated water to nearby

watercourses.

The recommendations were in line with the IMC report (AMD Report) that had been drawn up by a team of experts in 2010, as previously discussed.

By way of enhancing its technical capacity, TCTA went out on tender for a professional service provider (PSP) to complete the following tasks:[21]

- Due diligence;
- Tender design;
- Detailed design and construction supervision; and
- Project close out.

One of the anomalies in the procurement procedures for this process was the appointment of the same group of companies that had been tasked to carry out the preceding activities. The client – in this particular case the government of South Africa – should not have been compromised in terms of pricing of the project. Also, the due diligence report could have been biased if the consulting companies were aware that they themselves were going to be awarded the tender to carry out the construction of the treatment plants. While the process of preparing the construction of the AMD treatment plants in the three identified critical basins was in progress, the Parliamentary Portfolio Committee on Water and Environmental Affairs (PPCWEA) was gathering information from various stakeholders on the best way forward in trying to find a sustainable short-term and long-term solution for AMD in the Witwatersrand Basins.

STAKEHOLDERS' PRESENTATIONS TO PPCWEA ON SUSTAINABLE AMD TREATMENT

The presentations to the PPCWEA by stakeholders started soon after the appointment of TCTA to implement the short-term solution. The short-term solution was supposed to be integrated into the long-term solution. Among the major stakeholders, apart from research councils and TCTA, were the mining and water treatment companies which responded to directives from DWAF in 2005.

The Western Utility Corporation (WUC), a Section 21 company, was formed by mining companies as a special purpose vehicle to deal with AMD treatment challenges. The presentation by WUC was a chronology of events that started as a directive by DWAF in 2005. The interim solution that WUC presented was based on the utilisation of current mine infrastructure to pump water to current mine treatment sites in the Western, Central and Eastern Basins. The interim solution was supposed to neutralise the acid mine water and then release it into the environment. Additional or new infrastructure to be added to the interim project was in the form of abstraction and piping equipment. The WUC approach to the AMD problem considered the following:

- Definition of the scale of the AMD problem – qualities and quantities;
- Various options considered;
- Detailed feasibility study;
- Risk assessment;
- Extensive regulator and public engagement;
- Final Scoping — EIA Report; and
- Water Use Licence Application (WULA) ready for submission.[22]

DWA was quite involved and was monitoring the progress of the studies, aware that it was receiving full cooperation from the mines. WUC, according to its study, was poised to raise R1,52 billion through private finance, and the return on investment was to come from the sale of potable water and other saleable by-products that were to be generated from the process.20

According to WUC, the key attributes of the proposal were the following:

- Sound governance — public-private partnership;
- Regional-scale solution;
- Consideration of regional impact — Vaal River salt load;
- Material to future Vaal strategies;
- Stageable;
- Economically viable and externally financeable;
- Significant BEE opportunity;
- Blueprint for other mining regions; and
- The proposal was ready for implementation.[23]

While WUC indicated to PPCWEA that they had done what the government had directed them to do, they were not amused by DWA's subsequent formal rejection of their proposal in preference to TCTA as its implementing agency; TCTA did not do an investment or feasibility study until after its appointment. In WUC's view, its proposal was sustainable, economically viable, financeable and structurally sound.

Another presentation made to PPCWEA was that by Dr Roger Paul of Mintek. It mainly aimed at marketing the SAVMIN technology developed by

Mintek for AMD treatment. One critical factor explained in this presentation was that the SAVMIN process has the lowest operating cost of the various biological sulphate removal technologies. However, no cost-benefit analysis was provided to support this claim and no comparison was made to other sulphate removal technologies, for example, the ABC process.

The trade union, United Association of South Africa (UASA), is another stakeholder; it presented a promotional document to PPCWEA, supporting KeyPlan's reverse osmosis process as an alternative sustainable solution to AMD. However, it is known that the joint implementing association (Anglo American Thermal Coal, BH Billiton, Exxaro, Optimum Coal and Eskom) was subsidising the eMalahleni Water Treatment Plant run by KeyPlan, as the revenue from potable water alone cannot ensure that the process breaks even.

The benefits anticipated by UASA from the KeyPlan technology include:

- Job creation;
- GDP growth;
- Additional potable water;
- Enhancement of the national coffers through taxes;
- Burden removed from government;
- Removal of burden from mining operators after end of life of mine; and
- Removal of the threat of AMD.[24]

However, these benefits can only be realised if the process is sustainable. This means the potable water generated from the KeyPlan's reverse osmosis (RO) process should match in price that produced by other water boards. However, current market knowledge shows that the RO process is very expensive to install and run. If the government were to change its contractual and implementing models, more firms might be joining the foray into AMD treatment and the most sustainable technology would win the game.

The presentation done by TCTA to PPCWEA was a critical one, as it was based on the strategy the government had adopted to deal with AMD challenges in the Witwatersrand Basins through DWA. PPCWEA was informed that the designs for AMD treatment plants had a life-span of 30 to 50 years. The short-term solution was actually the first phase of the long-term solution. The target for the designed plants was to pump to below environmental critical level (ECL), which varies from basin to basin. The detailed presentation by TCTA covered all the activities that were to be carried out in the three basins of the Witwatersrand area. This chapter is of the view that emphasis in the Eastern Basin should have been on desalination, rather than on removal of the very low levels of iron present in that water.

CURRENT AMD MANAGEMENT PLANS BEING IMPLEMENTED BY DWA

Since the appointment of IMC by the South African Cabinet in 2010, DWA took a number of actions in response to the IMC Report of 2010. The DWA issued a directive to TCTA to implement the short-term emergency solutions that they referred to as short-term interventions (STIs) for the AMD project. In response to the directive, TCTA appointed BKS (Pty) Ltd, in conjunction with Golder Associates, to design and implement the STI. The scope of work given to the two contracted companies covered the following tasks: [25]

- **Task 1**: A due diligence review of the Inter-Ministerial Committee Report (as provided by TCTA) and the recommendation of a solution for each of the mining basins;
- **Task 2**: Development and production of documents supporting the Integrated Regulatory Process for all basins;
- **Task 3**: Development and production of engineering design and tender documents that will be used for competitive procurement of a competent contractor, as well as detailed engineering designs for the agreed and approved solutions for each of the mining basins, complete with construction drawings;
- **Task 4**: Monitoring of the contractor's activities and commissioning of the works;
- **Task 5**: Monitoring of the works during the defects liability period, taking corrective action if required, and the provision of formal operation and maintenance manuals as well as close-out reports; and
- **Task 6**: Operation and maintenance support to the TCTA for all constructed basins.

The fulfilment of the preceding tasks resulted in the generation of a total of 18 reports, which, apart from the Due Diligence Report, covered mainly the long-term solution for AMD treatment and management. A series of these reports have been produced under the broad context title 'Water resource planning system series: feasibility study for a long-term solution to address the acid mine drainage associated with the East, Central and West Rand underground mining basins'.

THE DUE DILIGENCE REVIEW REPORT

The Due Diligence Review by BKS (Pty) Ltd and Golder Associates on the IMC Report (2010) was guided by the following technical aspects:

- The environmental critical level (AMSL) for each of the three basins (Western, Central and Eastern);
- The volumes and flow rates of AMD for each basin; and
- The AMD water quality.

These three aspects were critical in coming up with a technical solution in terms of process selection and the size or capacity of infrastructure required to abstract and treat the AMD.

The findings of the due diligence review (DDR) for the short-term intervention are listed as follows:[26]

Western Basin:

- Abstraction of AMD via installed pumps in Rand Uranium's No. 8 Shaft at a depth to achieve the ECL;
- Construction of a new high density sludge (HDS) treatment plant on the Randfontein Estates site;
- Construction of a treated water pipeline to a suitable discharge point on the Tweelopiespruit, flowing to the Crocodile West River; and
- Construction of waste sludge disposal pumps/a pipeline to the old open-cast pits, including West Wits Pit and the Training Centre Pit.

Central Basin:

- Abstraction of AMD via installed pumps in the South West Vertical (SWV) Shaft (either to pump to the ECL or to the Central Rand Gold-proposed mining level of 400 m below SWV Shaft level);
- Construction of a new HDS plant at SWV Shaft;
- Construction of a waste sludge pipeline to the DRD Gold (Crown) Knights Gold Plant;
- Construction of a treated water pipeline to a suitable discharge point on the Elsburgspruit; and
- Investigation and planning for a future waste sludge pipeline to the ERGO Brakpan tailings storage facility (TSF), alternatively, to ERPM's old underground workings.

Eastern Basin:

- Abstraction of AMD via installed pumps in Grootvlei No. 3 shaft at a pump depth to achieve the ECL level or the level to allow Gold One to continue mining Sub Nigel No. 1 Shaft;
- Construction of a new High Density Sludge (HDS) treatment plant adjacent to the Grootvlei No. 3 shaft, on the agricultural smallholding site south of the abstraction point;
- Construction of a waste sludge pipeline to the DRD Gold Daggafontein Gold Plant for co-disposal on the Daggafontein TSF; and
- Construction of a treated water pipeline to a suitable discharge point on the Blesbokspruit.

However, a critical analysis of what is known about the Central Basin mine water composition shows that pH levels of water is neutral to near neutral. Considering that the major problem of this water is salinity, one has to ask if the construction of a new HDS plant for this basin was the best policy after the due diligence process. The critical parameter of the Eastern Basin mine water is the sulphate, which contributes to its salinity. However, a fundamental point in the report is that it sets the ground rules to be followed in AMD treatment in South Africa. All the subsequent activities under the short-term intervention solution were based on the findings of the Due Diligence Report. The Due Diligence Report was also compromised by the fact that the contractor that generated the report implemented his own findings – hence the alternative view that some of the findings were tailor-made to suit the contractor's technical capability at the implementation stage.

WATER RESOURCE PLANNING SYSTEM SERIES REPORTS

Soon after the appointment of TCTA, in April 2011, by the Minister of Environmental and Water Affairs, to implement the short-term intervention (STI) project on AMD, the DWA started planning for the long-term solution. Bids were invited through a public tender system, by a request for proposals. The focus of this invitation to tender was the following information: economic feasibility, technical feasibility, choice of lead adviser, and the financial and legal aspects of the long-term solution (LTS). A joint venture of three consulting companies – Aurecon, SRK Consulting and Turner and Townsend – was awarded the tender to produce documents that would guide the implementation of LTS projects for AMD. As mentioned previously, a total of 18 reports were generated on the feasibility study of how the LTS was to be implemented. The following sub-sections provide a brief overview of some of the critical documents generated.

STATUS OF AVAILABLE INFORMATION STUDIES BY DWA

The specific objectives of the status report on available information were to:[27]

- Collate and present the information (i.e. databases, spatial data and media articles) that has been made available to the study team;
- Create a theoretical framework for the study with regard to the knowledge areas that form part of the study and also to identify gaps in the information that should ideally be the subject of future research. Where such information gaps may affect this study, recommendations will be made on how to address this; and
- Convey details on the type of information required, and on the stakeholders from whom it was obtained.

The objectives of this part of the study were noble and critical, as information obtained was vital for the DWA in terms of its technology selection process. However, the collection of information on technologies available is always problematic, as developers are unwilling to provide all their research and development information, as a shield against competitors. It is only with traditional processes that have reached maturity that information is available in the public domain. Thus, recommendations by the contractors that information on technologies available should be obtained through a 'request for information' were quite appropriate in this particular context.

TECHNICAL FEASIBILITY REPORT

The technical feasibility report (TFR) was a critical review document dealing with the feasibility study of the long-term solution (FSLTS).

The objectives of the TFR[28] were to:

- Summarise the technical options for abstraction, water treatment, water use and waste disposal, as presented in other reports;

- Describe combinations of the various components into a number of complete alternative technical options for the long-term management of AMD;
- Present the process used to screen the options and the results of this process, i.e. a short-list of options for economic analysis;
- Describe the project economic analysis and the results, which lead to the definition of the Preliminary Reference Project;
- Select a Preliminary Reference Project against which tendered solutions must be compared, after refinement in DWA AMD FS 2012, Study Report No. 6: 'Concept Design Report';
- Describe the Preliminary Reference Project in sufficient detail so that:
    - the cost estimates (capital, operating and maintenance) can be used in the initial financial and macro-economic model;
    - the scope of the more detailed work required in the Concept Development is clear;
    - the locations of the alternative component layouts, which may need to be used in the initial phases of the Environmental Impact Assessment (EIA) process, are defined;
    - any components or options that cannot be recommended for implementation immediately, but which have potential in the longer term, are clearly identified for further study; and
    - consider the principles and approach for implementing the long-term solution (LTS).

Some of objectives described above for the FSLTS should have induced the DWA to obtain helpful information for the LTS. One wonders how designs and drawings could have been produced without the specified process to be used for the LTS. Perhaps the description of the project economic analysis could only have been done if there was already a known selected process for use in the LTS project. By 2013, when the TFSR was produced, there was no indication that DWA had made a decision on the technology it was going to use for the LTS. Again, one is persuaded to infer that the FSLTS was prematurely done, without some decisions that should have been made prior to FSLTS.

CURRENT STATUS OF THE TECHNICAL MANAGEMENT OF UNDERGROUND AMD

DWA undertook a review of the status of the technical management of underground AMD prior to the implementation of the LTS. The objective was to describe the current and expected status of the technical management of AMD, primarily within the study area.[29] In this report, several AMD treatment projects, especially in the United States (US), the UK and Canada, were highlighted. Although the initial process used in these countries was the conventional HDS process, several variants of this process were used later, after observing some of the limitations of the original process. The report on technical management of underground AMD also dealt with a review of mine water treatment infrastructure. The emphasis was on determining the infrastructure that was already in existence in the three basins of the Witwatersrand goldfields. One of the major short-comings of the 'Current Status of the Technical Management of Underground AMD' report is that it was used to review the STI for the Central and Eastern Basins before the infrastructure was built. Hence, the review was not helpful regarding the lessons learnt for the LTS. This review should have been carried out after the STI was in its operational phase. The approach to be followed in the LTS phase was supposed to be guided by experience gained with the STI.

The third aspect that was reviewed in the 'Current Status of the Technical Management of Underground AMD' report was the issue of sustainability of the STI project. The sustainability part of the report reviewed the following: the abstraction of AMD to ECL, the discharge of neutralised water, the discharge of neutralised and desalinated water, and sludge management and disposal. Again, as stated in the preceding discussion, this review was premature, as most of the construction work for the STI was not yet complete by early 2014 when the review document was already in the public domain. The disposal of neutralised water was reviewed, although the three AMD treatment plants built in the Witwatersrand Basin for STI were only for neutralisation. On the issue of disposal of neutralised water, the Tweelopiespruit was recommended as the channel of choice in the Western Basin. However, the Tweelopiespruit is a tributary of the Crocodile River, which is in turn a tributary of the Limpopo River, which is now perennial. No environmental impact assessment (EIA) was done for the disposal of saline water into these two major rivers, which pass through sensitive ecological regions. The disposal of saline water into the Crocodile and Limpopo Rivers could have unintended impacts on farmers and wildlife. Hence, it is critical that the desalination stage of the treated acidic mine water should be a priority for the LTS project.

OTHER LTS FEASIBILITY REVIEW REPORTS BY THE DWA

The DWA commissioned other feasibility studies for which reports were produced, apart from those critiqued in the preceding sections. Most of these reports were in line with strategic planning for a long-term endeavour. The following reports were part of the studies the DWA commissioned in pursuit of an LTS for AMD management in Gauteng:

- Assessment of the water quantity and quality of the Witwatersrand mine voids;
- Options for use or discharge of water;
- Treatment technology options;
- Options for the sustainable management and use of residue products from the treatment of AMD;
- Implementation strategy and action plan;
- Key stakeholder engagement and communications;
- Communication strategy and action plan; and
- Feasibility report.

These reports show how the DWA was seriously striving to deal with AMD treatment sustainably. These reports were initiated in terms of the bigger picture of how AMD should be managed. Some of the studies DWA commissioned as part of the full scale long term solution (FSLTS) were not published for confidentiality reasons, i.e. future procurement and legal issues. The following list contains a group of reports that were not released, based on confidentiality reasons:[29]

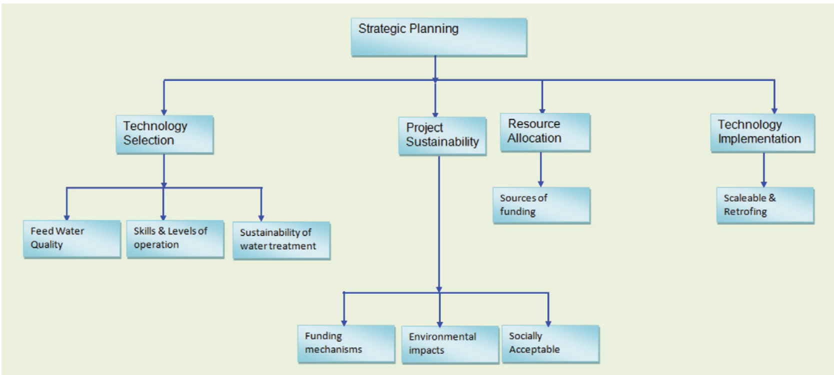
- Legal Considerations for Apportionment of Liabilities;
- Alternative Approaches for Apportioning Liabilities;
- Concept Design;
- Concept Design: Drawings;
- Concept Design: Costing; and
- Institutional Procurement and Financing Options.

The confidential reports include Concept Design, and Concept Design: Drawings. The titles of these reports suggest that the technologies that were going to be used for the LTS were already selected. It is not possible to have concept design drawings for non-existent technologies. If the technologies for the LTS were already selected by the DWA, this then contradicted information provided in the Treatment Technology Options report. The Treatment Technology Options Report indicated that there would be a number of procurement options, in order to give those firms with unproven technologies a chance to apply these technologies in the LTS AMD treatment projects. There are a lot of contradictory ideas in DWA publications about an LTS that is sustainable in terms of financial viability, legal standing, socially acceptability and environmental friendliness.

SUSTAINABILITY OF CURRENT APPROACHES

The strategic planning processes that DWS has undertaken and those it needs to undertake to deal with acid mine drainage in the Witwatersrand goldfields are discussed in this section. The sustainability of the whole AMD project management process is hinged on the strategic planning process being carried out by DWS. Zinowanda et al.[30] proffered a strategic planning framework as shown on Figure 7.2. The frame details tasks that need to be considered during the planning and implementation stages of the acid mine drainage management processes. The first level tasks cover technology selection, project sustainability, resource allocation and technology implementation.[31]

Figure 7.2: Proposed criteria for assessing the planning process for AMD management[32]



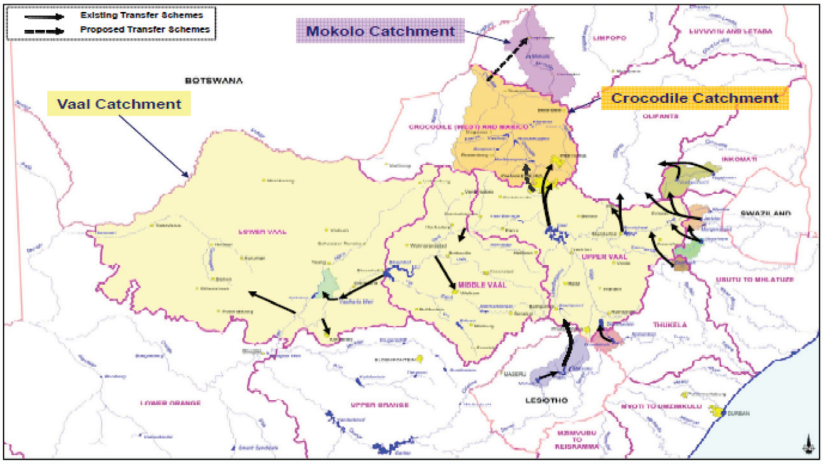
The ideal planning process for sustainable AMD management should take into account the following factors:

- An appropriate technology based selection process;
- Influence of feed water quality on the technology selection process;
- Skills and level of operation of technology selection process; and
- Sustainability of water treatment.

The most appropriate scientific technique that evaluates the importance of the factors described in this section is for one to apply the analytical hierarchy process (AHP). The AHP is one of the multi-criteria decision analysis (MCDA) and the most straightforward process described,[32] which DWS should have considered before implementing the short-term intervention project.

The environmental impact associated with the treatment of AMD by conventional HDS is the highly saline wastewater often released into the open water channels. Currently, the water treated by the STI WWTP at Shaft 8 is released into the Tweelopiespruit, which flows into the Hennops River, and the saline water is finally deposited into the Crocodile River, which is a tributary of the Limpopo River. The release of saline water into the Tweelopiespruit is thus a trans-boundary pollution issue. Countries affected include South Africa, Botswana and Zimbabwe (Figure 7.3), which are likely to receive polluted water from the Crocodile River, if the treatment of AMD in the Western Basin by HDS is continued. Hence, if the challenges of AMD in the Western Basin persist for the foreseeable future, South Africa needs to consider technologies that will desalinate the AMD water being treated in this basin. Releasing saline water into the environment, as is currently being done, transfers the AMD challenges to outside third parties. The responses given by the experts who participated in this survey confirmed that the conventional HDS process is far from adequate in dealing with the AMD challenges caused by AMD in the Witwatersrand goldfields. Hence, this study recommends a sustainable approach in which water produced from AMD should meet certain minimum standards that will make it acceptable for use in agriculture and industrial processes.

Figure 7.3: Crocodile and Limpopo river systems shared by SA, Botswana and Zimbabwe[33]



A significant number of stakeholders feel strongly that mining companies are being let off the hook, as they have limited liabilities on the AMD situation. However, when mining started in South Africa over a century ago, nobody anticipated the current scenario. Hence, there were no regulatory requirements for mines to prepare a closure plan to care for the mine shafts after closure. The impact of decanting AMD took more than half a century to be realised. Current legislation obligates operating mines to deposit monies into a trust fund as a contingent measure to deal with unplanned closure of mines through liquidation or business failure. However, the legacy issues seem to be the responsibility of government. The funding model should be thoroughly investigated, as AMD issues are not going to go away any time soon. Although the findings of this study seem to indicate that experts are comfortable with direct AMD financing from the government's national budget, the quest for sustainable management of these remains a daunting challenge.

The case of the Western and Central Basins, which were financed and operated under the full control of TCTA, provides an interesting dimension to the challenge of stakeholder interaction and management. Seemingly, contractors appointed by DWS/TCTA have negated the risks associated with AMD. The author is thus of the opinion that, since the technology being used was selected by DWS and TCTA, any weakness in the process cannot be apportioned to the designer or the operator. Ideally, the sponsor or customer should only set specifications for the product requirements. In the case of

AMD treatment, the DWS/TCTA perhaps should have only set the parameters for the quality of the water they were expecting from the contractor, i.e. the product. A contract could have been designed in such a way that payment to the contractor was based on volumes of AMD treated meeting agreed specifications. By so doing, DWS could have transferred some process and operational risks, as discussed previously. It is against this background that DWS should take steps to review its contractual obligations with its contractors, in order to minimise its exposure to design and operational risks.

This study suggests that the government of South Africa should provide adequate financial resources for AMD treatment, and transfer implementation to contractors. The government has options to raise funds through levying companies or general tax payers. That means the government should investigate possible sources of financing the legacy AMD that have a minimal impact on the national budget. By involving itself in the implementation phases, the government will expose itself to unnecessary risks. The best people to carry operational risks are the contractors, as they are selected based on their ability to implement such projects.

Generation of potable quality water from AMD will see the water being sold to water distributors, such as water boards and municipalities. This is critical in as far as sustainability of the project is concerned. Hence, DWS should continue to investigate the viability of treating AMD to potable quality. Another alternative that DWS should investigate is the treatment of AMD to industrial quality before considering potable quality, since there are fewer ethical issues with industrial water. Potable water production from AMD might find strong resistance from bulk water distributors, such as municipalities, since due process needs to be followed before such water is supplied to residents.

CONCLUSION

Strategic planning and sustainable management of AMD is a necessity, not an option. The government has to play a leading role and take full responsibility for maintaining the defunct mines that are flooding with acidic water and posing a threat to the environment. The discharge of saline water into fresh water bodies and streams is not only a local challenge, but a transboundary pollution issue, which calls for a holistic approach to ensure integrated water resources management. The AMD challenge requires human capital characterised by multi-disciplinary experts, ranging from water quality experts, social scientists, and hard natural sciences with skills on levels of technology operation, maintenance and sustainability of water treatment facilities. The fusion of both short-term and long-term intervention strategies is key in confronting the AMD challenge. Lastly, no single technology can provide a solution to the AMD problem – hence the need for integrated holistic approaches that fuse both soft approaches and hard technological interventions, as described in elsewhere in this book.

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CHAPTER 8

Interrogating and Reviewing Legal and Policy Frameworks Governing Acid Mine Drainage in South Africa

Olivia Lwabukuna

ABSTRACT

Mining is South Africa's historical breadbasket and it has brought great economic wealth to the nation. It has equally been accompanied by giant environmental and social baggage in the form of social inequalities and ills, the apartheid machinery and, of course, environmental injustices. A considerable group of historical mining beneficiaries have exited and continue to exit the industry in South Africa, taking with them massive wealth and leaving behind the scourge of a broken labour systems, social decay, poverty, and, of course, the abandoned and unmanned mine shafts holding billions of litres of acid mine drainage (AMD). This study interrogates and juxtaposes historical with current AMD intervention frameworks, including legal, policy and regulatory systems. It engages with the narrative of why such frameworks (if they exist) have not been practically translated into responses that address the issue. It also engages with the conundrum of who should ideally take responsibility for the current state of affairs. In the process, the paper contemplates the role of the South African Constitution, the Mineral Petroleum Resources Act and the National Environmental Management Act and the National Water Act, which are, in themselves, progressive environmental frameworks.

INTRODUCTION

AMD in South Africa's environment cannot be underrated. The mining industry has been instrumental in South Africa's history, economy and demography as described in the introductory chapter. Nevertheless, mining's positive contributions have been overvalued, whilst its negative impacts, including social injustice and environmental degradation, have been underrated by both government and mining houses.[1] Past and present action by regulators, decision makers, the private sector, scientists and the oblivious public have created an intricate web of circumstances hinged on dubious political, socio-economic, scientific and legal matrix.[2] To worsen matters, the subjects of the above actions and responses have conflicting views regarding the causes of, and solutions to, the environmental and economic issues arising from AMD.[3]

Apparently, various government initiatives to engage the mining houses and apportion responsibility for environmental rehabilitation have been met with refusal and denial by such companies.[4] These companies had developed relationships that were economically beneficial to them and the government before and during the apartheid era. These benefits, coupled with political isolation and economic sanctions imposed upon the apartheid government, resulted in government overlooking the social and ecological harm produced by the operations of these companies. It has remained difficult to legally compel many mines to remediate such impacts, because most of them were insolvent or abandoned before the full environmental and socio-economic impact became evident. Such closures, coupled with non-compliance with laws stipulating rehabilitation by operational mines, have exacerbated the situation. At the moment, South Africa's largest challenge lies in proving the destructive consequences of unsustainable mining practices and apportioning liability.

It is nevertheless important to also note that AMD possess multiple manifestations. Because its manifestations vary, legal and regulatory solutions should not attempt a one-size-fits-all solution. Specific local circumstances pre-condition the impact of AMD. These may include infrastructure concentration and availability, nature of population, location, geomorphology, climate and the distribution of AMD generating deposits. Where such conditions are concentrated near rivers, river basins and dams, such as on the Witwatersrand, AMD impact becomes prevalent.[5]

South Africa's socio-institutional response dilemma is heightened by the fact that during past mining activities and closure of mines, legislation and regulatory practice in place might not have dealt with the rehabilitation of environmental consequences of operating such mines, as well as future consequences of abandoned, transferred or closed mines that continue to decant.[6] This challenge is worsened by the fact that most of the owners of these mines cannot be traced and this has complicated the role of legal and liability frameworks entrusted with the facilitation and rehabilitation of the mining sector and environmental protection. Legally speaking, lack of or failure to trace ownership of these mines eventually shifts liability to the government. If the owners cannot be found and liability for pollution cannot be allocated, the state has to take responsibility. This ultimately shifts responsibility to innocent taxpayers, who were neither responsible for the problem, nor benefitted from profits whilst the mines were operational.[7]

LEGAL CONSIDERATIONS AND APPORTIONMENT OF LIABILITIES ON RESOURCES

Legal issues associated with AMD are complex, dynamic and multifaceted. In order to thoroughly and comprehensively examine and provide the necessary legal opinions and recommendations required, it is imperative to consider various resources, including reviewing information on land and land rights ownership, especially as it relates to mining properties within the main affected basins.[8] One would have to delve into issues of historical liability, and any legislation or common law provisions that spelt out liability at the time. Engagement with key legal principles guiding the issue, both locally and internationally, might provide guidance, especially provisions catering for natural resource governance systems. Most importantly, because the South African AMD issue is predominantly an issue of legacy liability, one has to look at why enforcement and compliance was not properly administered. A number of questions central to the apportionment of liabilities remain a cause for concern. Among these; can past owners still be found and held liable, presumably based on liabilities they escaped then? Essentially not all derelict mines are in essence ownerless, let alone what has to be done with those ownerless mines? For ownerless mines, the impasse is whether government has to shoulder liability or whether such be shared by the mining fraternity based on the benefits derived from mining activities in the country and its responsibility and duty to care about the current and past side-effects of such benefits. It also requires interrogating mine ownership information stored by the regional and national Department of Mineral Resources (DMR). Various studies have been conducted on the issue of apportionment of liability, legislation and legal case studies, especially by the Council for Geoscience and the Water Research Commission.[9] Legislative and legal studies have also been conducted on the issue, including legal liability research undertaken by the Center for Environmental Rights, the Federation for a Sustainable Environment and various academics, research organisations, community groups and NGOs.[10] A widely received report by a team of experts was submitted to the Inter-Ministerial Committee on AMD, which contains useful information that has opened up more avenues for engagement on the issue.[11] Some of the information on the issue is also found in government directives issued to the Trans-Caledon Tunnel Authority (TCTA), as well as tender documents for short-term intervention initiatives (STI).[12] Municipal position papers on the issue have also been a source of direction on how to proceed in terms of legal liability.[13]

RELEVANT INTERNATIONAL ENVIRONMENTAL GOVERNANCE, INCLUDING AMD MANAGEMENT APPROACHES

As far back as 1903, pumped water on the Witwatersrand was already a reason for concern in terms of the AMD phenomenon.[14] A report to the Water Research Commission observed:

> Mining has been conducted with no concern for groundwater; it was a nuisance which had to be disposed of as cheaply and quickly as possible. Legislation should be aimed at reversing this attitude. Legislation must be introduced to facilitate this form of investigation in future. This should include "enforcement …[15]

Globally, AMD was recognised back in 1803. The United States (USA) subsequently established a river pollution commission to address AMD from coal mining in 1868. As early as the 1930's, 1940s and 1950s, one could obtain literature on the subject. The USA, which has dealt with AMD from coal mining, could provide direction for South Africa. Its Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980,[16] makes provision for a 'superfund' for long-term measures to clean up hazardous material contamination, including acid mine drainage.[17] The Summitville Superfund Site in Colorado presents an example of how the United States approached the issue of abandoned or bankrupt mines that could continue discharging toxins into water resources and the environment.[18] This initiative would be useful to South Africa, but access to information, particularly as it relates to financial provisions, is necessary to allow government to make informed decisions on setting up a superfund.[19]

The AMD challenge was witnessed in South Africa back in 1903 and subsequently the country became a signatory to various international frameworks, and where it has domesticated these frameworks, was bound by them.[20] Consequently, constitutional provisions in support of environmental rights reflect national legislation, policies, frameworks and international conventions that South Africa has signed or ratified.[21] A starting point is the Universal Declaration on Human Rights, which states that 'Everyone has the right to life, liberty and security of person'.[22] The Vienna Declaration and Programme of Action resulting from the World Conference on Human Rights, provides that 'the right to development should be fulfilled so as to meet equitably the developmental and environmental needs of present and future generations'.[23] This declaration is typified in South Africa through the Constitution and the Mining Charter, which indicates sustainable development, including socio-economic and environmental aspects, as an important cornerstone of South African mining policy. Lastly, and most importantly, the African Charter on Human and People's Rights reflects that 'all people have a right to a generally satisfactory environment which is favourable to their development'.[24] Section 24 of the constitution has entrenched the charter's continental aspirations into South African law.

Other agreements of relevance found to have pertinent environmental provisions include: the 1991 Treaty Establishing the African Economic Community; the 2000 Constitutive Act of the African Union, the Kyoto Protocol on climate change as part of the United Nations Framework Convention on Climate Change (UNFCCC) framework on climate change (and its successors) of 1992; the Convention on the Trans-boundary Movement of Hazardous Wastes and their Disposal (Basel Convention); the Cotonou Agreement; the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters (London Convention) and its 1996 Protocol; Marine Life Conservation Convention; and the Convention on Wetlands of International Importance (Ramsar Convention).[25] Principle 17 of the 1992 Rio Declaration also plays an important part in this discussion, as it points out the importance of environmental impact assessments being used as national instruments for proposed activities that might subsequently have adverse effects on the environment.

South Africa is party to, has signed and, in most instances, acceded to all the above frameworks. Additionally it is party to relevant regional frameworks, including the SADC Mining Protocol of 1997, the SADC Protocol on Shared Watercourse Systems of 1995, and the SADC Energy Protocol of 1996.[26]

FRAMEWORKS FOR AMD MANAGEMENT IN SOUTH AFRICA

CONSTITUTIONAL PROVISIONS

Section 2 invalidates law or conduct that conflicts with the constitution, which is the supreme law of South Africa. The recognition and promotion of environmental rights in the Constitution has entrenched environmental law into the South African legal system. Judicial interpretation and legislative pronouncement create opportunity to further improve and develop such constitutional environmental provisions.

This environmental right is entrenched in the Constitution and affords everyone an opportunity to benefit from a right to living conditions that are not detrimental to their physical health and welfare.[27] It also constitutionally mandates government to care for the environment through sound legislative and other initiatives that thwart pollution and environmental deterioration, encourage conservation, and protect environmental, social and economic sustainable development.[28]

Environmental protection is spelt out in section 24 of the Bill of Rights of the constitution of South Africa[29] and can be interpreted to include the governance of AMD in South Africa. The section provides that:

> Everyone has the right to an environment that is not harmful to their health or well-being; and to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that prevent pollution and ecological degradation; promote conservation; and secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development.[30]

In addition to the environmental rights articulated in the Constitutional Bill of Rights, the current environmental regulatory framework has benefitted from various other constitutional and human rights provisions that are relevant to its successful administration, governance and integrated management. Where section 27 of the constitution articulates the right to water and can be read together with section 24, the two are bound to form an undeniable basis for clean, accessible water in South Africa. Section 27 warrants that every South African has the right of access to sufficient water and obligates the state to take necessary legislative and other initiatives to protect its resources and deliver the progressive realisation of this right.[31] Read together, section 24 and 27 obligate the state to guarantee that there is adequate access to water and that it is conserved and protected. This requirement directly and indirectly mandates the state to address all AMD issues as they relate to access to sufficient, clean water and environment.

There are various other procedural and substantive constitutional human rights that overlap with the right to a clean environment. Thus, environmental protection can, and has, led to protection of other pertinent human rights including the right to: equality,[32] human dignity,[33] life,[34] property,[35] access to housing,[36] food, social security, healthcare, and water,[37] access to information,[38] just administrative action,[39] limitation of rights,[40] enforcement of rights,[41] and the interpretation of rights.[42] This means, the enforcement of procedural rights of access to information, just administrative action and access to courts will support environmental rights protection, because such rights are a basis for better public participation in environmental governance. Such rights become imperative when it comes to issues regarding the process of granting prospecting and mining rights.[43]

The above constitutional provisions have been reflected in legislation purporting to implement the transformative nature of the constitution and the rights it contains.[44] Thus, where legislation has been passed to execute a constitutional right, such as the right to a clean environment, the litigants may approach the court on the basis of such legislation.[45]

MINING ENVIRONMENTAL LEGISLATION AND POLICY

The 1998 Minerals and Mining Policy of South Africa discusses environmental management to a large extent. This is an indication that the issue is of an imperative nature to the country. The extractive industry in South Africa has been regulated by the Mineral and Petroleum Revenue Development Act of 2002 (and its subsequent amendments), the Mining Charter of 2002 (and its amendment), the Codes of Good Practice for the Mineral Industry, and the Housing and Living Conditions Standards for the Mineral Industry. The SA Department of Mineral Resources has initiated a programme to develop a framework promoting sustainable development in mining through international indicator systems. Key elements identified from the systems have been relied on to determine benchmark principles for sustainable development in South Africa. In addition, Part 4 of the 2010 South African Stakeholder's Declaration addressing strategy for meaningful transformation and sustainable growth of the mining industry in South Africa is also a benchmark of commitments made by the mining industry to improve environmental management and health and safety performance.

Despite the MPRDA's strong emphasis on the need to implement environmental rights by ensuring the development of mineral resources in an orderly and ecologically sustainable manner, the South African mining sector has failed to transform the lives of average South Africans to the level it has transformed the economic sector. In addition, there has been failure to strengthen and capacitate environmental impact assessment, including making it more independent. The MPRDA has not taken into account affected communities and their having representation in all decision making processes, including continuous provision for free, fair and informed consent at all stages of mining. This is a weakness of the MPRDA, which needs immediate redress.

Despite MPRDA rhetoric, mining companies have long been held liable for their action. There have been statutory obligations imposed upon them for over 70 years not to discharge polluted water. For instance, as per section 4(1)(1) of the Mines and Works Act of 1911, the Governor-General had the authority to produce necessary regulations regarding the safety and health of persons involved in or employed in or around mines. The provision also generally provided for safety of property, public traffic and general persons. The Mines and Works Regulations that were promulgated thereafter, in relation to the same provision, also clarified the issue, by providing (in regulation 7(b)) that: 'In no case may water containing any injurious matter in suspension or solution be permitted to escape without having been previously rendered innocuous'. In addition, regulation 157 required the mine manager to monitor its compliance.[46]

Pertinent regulatory framework for mining in South Africa, including the Mines and Works Act 27 of 1956 (and other regulations promulgated thereof),[47] the Minerals Act of 1991, and the Mineral and Petroleum Resources Development Act 28 of 2002 (and amendments thereof), have, over the years, continuously affirmed the status that mining houses are and should be responsible for redressing the environmental degradation of water resulting from their operations. For instance, regulation 5.9.2 of the 1970 mining regulations takes a position similar to that of the 1937 mining regulation 7(b). It states: 'In no case may water containing any injurious matter, in suspension or solution, be permitted to escape without having been previously rendered innocuous'. S 68 (2) of the Minerals Act of 1991 maintained this regulatory provision.[48]

To this extent, principles that underpin environmental governance in South Africa reflect:

- Public trust doctrine;
- Duty of care;
- Polluter (user) pays principle; and
- Life-cycle liability.

Polluters and users are currently legislatively held liable for rehabilitating and remediating water pollution, including aspects of historical pollution. This echoes approaches recognised in international and South African law that the polluter is, in principle, responsible for the cost of remediating the impact of his or her pollution.[49] But it is imperative to note that the effectiveness of a liability regime is dependent on its ability to identify and prove the existence of the responsible parties.[50] The problem in South Africa, is that this is usually the dilemma, since most defunct mines are currently ownerless, with the state left incapable of tracing owners, or unable to impose liability due to complex historical transfers of ownership, as well as legal limits to retrospective liability.[51] This might bring us into the realm of the public trust doctrine, where the state bears the responsibility to protect natural resources for its citizens. The public trust doctrine entrusts the state with custodianship of natural resources. This principle, and the polluter pays principle, are pertinent to the regime set to address and govern remediation of AMD in South Africa, which is marred by both legacy liabilities and continued pollution by current users, without strong legal recourse.[52] Yet lack of clarity persists with regard to how the public trust doctrine and the polluter pays principle can provide protection and the sustainable management of natural resources whilst catering for the controversial liability of damage to our natural resources.[53]

A subsequent common debate has been that, comprehensive as the statutory basis for the polluter (user) pay principle may be in South Africa, it cannot be applied to all liabilities arising from AMD, especially historical ones.[54] At the same time, relying on the public trust doctrine and holding the state liable, as the custodian of water as a natural resource, is not financially viable for the state. This has led to the suggestion of an expanded interpretation of the public trust doctrine. Since mining companies do play a part in pollution and benefit from its by-products, they should, in turn, at least bear a certain level of shared responsibility.[55] In line with this reasoning, a report commissioned by the South African government suggests that the mining industry should accept some of the short-term cost of providing remediation for historical pollution, including paying an environmental levy targeted at all operating mines, so that environmental legacies of mining, specifically AMD management, can be funded.[56] This approach is similar to the superfund approach set up in the US. Recommendations for similar initiatives (within the South African context) are made at the end of this chapter.

The constitutional dispensation section 24 of South Africa has become a basis for linking the public trust doctrine and the Constitution. Thus, by constitutionally entrenching an environmental right, the state became obligated to protect natural resources, including water, against pollution and degradation and to provide coherent management of such resources.[57] This approach also limits private rights and use of the resources to the extent that such rights or use are not detrimental to the full enjoyment and use of the resources by others. In South Africa, this also automatically translates into ensuring that liability for private misuse, pollution or failure to remediate, is established.[58]

Thus, various pieces of legislation and regulations have been enacted to implement (section 24 and 27) the constitution; they include: the National Environmental Management Act[59] (NEMA), which deals with regulating the protection of all environmental resources, including water (and its regulations);[60] the Water Services Act[61] (NWSA), dealing with the regulation of access to water; the National Water Act[62] (NWA), which deals with the protection and conservation of water resources, and the National Environmental Management: Waste Act [63](NEMWA), which regulates the management of waste, such as mining related waste, that may affect water resources. The above legislative instruments have, in unison, transformed constitutional obligations into statutory provisions, reiterating the public trust doctrine regarding water law.[64] These main statutes dealing with or related to constitutional provisions referred to above are augmented by additional statutes relevant to AMD management including: the Minerals Act[65] and regulations (replaced); the Minerals and Petroleum Resources Development Act[66] (MPRDA as amended) and regulations;[67] the Environmental Conservation Act[68] (ECA), which contains provisions on waste water; the Water Services Act[69] (WSA); the Disaster Management Act;[70] and the National Nuclear Regulator Act.[71] Other related regulations include: the DME mine closure regulations; Regulations on the Use of Water for Mining Related Activities Aimed at the Protection of Water Resources;[72] and the DWAF ground water management policy. Despite the appearance of multiple regulatory and legal frameworks to address AMD (administered by different departments) the final section of this chapter points out weaknesses, paralysis and inefficiencies displayed by the myriad water and mining governance documents.

RESPONSIBILITIES UNDER NEMA:

NEMA spells out a continuing (retrospective) legal duty of care and remediation for environmental damages. The Act is an add-on to historical legal obligations bestowed upon mining companies by various older regulations.[73] It provides (in section 28 (1)) that:

> Every person who causes, has caused or may cause significant pollution or degradation of the environment must take reasonable measures to prevent such pollution or degradation from occurring, continuing or recurring, or, insofar as such harm to the environment is authorised by law or cannot reasonably be avoided or stopped, to minimise and rectify such pollution or degradation of the environment.

Sub-section 1A is also meant to apply retrospectively to substantial pollution or degradation that:

> (a) Occurred before the commencement of this Act;
> (b) Arises or is likely to arise at a different time from the actual activity that caused the contamination, or;
> (c) Arises through an act or activity of a person that results in a change to pre-existing contamination.

Section 28(2) expands the application of the Act, not only to owners, but also to users, by providing that:

> Without limiting the generality of the duty in sub-section (1), the persons on whom sub-section (1) imposes an obligation to take reasonable measures, include an owner of land or premises, a person in control of land or premises or a person who has a right to use the land or premises on which or in which: (a) any activity or process is or was performed or undertaken; or (b) any other situation exists, which causes, has caused or is likely to cause significant pollution or degradation of the environment.

In this instance, retrospection in terms of duty of care is silent, since inference is made that the duty arises only where 'a situation exists' and does not require another causal link between the person responsible and the pollution.[74]

Section 28(4) authorises the Director-General, or provincial head of the Department of Environmental Affairs, to issue a directive requiring the taking of reasonable measures to 'any person' who fails to take measures spelt out in Section 1 and 2. Where such person fails to do so, this then becomes the basis for state intervention to remedy the situation. It may subsequently recover the costs thereof from a wide net of stakeholders.[75]

Section 8 extends liability to directors or controllers of companies by stating that:

> Notwithstanding the Companies Act, 2008 (Act No. 71 of 2008), or the Close Corporations Act, 1984 (Act No. 69 of 1984), the directors of a company or members of a close corporation are jointly and severally liable for any negative impact on the environment, whether advertently or inadvertently caused by the company or close corporation which they represent, including damage, degradation or pollution.

NEMA outlines the South African environmental management approach and it proposes innovative regulatory systems.[76] Some of these regulations include: providing a comprehensive list of national environmental principles; obligating an environmental impact assessment (EIA) on activities that could be detrimental to the environment to a significant degree; and provision for a statutory duty of care with regard to environmental degradation and pollution, as reiterated above.[77]

RESPONSIBILITIES UNDER THE NWA

NWA provides for specific integrated management of water resources in South Africa and responds to prevention and remedying the adverse effects of pollution through section 19. The section provides that: '(1) An owner of land, a person in control of land or a person who occupies or uses the land on which: (a) any activity or process is or was performed or undertaken, or (b) any other situation exists, which causes, has caused or is likely to cause pollution of a water resource, must take all reasonable measures to prevent any such pollution from occurring, continuing or recurring.'

RESPONSIBILITIES UNDER THE MPRDA

This Act is relevant in addressing historical AMD liabilities, because it is responsible for the continuation of old order mining rights. It states in section 7 (1):

> Subject to sub-items (2) and (8), any old order mining right in force immediately before this Act took effect continues in force for a period not exceeding five years from the date on which this Act took effect, subject to the terms and conditions under which it was granted or issued or was deemed to have been granted or issued. (4) No terms and conditions applicable to the old order mining right remain in force if they are contrary to any provision of the Constitution or this Act.

The Act also offers continuation of a previously approved environmental management programme through section 10 (1), which provides that, 'Any environmental management programme approved in terms of section 39(1) of the Minerals Act and in force immediately before this Act took effect and any steps taken in respect of the relevant performance assessment and duty to monitor connected with that environmental management programme, continues to remain in force when this Act comes into effect.' (5) Section 38 applies to a holder of an old order prospecting right or old order mining right.[78]

Together, the National Environmental Management Act (NEMA Act 107 of 1998), as well as the National Water Act (NWA Act 36 of 1998), stipulate that a party take all reasonable measures to prevent pollution or degradation from occurring, continuing or recurring, as a consequence of mining operation falling under its responsibility. In the process of responding to prevention and remedying the adverse effects of pollution, the acts stipulate training, termination or modification of activities or processes, containment, and remediation to be undertaken by the responsible party. NEMA also provides for the duty of care (a common law principle) that requires the duty holder to maintain care toward pollution, prevention and remediation.[79]

The Mineral and Petroleum Resources Development Act, 2002 (with amendments) addresses the specific responsibility of holders of a mining right, permit, or any other permission. The statute obligates the holder of the mining permit to assume responsibility for rehabilitating environmental consequences of mining, and restoration of the affected environment to its natural state, or to reasonably comply with the principle of sustainable development.[80] It also extends the responsibility of such holder to environmental damage, pollution, or ecological degradation as a result of his or her operations that may occur inside or outside the boundaries of the mining area to which such a right, permit or permission relates.[81] It apportions responsibility to those entities whose mining causes, or results in, ecological degradation, pollution or harmful environmental damage affecting the health or wellbeing of anyone. Further provision is made that such holder will 'remain responsible' for any environmental liability, pollution or ecological degradation and the management thereof until a closure certificate has been issued.[82] This act is accompanied by specific regulations that have to be satisfied prior to the issuing of a closure certificate. Together with the regulations, the Act prescribes for financial and emergency remedial provisions, among other initiatives, for rehabilitation or management of negative environmental impact. [83]

The three statutes namely, the MPRDA, NEMA and NWA by inference, extend liability to the mining company director in a personal capacity, thus creating personal liability. The MPRDA provides for provisions to pierce the corporate veil, and go past provisions of the Companies Act[84] and the Close Corporation Act.[85] It stipulates joint and individual liability for company directors or members of a close corporation with regard to any unreasonable negative environmental impact, including any damage, degradation or pollution intentionally or negligently caused by the company or close corporation they represent or represented. These provisions are reiterated by NEMA, which places personal liability upon any person who is a director of a mining company at the time of the commission by that company of an offence under a provision listed in Schedule 3 (including NWA), where such director failed to take all reasonable steps necessary under the circumstances to prevent commission of the offence.[86]

At the same time, both NEMA and NWA impose the duty of care on relevant parties (NEMA being limited to the owner or person in control and so forth, whilst NWA's obligation is to everyone, as qualified by section 28(2)). Whilst the duty imposed by section 28 of NEMA extends to pollution and environmental degradation, the one in NWA is limited to water pollution, but both point out the necessary obligations, echoing section 24 of the Constitution. In fact, both Acts spell out additional fault based criminal liability for pollution or environmental degradation, or significant detrimental environment or water resources effects. This seems like a good imperative, since administrative penalties are failing to compel parties to comply with directives issued. But the fines and penalties imposed are also negligible and not adequately prohibitive when compared to the 'big business' profits of failing to remediate. The fines extend to a maximum of R200 000 or 10 years imprisonment under NWA, and R1 million or a year imprisonment under NEMA.[87] In addition, the NWA, through amendment Act 14 of 2009, inserted sub-section 28(1) A, which also spells out retrospective responsibility. This was in response to the decision in Bareki v Gencor, whose judgement had opined otherwise. Section 28 (1) A is what strengthens the remediation obligation for historical liability in South Africa.

From afar, quality mine closure policy and environmental remediation for negative mining impacts seem well provided for. Yet when mines are closed, environmental treatment is left pending, or unsatisfactory, AMD and remediation thereof are not addressed, and a reasonable number of mines do not seem to have obtained water licence certificates or closure certificates. Where such have been obtained, somehow certain things seem to have been overlooked. Thus the loophole lies in implementing enforcement and compliance for environmental damages. Besides the above Acts being good pieces of legislation, the main challenge is that of ensuring liability for pollution by responsible companies (under polluter pay principles) and apportioning liability as most mine owners cannot be traced in South Africa. In cases where mine owners are traceable, issues of compliance and enforceability, and fragmented follow up systems are to blame.[88] But *Harmony* has crossed some of the above frontiers by stating that where mine closure certificates have been issued and ownership changed, liability can still be maintained, and the polluter must still pay.[89]

CASE LAW AND COMMON LAW PROVISIONS ON MINE CLOSURE AND GENERAL LIABILITY APPORTIONMENT

Mining companies have always been obligated under common law to responsibly use the properties on which they conduct their business to avoid causing injury to others and their property. This regulation was actually a reiteration of the Roman maxim *sic utere tuo alienum non laedas*. These obligations under common law have not ceased to exist: they are reflected, albeit in a different manner, in statutes, including section 38(1) (e) of the MPRDA, which provides that the holder of a mining authorisation:

> … is responsible for any environmental damage, pollution, or ecological degradation as a result of his or her reconnaissance, prospecting or mining operations, and which may occur inside and outside the boundaries of the area to which such right, permit or permission relates.

Cases related to AMD were lodged as far back as 1951 in Rex v Marshall and Another [1951] 2 All SA 440 (A). In that case, the Appellate Division of the Supreme Court, as it then was, unanimously held that a mining company had, through seepage, released into a spruit 'unwholesome' and very acidic water from evaporation ponds and fields, which eventually contaminated the stream. A decision by the magistrate's court, which had initially found the mine manager and resident engineer criminally guilty and imposed a fine upon each one of them, was upheld on appeal. The qualified engineer had given evidence that proved that it was commonly known that, as far back as 1902, the mine in question was releasing acid water. It was also established from the evidence of the mine manager that from April 1924 to January 1947, he had taken steps to minimise the acidity of the water. This is one of those cases that did not simply point out the well-known fact that AMD is a common problem in the South African mining industry, it also pointed out that, as far back as 1951, mining companies were being held liable (even criminally) for careless release of AMD into the surrounding environment.

In Lascon Properties (Pty) Ltd v Wadeville Investment Co (Pty) Ltd 1997 (4) SA 578 (W), in interpreting the 1970 mining regulation, which is similar to regulation 7 (b) of 1937, the court held:

> It was … intended to place both the duty to prevent the escape of noxious water arising from mining operations and the risk of damage caused by such water on the persons for and benefiting from the mining operation.

In this case, further recognition was placed on the fact that the statutory obligation imposed by this regulation extended to civil (personal) liability for damage caused by breach. The law of delictual liability and the law of damages provide common law remedies. For instance, the above case provided that a remedy in nuisance would depend on whether the contamination escaped from the land that was subjected to mining activities, consequently affecting other properties. Thus, for the remedy to stick, it would arguably require a foreseeability of harm on the part of the mining companies. Where nuisance has been established, the usual remedies are damages or an interdict. Sometimes, even where the risk of harm to the plaintiff was foreseeable, liability might still depend on what action, if any, could reasonably have been taken, under the circumstances, to avert risk. In addition, the standard of care required is that of a reasonable person under similar circumstances, with a higher standard of care required of persons possessing special skills or expertise. In the Lascon case, a number of experts were involved in the design, construction, use, operation, maintenance and closure of the tailing dams. All these experts were required by the regulations to exercise a degree of care commensurate with their skills and experience, which is a higher degree of care.

The above case also goes further to limit defences raised by mining companies. Whereas Acts of Parliament might simply focus on the effects of activities, the basis for common law remedies, in negligence and nuisance, interferes with private rights. As such, these remedies are available to the parties that suffer harm, and not necessarily third parties. The common law applies to all mining operations, whenever the licences of permits were acquired, unless amended by legislation. Under common law, the landowner is under no obligation to clean up contamination caused by another party on his or her property; nor is there a special power vested in the local authority that empowers it to order the landowner to clean contamination caused by another party. Nevertheless, should that landowner allow hazardous material that has accumulated on his property to escape and damage the property of another, such landowner would be liable to the other landowner, as per Lascon and subsequent cases.

The most notable court judgement on legal obligations regarding AMD is Harmony Gold Mining Co Ltd v Regional Director: Free State, Department of Water Affairs and Forestry and Others 2006 SCA 65 RSA. In this case, the SCA upheld a directive issued under the National Water Act's section 19(3) requiring the pumping of polluted mine water to continue and to be funded by two mining companies. The directive was issued to Harmony, AngloGold and other mining houses. In the appeal against review application decision in the WLD, Howie, JA stated:

> The situation we have here is one where various mines concerned have been required to join forces in continuing with a dewatering process already physically under way but insufficiently funded. I cannot see that it is outside the scope of 'reasonable measures' to require this collaboration and to require the companies concerned to share the expense of it. That is what the directive in issue demanded, and in my view the first respondent was empowered by section 19(3) (read with section 19(1)) so to demand.

The Constitutional Court subsequently also dismissed the application for leave to appeal against the SCA's judgment. This automatically means that mining companies that are recipients of directives may, depending on the terms, remain liable for the cost of remediation, including the pumping and treatment of groundwater, such as AMD, even if they are no longer mining in the specific area. The case has set up authority for the principle that mining companies can be held responsible for water pollution caused by them, even if they no longer own, control, occupy or use the land where the pollution emanates. However, in this case, the pollution was temporal in nature and the courts did not have to address the thorny issue of AMD related historical pollution. In this particular case, current owners and previous owners were well-known and traceable. There was no ownerless historical liability. To address such complicated liability, it becomes imperative to revert to the South African Constitution, the environmental rights expressed therein and the role of the state, as well as natural and juristic persons.[90] In essence, this means that the Bill of Rights, specifically section 24(a), binds (within the realms of duty of care) private companies that have an individual or group role in the said pollution to provide the necessary solutions to minimise, remediate and prevent AMD.[91]

Space Securitisation (Pty) Ltd v Trans Caledon Tunnel Authority and others[92] is perhaps even more pertinent to the issue, because it deals with the power of the Minister of Water and Environmental Affairs (as she was then) to undertake emergency works to treat AMD in the Witwatersrand goldfields in terms of the National Water Act, 1998. Reports emanating from directives issued pursuant to this case have been the basis for various AMD intervention strategies.[93] In that case, the Minister took steps to remediate AMD consequences at Rietfontein, in order to avert an imminent environmental crisis, by issuing a directive to the Trans Caledon Tunnel Authority (TCTA), under section 103(2) of NWA 36 of 1998, to set up an AMD emergency treatment plant to address the needs of the Central Basin of the Witwatersrand goldfields. The contents and merits of the case are not necessary for this discussion, but the case shows that steps, including extreme steps (such as expropriating a right of servitude over an applicant's property) can be taken by government organs to remediate the effects of AMD for public interest purposes. In this case, the Minister decided, in terms of section 110(2)(a) of the NWA, to declare all measures undertaken above by the DWA to be of an emergency nature, and not subject to approval of an environmental impact assessment study. Despite the fact that the department had delayed undertaking the necessary measures, which was attested to during the case, the court did not interdict the decision to undertake such emergency measures, because the nature of the situation called for such.

CONCLUSION

Based on the common law and case law point this chapter denotes that, the state is the custodian of South Africa's AMD liability and mining companies share such a responsibility based on the duty of care and general principles of the Constitution. The discussion then descends to describe how state organs are failing to positively take up their duty to prevent, minimise and remediate AMD in cases of ownerless historical liability. Similarly, the private sector has failed to take up responsibility in cases it ought to. This discussion is actually the crux of the AMD problem in South Africa.

Issues that arise are actually socio-institutional and legal in nature and they affect or limit legal liability, legal responses and apportionment of liability. They include matters relating to abandoned or ownerless mines, and closed mines that are marred by historic or legacy liabilities. The other matter of concern for AMD relates to old, transferred and insolvent mines. Then the issue of non-compliant mines follows. It is interesting that a reasonable number of operational mines have been shown to have failed to comply with water licence acquisitions, mine closure certificate procedures and many other processes. It is understandable that AMD historical liability is due to a regulatory system that was not efficiently geared at enforcing liability at the time. But it is also problematic to see current mines escape their present and future liabilities due to inefficiencies in enforcement and weak coordination in environmental governance systems.

Fragmented and overlapping responses (institutional and legal), environmental governance frameworks and economically ambitious agendas have exacerbated the ineffectiveness of statutory liability. Such issues must be approached and addressed. Within existing frameworks, the delegation of power between various government bodies at the national, provincial and municipal levels is not well specified. There is fragmentation in how roles and responsibilities are assigned, mostly resulting in overlaps. Such issues need to be defined, rationalised and aligned into existing policy, including legislation. This must start at national level by aligning national departmental leadership with the new promulgated statutory provisions.

Overall, there seems to be a lack of a streamlined compliance and enforcement policy strategy. The issue of too many participants in AMD remediation initiatives has complicated the process. The initiatives are many and overlapping, and failure to publicise them has led to duplication. Civil responses to address the issue have been restricted by a lack of appropriate legal skills within necessary departments. Most legal services within departments responsible for coordinating responses to AMD remediation operate on a risk-averse approach to imposing liability on the responsible mining industry. State attorneys and the Attorney General's office have not shown the necessary initiative to prosecute, despite the existence of strong legal provisions. Lastly, there isn't enough political support from senior management in government in terms of implementing long-term AMD remediation, or liability apportionment. In terms of implementing criminal liability, very few officials in the departments responsible have the criminal investigation skills required for investigating and prosecuting environment-related mining offences. In addition, the issue of a lack of interest and support from prosecutors in the criminal prosecutorial system, as well as a lack of political will, is once more an issue. Perhaps a coordinated effort to train specific prosecutors in environmental law and training for members of departments in legal skills would go a long way in enforcement.

Statutes (including NEMA, MPRDA and NWA) have been revised through amendments or regulations and initiatives to align them and make them more functional as far as environmental and AMD governance is concerned. However at departmental level, there is still collision on who takes responsibility and lead as far as environmental issues that fall within the mining realm are concerned. The issue of capacity should also be looked at. Most of the departments involved do not have the necessary capacity to carry out the monitoring, enforcement and environmental impact assessment studies required. This is a pertinent issue that must be resolved.

The discussion around pollution monitoring and enforcement capabilities is long overdue. Government departments are obligated to cooperate and align the regulatory process that are, at present, piece-meal at most.[94] Issues of environmental governance, as it relates to AMD, require coordination between local and national government. To this extent, there is a disjuncture that has been the basis for a dysfunctional compliance and enforcement system. Herein lies the problem: environmental management as relates to mining activities in South Africa is currently co-managed by various departments. The Department of Mineral Resources deals with mine environment regulation through its Mineral Regulation Branch and its regional offices ensure the execution of the provisions of the MPRDA, through processing applications, issuing or granting rights and permits, approving environmental management programmes (EMPs), monitoring performance, undertaking corrective actions and issuing closure.[95]

But the minerals and mining policy has also created overlaps and confusion in terms of maintaining compliance. On one hand the Department of Water Affairs and Forestry (as it then was) was the lead national water resource whilst mining regulation was assigned to DME concurrently. The

Minister of Mineral Resources has a mandate to promote mining and mineral development. Concurrently, he is also vested with the power to approve mine environmental management programmes, subject to consultation with the minister of water affairs.[96] On the other hand, the NWA empowers the minister of water affairs to license the use of water by a mine, which use can encompass dewatering processes for excavation purposes and disposal of contaminated water and residue emanating from mining. The appointment of a minister for environment, separate from one for water affairs, exacerbates environmental governance fragmentation and lagged responses. This has the effect of inefficient mine regulation and weak environmental legislation enforcement.[97] On the one hand, DMR and DME are more concerned with economic agendas, with little attention being paid to environmental governance. DWA manages water resources and their apportionment, but not necessarily all environmental issues. DEA on the other hand has to be involved and coordinate with all other departments to obtain access to mine related, or water related issues whilst working on limited capacity, resources and knowledge.[98]

The Constitution has provisions dealing with to cooperative governance, and provides for legislative requirements at various tiers of government. The most relevant of its provisions, as far as the fragmentation issue is concerned, are Schedules 4 and 5 of the Constitution, dealing with the issue of concurrent legislative competence at national and provincial level, and the exclusive legislative competence at provincial level. These provisions must be put into practice when it comes to finding AMD solutions in South Africa.

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50 Feris, L., 2012. The Public Trust Doctrine and Liability for Historic Water Pollution in South Africa, *Law, Environment and Development Journal,* 8(1), p.4.

51 See, for example, Bareki NO and another v Gencor Ltd and others, Transvaal Provincial Division, Judgement of 19 October 2005, [2006] JOL 16600 (T), where the court held that fairness mitigates against applying the National Environmental Management Act, which holds polluters strictly liable, retrospectively.

52 Feris, L., and Kotze, L., 2007. So many laws, so little liability: AMD and the liability vacuum in South African law; Du Plessis, W., and Kotzé W.L.J., 2007. Absolving historical polluters from liability through restrictive judicial interpretation: some thoughts on Bareki NO and another v Gencor Ltd, *Stellenbosch Law Review* 18(1), p.161; and Kotzé, L.J. and Lubbe, N., 2007. How (not) to silence a spring: the Stilfontein saga in three parts. *South African Journal of Environmental Law and Policy,* 16(2), p.49.

53 Feris op. cit, p.1.

54 Ibid, p.5.

55 Ibid, p.6.

56 AMD Inter-Ministerial Report op. cit, p.80.

57 Feris op. cit, p.13.

58 Ibid.

59 Act 108 of 1998.

60 NEMA 2014 Regulations on Financing Remediation. The purpose of these regulations is to regulate the method for determining and making financial provision for the costs associated with the management of environmental impacts from prospecting, exploration, mining or production operations through the life of mine and that may become known in the future. These Regulations apply to a holder under the Mineral and Petroleum Resources Development Act, 2002.

61 Act 108 of 1997.

62 Act 36 of 1998.

63 Act 59 of 2008.

64 Feris op. cit, p.13.

65 Act 50 of 1991.

66 Act 28 of 2002.

67 MPRDA 2004 Regulations.

68 Act 73 of 1989.

69 Act 108 of 1997.

70 Act 57 of 2002.

71 Act 47 of 1999.

72 GN.R.704 of 4 June 1999; Section 6 of the regulations provides that: 'Every person in control of a mine or activity must: (a) Confine any unpolluted water to a clean water system, away from any dirty area'. In terms of GN. R. 704 'dirty area' means any area at a mine or activity which causes, has caused or is likely to cause pollution of a water resource; See Liefferink, M., 2014. Tour of the West-Rand Gold Fields by Federation for a Sustainable Environment background information document, p.17.

73 As recognised in Bareki v Gencor 2006 (1) SA 432 (T).

74 Towsend op. cit.

75 See section 28 (7) of NEMA: These could include 'responsible person'- companies, directors, financials, (owners)-of land, and any other person; also used as basis for pre-directive in the Harmony case.

76 Humby op. cit, p.4.

77 Regulation 385 – 387 GG 28753 of 21 April 2006. The EIA process is detailed in the NEMA EIA regulations. The NEMA was additionally amended to incorporate mining into the EIA framework; See the National Environmental Management Amendment Act 62 of 2008, which came into operation on 1 May 2009 (GN 27

GG 32156 of 24 April 2009). Provisions relating to mining only came into force upon the commencement of Act 49 of 2008.

78 See also section 45 of MPRDA and NEMA section 28 on historical liability.

79 See section 28 of NWA.

80 In section 38(1)(d) of MPRDA.

81 See section 38(1)(e) of MPRDA.

82 See section 43(1) of MPRDA.

83 Regulation 36, section 41, 45 and 47 of the MPRDA.

84 No 61 of 1973.

85 No 69 of 1984.

86 See section 32(2) of MPRDA.

87 See section 28 (14)(c) of NEMA and section 151 of NWA.

88 On the general issue of fragmented environmental governance in South Africa, see, among others, Kotzé, L.J., 2007. Environmental governance. *SAPL,* pp.34–60; Kotzé et al 2007. Environmental governance. *SAJELP,* pp.57–81; Kotzé, L.J., *Environmental Governance,* p. 103–125.

89 The Court did not agree and ruled that the directive remains valid until it has been fully complied with. See Harmony Gold Mining Company Ltd v Regional Director: Free State Department of Water Affairs 2012 ZAGPPHC 127 (29 June 2012), para. 48.

90 See section 7(2) on positive obligation of state organs and section 8 (2) on rights against private actors as per the South African Constitution.

91 See Judge Dennis Davis' observation with regard to section 8(2) of the Constitution in the McCarthy v Constantia Property Owners Association case.

92 South Gauteng High Court Unreported Case No 13852/2013, Judgment issued on 03/09/2013.

93 See TCTA due diligence report of 2011; See also Department of Water Affairs AMD Report., 2013.

94 Section 6 and Chapter 3 of the 1996 South African Constitution provide for the notion of cooperative governance and how to implement and apply it.

95 Please see http://www.dmr.gov.za/mineral-policy-a-promotion/mining-a-mineral-policy-development.html [Accessed 23 February 2015].

96 As per MPRDA.

97 For further discussion on fragmented environmental governance in South Africa see writings by Kotze L.J, op. cit.

98 Feris and Kotze op. cit, pp.2111–2112.

CHAPTER 9

Mathematical Modelling in Acid Mine Drainage

Geoffrey S Simate

ABSTRACT

For over 50 years, acid mine drainage (AMD) pollution has been recognised as an important and widespread societal problem. Actually, it has been described as the single most dangerous threat to South Africa's environment, after climate change. Despite several years of research, there has been no single, independent and quick solution to remedy or treat AMD. However, over the years, it has been recognised that mathematical modelling and simulation can contribute to the understanding of AMD generation and the subsequent design of treatment processes. Mathematical models are useful tools that allow rapid and varied evaluation of causes and effects. Their principal advantage is that they enable an analysis of even long-term actions with limited investment costs. This chapter provides an overview of popular conceptual models used for simulation of major elements of AMD generation, transport and treatment processes.

Since AMD generation and transport take place in a multifaceted system, involving numerous coupled geochemical, physicochemical and transfer processes, the interplay of these processes is difficult to understand, let alone quantify. Nevertheless, accurate prediction of the chemistry and transfer of AMD is vital. Therefore, the successful development of AMD generation and transfer models would aid the proactive design and operation of control and mitigation measures. On the other hand, the treatment process models describe the chemical and physical processes involved in technical purification of AMD. In the last few years, various models have been developed that describe chemical and physical processes in targeted unit operations. Examples are models for sulphate reduction in anaerobic bioreactors for treating water containing heavy metals and clarifier models for evaluating the settling velocity of solids (such as sludge from lime treatment plant). These AMD treatment process models enable process optimisation, troubleshooting and identification of low-cost treatment alternatives. Therefore, they are an integral part of the decision-making process. However, there

are also several aspects that need to be investigated further to ensure better design and operation of AMD systems.

INTRODUCTION

The adverse effects of AMD on human health, plant life and aquatic species are well documented[1] and the problem of AMD has been the focus of several studies. There are three key strategies in AMD management, namely, control of the AMD generation process, control of acid and metal migration and collection and treatment of AMD.[2] Unfortunately, there is no single, independent and quick solution. A proactive and holistic approach is needed – from understanding the physicochemical processes involved in the generation of AMD to the design and operation of mitigation measures. Generally, an understanding of AMD generation, transport and treatment processes has been gained through laboratory and field experiments. However, over the past years, tremendous progress has been made in the development of modelling techniques. Modelling is a fundamental engineering problem-solving methodology.[3] The definition of modelling varies, depending on the application, but the basic concept remains the same: the process of solving physical problems by appropriate simplification of reality.[4] Modelling has significant value – it enables predictions to be made, acts as a guide for future experimentation, and aids in organising or managing data and synthesising information and knowledge.[5,6] This chapter discusses models developed in the recent past for assessing the generation of AMD, migration and treatment processes. The chapter is divided into six themes, covering an overview of the types of engineering models, geochemical evolution and transport of AMD, modelling of various AMD treatment processes, a case study, challenges and future prospects and conclusions.

TYPES OF ENGINEERING MODELS

There are numerous models. Some are purely conceptual, some are physical models, such as in flumes and chemical experiments in the laboratory, some are stochastic or structure-imitating, and some are deterministic or process-imitating.[7] A distinction can also be made between forward models, which project the final state of a system, and inverse models, which take a solution and attempt to determine the initial and boundary conditions that gave rise to it.[8] Therefore, when studying models, it is helpful to identify the broad categories of models. In engineering, modelling is divided into two major areas: physical/empirical modelling and theoretical/analytical modelling.[9] Nevertheless, a number of distinct approaches to modelling AMD have emerged to date (from AMD generation, migration and treatment processes). In general, all the models attempt to describe the time-dependent behaviour of one or more variables of a system in terms of observed behavioural trends (empirical models) or chemical and physical processes that are believed to control AMD (deterministic models).[10] Betrie et al.[11] (Table 9.1) gave a summary of some of the deterministic and empirical models commonly applied to evaluate the quality of AMD.

Table 9.1: Summary of deterministic and empirical models used for evaluating mine drainage quality[12]

Deterministic model	Empirical model
MINTEQ[13]	EDCM[14]
PHREEQC[15]	18–40
MINTRAN[16]	2000–6000
WATAIL[17]	1200–3600

Empirical models extrapolate values for the desired output variables (for example, acid generation) from existing laboratory and field test data over time, so as to predict the long-term trend.[18,19] However, empirical models do not explicitly consider the causal mechanisms driving the process.[20] The method of extrapolation typically involves determining the 'best-fit lines' through test data points.[21,22,23] The equations derived may then be solved to provide, for instance, the acid generation rate of a particular waste unit at some time in the future. Using the projected acid generation rate as an input to a separate hydro-geochemical model, which accounts for attenuation of seeping constituents in soils and dilution in receiving water, the estimated constituent loading rates and consequent receiving water quality (at a given time) may be estimated.[24,25] Empirical models, by their nature, are site-specific and composition-specific. Because the models rely on actual trends observed at a specific site or for a specific composition, rather than generic causal mechanisms, the best fit lines for one site or composition cannot be assumed to be representative for another site or composition.[26]

Furthermore, significant changes in waste unit composition, geometry, or controls over time may invalidate previous representativeness of empirical models. So empirical models may provide cost-effective and reasonably reliable estimations, instead of very long-term testing procedures.

On the other hand, deterministic models simulate changes in system values by solving systems of equations that represent the various controlling factors in the process.[27,28] In other words, deterministic models simulate changes in system values according to causal mechanisms that relate each element of the system to the others.[29] The most important differences between the models lie in the particular causal mechanisms (for example, oxygen diffusion, change in particle size, temperature variations due to exothermic reactions) addressed in each model.[30] However, the models may rely solely on the causal relationships described in the equations, or may include empirical data as exogenous drivers (outside the model structure) to solve certain aspects of the system.[31] The greatest advantage of deterministic models is that they may, for example, allow the user to predict AMD as it evolves over time under the changing influence of rate controlling factors.[32]

The next section provides examples of the models used in AMD generation and transport, and the following section discusses AMD treatment processes. A case study of the applications of mathematical models in a real AMD treatment plant then follows.

GEOCHEMICAL EVOLUTION AND TRANSPORT OF ACID MINE DRAINAGE

As already stated in various chapters of this book, AMD originates from the oxidation of sulphides. The acidity generated by the reactions creates conditions under which metals can be leached, thus representing a threat to surface and ground water.[33] While research is progressing rapidly into various treatment processes, such as leachate collection and neutralisation, there are significant knowledge gaps regarding the generation and behaviour of AMD. The geochemical composition and discharge rate of AMD from sulphide minerals depend on a variety of factors, including local climatic conditions, mineralogical composition, as well as the depositional structure and hydraulic properties.[34] These multiphase systems are difficult to understand and quantify. Nonetheless, in recent years, numerical modelling has proven to be a useful tool for assessing conceptual models of AMD generation and transportation. Therefore, this section discusses a selection of geochemical and transport models for AMD. Each model can be viewed as addressing a particular AMD prediction objective.

Perkins et al.[35] (Table 9.2) provides a list of geochemical processes and classifies geochemical processes into mass transfer processes involving minerals in waste-rock and the rate-determining processes which control the path of these reactions.[36] However, the geochemical processes which mainly control AMD quality are precipitation and dissolution, chemical diffusion, and surface reactions.[37] Precipitation and dissolution control the neutralisation of acidic solutions and fixation of metals within solids. Chemical diffusion and surface reactions control the rate at which all precipitation and dissolution reactions occur.

Table 9.2: Classification of geochemical processes[38]

Mass-transfer processes	**Rate-controlling processes**	**Rate-modifying factors**
Dissolution/precipitation:	Diffusion:	Catalysist:
• acid base reaction • hydrolysis • redox reactions • co-precipitation • gas release/capture • wetting//drying	• macroscopic • microscopic • atomic scale	• bacterial • galvanic • abiotic
Ion exchange/sorption	Nucleation	Temperature
Radioactive decay	Surface reaction	Pressure
	Adsorption/desorption	Surface area

Over the years, a limited number of models have been specifically designed to model the acid waste water problem. However, there are a number of 'general' geochemical models that may be suitable for the purpose. Existing geochemical models are divided into five classes: equilibrium thermodynamic models, mass transfer models, coupled mass transport / mass transfer models, supporting models, and empirical and engineering models.[39] As stated earlier, each class of geochemical models can be viewed as addressing a different type of AMD prediction objective. Equilibrium geochemical thermodynamic models address the issue of identification of the soluble and mobile metal species and maximum metal concentrations. Mass transfer models address maximum metal concentrations and their evolution with time more specifically. Mass transfer flow models address the prediction of concentration and load versus time. Engineering models are more directed towards the relationship between changes in geochemical variables (for example, pH, Eh, etc.), taking place in the geochemical environment, and related changes in physicomechanical properties, such as stress distribution, thermal and moisture conditions and other physical conditions. Readers are referred to Perkins et al.[40] for an in-depth discussion of the different classes of geochemical models.

Transport models have also been developed to investigate the migration of acid and associated metals, gases, fluids and solids. These models have been applied to assist in constraining water infiltration rates, interpreting the sealing of flow paths due to mineral precipitation, and investigating post-closure geochemical monitoring strategies.[41] Typical pathways of AMD include transport through leaching, infiltration through the soil or vadose zone (unsaturated zone), movement through alluvial aquifers and fractures in bedrock, transportation in groundwater, discharge to surface water, transportation in surface water and sediment, and uptake and transfer via biological pathways.[34] Maest and Kuipers[42] provided an extensive review of models that focus on water flow and contaminant transport.

In addition, modelling of gas transport has also been a subject of intensive research. Gas transport, particularly the transport of oxygen into unsaturated waste-rock piles, can be an important process affecting the generation of AMD. Airflow and AMD production in waste-rock piles result in complex processes involving multiphase flow (gas and water), chemical reactions, heat transfer, and mass transfer in the liquid phase (infiltration) and in the gas phase (advection, diffusion).[43] Therefore, numerical simulation is needed to handle all these processes and understand their interactions. However, very few numerical models (for example, FIDHELM and TOUGH AMD) that represent the physical processes acting within waste-rock piles are currently available. Nevertheless, the principal mechanisms contributing to airflow and oxygen transport in a waste-rock pile include:

(i) Diffusion;
(ii) Advection due to a thermal gradient (chimney effect) or wind pressure gradient; and
(iii) Advection due to barometric pumping.[44]

While diffusion is typically limited to a near-surface zone with a depth of a few metres, advection and barometric pumping have the potential to move air (and oxygen) to much greater depths in the pile. In general, the more permeable the waste-rock material and the greater the height-to-depth ratio of the waste-rock pile, the greater the potential for advective air movement. The reactivity of the waste-rock material, as well as the coarseness (hence air permeability) and the spatial variability of these properties in a pile, have a strong influence on the magnitude of thermally induced advection. In contrast, air movement due to barometric pumping is controlled by waste-rock porosity, changes in ambient air pressure and the heterogeneity of air permeability of the waste-rock dump. Readers are referred to Wels et al.,[45] which provides a comprehensive overview of the role of gas transport in AMD generation and methods that can be used to model gas transport.

MODELLING OF ACID MINE WATER TREATMENT PROCESSES

Until the 1990s, the only 'proven technologies' for abating mine water pollution were what are now termed active treatments.[46,47] Nowadays, a variety of treatment processes are available, including passive treatmen ts.[48,49,50,51,52,53,54,55,56] However, these techniques are very expensive and unsuitable in the long term.[57]

The next sub-sections of this chapter discuss a selection of mathematical models that have been developed with respect to AMD treatment processes. Most of these models focus on optimisation, while others are useful in assessing alternative remedial options.

ACTIVATED SLUDGE PROCESS

The activated sludge process is a biological wastewater treatment process widely used for domestic, municipal and industrial wastewater treatment.[58,59] It is used to treat a wide variety of recalcitrant and potentially toxic wastewater, normally in admixture with domestic sewage.[60] Activated sludge is also used to remove acidity, sulphates and metals from AMD-impacted water. In the activated sludge process, solids are first removed from influent raw wastewater before the wastewater is mixed in suspension under anaerobic conditions (aerobic conditions in some applications) with activated sludge that is comprised of a diverse population of microbial organisms.[61]

While numerous abiotic and microbially catalysed reactions occur in activated sludge systems, sulphate reduction, mediated by sulphate-reducing bacteria (SRB), is primarily responsible for pH neutralisation and sulphate and toxic metal removal.[62] Bacterial sulphate reduction produces approximately two moles of alkalinity per mole of sulphate that is reduced; the exact amount of alkalinity varies with the structure of the electron donor. For example, a reaction with acetate as the electron donor gives a 1:2 alkalinity production ratio, as shown in equation (1):

$$CH_3COO^- + SO_4^+ + H^+ \rightarrow H_2S + 2H_2O_3^- \qquad (1)$$

One mole of sulphide is generated per mole of sulphate reduction, and the sulphide then precipitates heavy metals with low metal solubility products (equation 2)):

$$Me^{2+} + H_2S \rightarrow MeS + 2H^+ \qquad (2)$$

Where: Me^{2+} represents a divalent heavy metal.

Over the years, several models have been developed to simulate the rate of biological sulphate removal under different conditions, including different sources of energy. In fact, mathematical modelling of activated sludge processes has wide application in research, plant design, optimisation, training and model-based process control.[63,64] This section discusses such models. As stated already, in the activated sludge process, one mole of sulphide is generated for every mole of sulphate reduced, and the sulphide subsequently precipitates most of the heavy metals.[65] The metal sulphide precipitates can be removed from the resulting water by means of physical separation processes such as a settler. Therefore, this section will also discuss settler models.

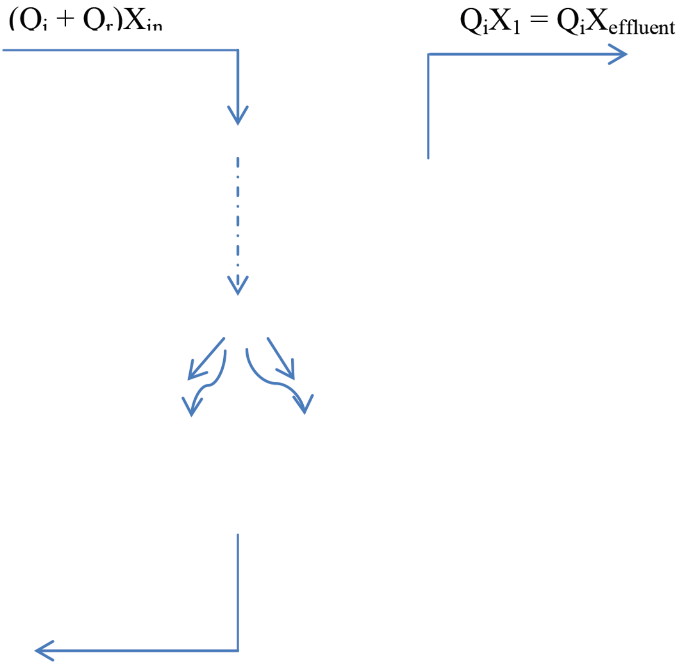
Modelling of the biochemical processes (including activated sludge) is based on several basic kinetic equations, describing bacterial growth, substrate utilisation and the endogenous metabolism (decay) of bacteria, as well as the hydrolysis of entrapped organics.[66] In the last five decades, several activated sludge models have been developed that describe the biochemical processes in various ways.[67,68,69] Of particular interest amongst all the models developed is the one developed by the International Water Association (IWA). In 1983, IWA formed a working group tasked with promoting and facilitating practical methods of designing and operating biological wastewater treatment systems. As a result, the Activated Sludge Model (ASM) family was developed.[70,71]

The Activated Sludge Model No.1 (ASM1), proposed by the IWA in 1986,[72] can be considered as the reference model.[73] It is based on chemical oxygen demand (COD),[74] uses 13 state variables,[75] and allows the dynamic simulation of organic matter degradation and nitrification/denitrification processes.[76,77,78] Increasing popularity and understanding of the biological phosphorus removal phenomenon led to the development of ASM2.[79] In 1999, ASM2 was further expanded to ASM2d, with denitrifying phosphorus-accumulating organisms being included.[80,81] There are 21 processes taken into account in the ASM2d: 19 are biological and two are chemical.[82,83] The ASM3 model was developed in 1999 to correct some of the deficiencies of ASM1 and it includes the advances in activated sludge modelling achieved in the decade following the publication of ASM1.[84,85,86] It includes 12 biochemical processes and 13 components. Neither biological nor chemical phosphorus removal processes are included in ASM3.[87] For an in-depth analysis of ASMs, readers are referred to Szilveszter et al.[88]

Numerous other mathematical models of the activated sludge, apart from the ASMs, are reported in literature,[89,90] for example, the ASAL models (based on biochemical oxygen demand (BOD)) and the TUDP model (which describes the metabolic behaviour of the involved organisms in detail). Most of these models are able to simulate organic matter removal, nitrification, denitrification and sometimes also phosphorus removal by biochemical and physical-chemical methods. However, all ASAL models cannot handle influents with phosphorus in them.[91] In addition, the large numbers of processes described by even more parameters result in a high complexity of the model.

Without a clarifier (or settler) model, the mass balance of an activated sludge of a wastewater treatment plant, using biomass recirculation, cannot be closed. The clarifier models are based on settling functions, which evaluate the settling velocity of the particles, depending mainly on the solids concentration.[92] The most popular models are simple 1-D models that are based on the layer approach proposed by Takács et al.[93] These models predict the solids concentration profile in the settler by dividing the settler into a number of layers of constant thickness and by performing a solids balance around each layer[94] and are based on the following assumptions: incoming solids are distributed instantaneously and uniformly across the entire cross-sectional area of the clarifier layer where only vertical flow is considered (Figure 9.1).

Figure 9.1: Layered settler model[95]



These models describe settling and thickening with an acceptable level of accuracy and have a low computational demand. The 1-D models are adequate for coupling with activated sludge models, because they give a reasonable approximation of the sludge balance and the sludge shift from the aeration tank to the secondary clarifier.[96] However, conversion processes are typically not included in these models, because they are considered less important.[97]

In practice, clarifier models are implemented using the layer approach, which is a method for applying the flux theory in computer code.[98] The settler tank is divided into horizontal layers and the differential form of the mass conservation equation is solved in each layer. The feed usually enters at an intermediate layer (Figure 9.1).

IRON OXIDATION AND REMOVAL

Iron is by far the most prevalent heavy metal in AMD. For example, AMD can contain high concentrations of ferrous iron (Fe^{2+}) in excess of 100 to 1000 mg/l.[99] Iron can be removed from AMD with a chemical treatment process consisting of three physicochemical unit operations: neutralisation, oxidation and sludge separation. The addition of alkaline chemicals neutralises acidity and/or precipitates some of the metals as hydroxides. Oxidation converts dissolved Fe^{2+} to Fe^{3+}, which hydrolyses and forms ferric hydroxide [Fe(OH)3] precipitate. The final operation is liquid-sludge separation prior to discharge of the treated water to the receiving stream. Typically, AMD treatment results in the depletion of dissolved oxygen in the water; and the depletion of dissolved oxygen can be crucial to the rate of Fe^{2+} oxidation and AMD treatment plant design.

The common chemical model used to predict the rate of Fe^{2+} oxidation expresses the rate as a function of Fe^{2+}, dissolved oxygen concentration, and Ph[100] – referred to as the iron-dependent model. An alternative model that predicts oxidation rates more accurately under conditions of AMD treatment has also been developed – referred to as the oxygen-dependent model. This section discusses such models used to predict Fe^{2+} oxidation rates. The section will also discuss models of oxygen aeration equipment.

The iron-dependent model uses flow rates, initial Fe^{2+} concentration, initial pH, and initial dissolved oxygen to predict reaction rates (of equation (3)), and consequently the required aeration times to achieve iron removal by precipitation.

$$Fe^{2} + \tfrac{1}{4}O_2 + H+ \rightarrow Fe^{3+} + \tfrac{1}{2}H_2O \qquad (3)$$

The iron-dependent model indicates that for mine wastewater above pH 3.5, the oxidation rate of iron in equation (3) has a first-order dependency on $[Fe^{2+}]$ and $[O_2]$, and a second-order dependency on $[H^+]$, as indicated by the following rate equation (equation (4)):

$$\frac{-d[Fe^{2+}]}{dt} = \frac{k_{Fe}[Fe^{2+}][O_2(aq)]}{[H^+]^2} \qquad (4)$$

Where: k_{Fe} = 3×10^{-12} (mol/ℓ)/min, at 20°C

$[Fe^{2+}]$ = Fe^{2+} concentration, mol/ℓ

$[O_2(aq)]$ = O_2 concentration in aqueous phase, mol/ℓ

$[H^+]$ = H^+ concentration, mol/ℓ

For Fe^{2+} oxidation to continue after O_2 depletion, an additional physical reaction should become part of the Fe^{2+} oxidation mechanism. That reaction is the mass transfer of O_2 from the gas into the aqueous phase. This is expressed as (equation (5)):

$$O_2(g) \rightarrow O_2(aq) \qquad (5)$$

Where: $O_2(g)$ = O_2 in gas phase, mg/ℓ
$O_2(aq)$ = O_2 in aqueous phase, mg/ℓ

Of the two reactions in the oxidation process (equations (3) and (5)) it is generally believed that the O_2 transfer reaction is slower.[101, 102] This is due to O_2's relative insolubility in water at ambient temperatures and pressure rates.

The iron-dependent model adequately expresses the role of O_2 in Fe^{2+} oxidation, provided an ample amount of O_2 is present in the solution. However, it does not model the proposed rate limiting reaction (equation 5) in AMD that has a high Fe^{2+}concentration at near neutral pH conditions. As a result of deficiency of the iron-dependent model, an oxygen-dependent model was developed for Fe^{2+} oxidation, based on the hypothesis that O_2 transfer is the rate-limiting step in Fe^{2+} oxidation. It models the stoichiometrically predicted reactions involved in the treatment of AMD with high Fe^{2+}concentration: O_2 transfer and Fe^{2+} oxidation (equations (5) and (3), respectively).

In literature,[103] the O_2 transfer rate is given as (equation (6)):

$$\frac{d[O_2]}{dt} = k_{O_2}([O_2]_{sat} - [O_2]_t) \qquad (6)$$

Where: k_{O_2} = O_2 transfer rate coefficient, min^{-1}
$[O_2]_{sat}$ = O_2 at saturation, mg/ℓ
$[O_2]_t$ = time depenedent concentration of O_2 , mg/ℓ

If O_2 transfer is much slower than Fe^{2+} oxidation, then it becomes the rate-limiting step, and the rate of Fe^{2+}oxidation can be expressed as (equation (7)):

$$\frac{-d[Fe^{2+}]}{dt} = \frac{7d[O_2]}{dt} = 7k_{O_2}([O_2]_{sat} - [O_2]_t) \qquad (7)$$

Where: $[Fe^{2+}]$ = Fe^{2+} concentration, mg/ℓ

The factor of 7 is obtained from the Fe^{2+} oxidation stoichiometry, whereby 55.85 mg/l of Fe^{2+} is oxidised by 8 mg/l of O_2 (equation (3)).

Since Fe^{2+} rapidly consumes O_2 in circumneutral solutions and $[O_2] << [O_2]_{sat}$, equation (7) becomes (equation (8)):

$$\frac{-d[Fe^{2+}]}{dt} = 7k_{O_2}\,[O_2]_{sat} \tag{8}$$

Integration of equation (8) at the boundary conditions yields (equation (9)):

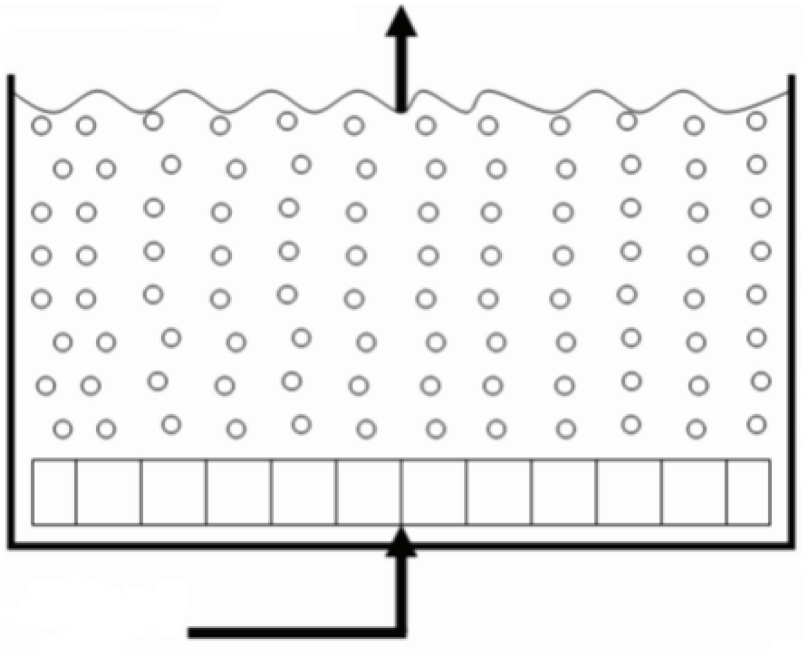
$$[Fe^{2+}] = [Fe^{2+}]_0 - 7k_{O_2}\,[O_2]_{sat}{}^{t} \tag{9}$$

Therefore, if the hypothesis of O_2 transfer being the rate-limiting step in Fe^{2+} oxidation is correct, then the measured O_2 transfer rate should predict the rate of Fe^{2+} oxidation at circumneutral conditions.

Oxygen transfer, the process by which oxygen is transferred from the gaseous to the liquid phase, is a vital part of a number of wastewater treatment processes,[104] and not only for ferrous iron oxidation in AMD. Because of the low solubility of oxygen and the consequent low rate of oxygen transfer, sufficient oxygen (needed to meet the demands of wastewater treatment processes) does not enter water through the normal surface air-water interface. To transfer the large quantities of oxygen needed, additional interfaces must be formed. To create additional gas-water interfaces, oxygen can be supplied into the water by means of air or pure oxygen.[105] In fact, in wastewater treatment plants, aeration is most frequently accomplished by dispersing air bubbles in the liquid.

The diffused or bubble aeration process consists of contacting gas bubbles with water for the purpose of transferring gas to the water. There are several bubble aeration systems[106] and for a given volume of water being aerated, aeration devices are evaluated on the basis of the quantity of oxygen transferred per unit of air introduced to the water for equivalent conditions.[107] Nevertheless, the most commonly used diffuser system consists of a matrix of perforated tubes (or membranes) or porous plates arranged near the bottom of the tank, so as to provide maximum gas to water contact (Figure 9.2).

Figure 9.2: Schematic of diffused air aeration system[108]



For good performance, the rate of supply of dissolved oxygen should be equal to the rate of oxygen consumption exerted by the mixed liquor under any given set of circumstances. In diffused air systems, bubbles are distributed from diffusers at the base of the reactor. Oxygen transfer takes place from the rising bubbles to the mixed liquor to supply the oxygen requirements for the wastewater treatment process.

A number of equipment and operational parameters interact to influence the efficiency and rate of transfer of oxygen, such as: tank length, depth and width, aeration size, type and location, and airflow rate. These parameters determine factors such as bubble size and the degree of turbulence. Conditions in the mixed liquor also have an impact on the transfer, for example, temperature, ionic strength, presence of surface-active compounds, and solids concentration.

The rate of oxygen transfer (under the conditions prevailing in an aeration basin) is governed by the liquid phase mass transfer coefficient, k_L. Determination of k_L poses experimental problems in that knowledge of the interfacial area for mass transfer (A_t) per unit volume (V) is required. For this reason, the rate of transfer for a particular system is usually reflected by the overall mass transfer coefficient, K_La, without attempting to separate the factors K_L and (A_t/V) (equation (10)):

$$K_La = K_L \frac{A_t}{V} \tag{10}$$

Where: K_La = apparent volumetric oxygen mass transfer coefficient in clean water, hr^{-1}

V = water volume in the tank, m^3

A_t = interfacial area of mass transfer, m^2

$a = \frac{A_t}{V}$, the interfacial area per unit volume, m^2/m^3

CONSTRUCTED WETLANDS

The majority of bioremediation options for AMD are passive systems, and of these, only constructed wetlands (aerobic and anaerobic) have so far been used in full-scale treatment systems.[109] Constructed wetlands are engineered systems designed to optimise the treatment conditions found in natural environments (see Figure 9.3); consequently, constructed wetlands are complex systems that are difficult to understand.[110] Constructed wetlands consist of impermeable excavated basins, which use engineered structures to control the flow direction, liquid retention time and water level.[111,112] They are planted with aquatic macrophytes that are typical in natural wetland areas. According to the way water circulates through the basins, they can be classified as either Subsurface Flow Wetlands (SSF constructed wetlands) or Surface Flow Wetlands (SF constructed wetlands). In the first case, water circulates underground through the porosity of a granular medium, whereas in SF, constructed wetlands water circulates in contact with the atmosphere.[113] SSF constructed wetlands can also be sub-divided into horizontal flow or vertical flow systems.[114] In horizontal flow wetlands (HSSF constructed wetlands), wastewater is maintained at a constant depth and flows horizontally below the surface of the granular medium. In vertical flow systems (VSSF constructed wetlands), wastewater is distributed over the surface of the wetland and trickles downward through the granular medium.[115] Combinations of these two types of systems can be used in certain cases, benefiting from the advantages of the two.

Figure 3: Treatment plant based on constructed wetlands technology[116]

According to Johnson and Hallberg,[117] the major advantages of passive bioremediation systems are their relatively low maintenance costs and the fact that the solid-phase products of water treatment are retained within the wetland sediments. Aerobic wetlands are generally constructed to treat mine waters that are net alkaline. This is because the main remediative reaction that occurs within them is the oxidation of ferrous iron and subsequent hydrolysis of the ferric iron produced, which is a net acid generating reaction (equations (11) and (12)).

$$4Fe^{2+} + O_2 + 4H^- \quad 4Fe^{3+} + 2H_2O \tag{11}$$

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

If there is insufficient alkalinity in the mine water to prevent a significant fall in pH, as a result of the above reactions, this may be compensated for by the incorporation of, for example, an anoxic limestone drain.[118] In contrast to aerobic wetlands, the key reactions in anaerobic wetlands (or compost bioreactors) occur in the absence of oxygen. The term ‘compost bioreactor’ is an appropriate generic term to describe such systems, because some installations are enclosed entirely below ground level and do not support any macrophytes – so they should not be described as wetlands.[119] Passive bioremediation systems that utilise a combination of aerobic and anaerobic wetlands have also been used for full-scale treatment of AMD.

As stated already, constructed wetlands are complex systems that are difficult to understand. A large number of physical, chemical and biological processes are active in parallel and mutually influence each other.[120] Therefore, constructed wetlands have for a long time been considered as 'black boxes' and little effort has been made to understand the main processes leading to wastewater purification. However, in the recent past, numerical models have been developed to obtain a better understanding of the processes governing the biological and chemical transformation and degradation processes occurring in constructed wetlands, thus providing insight into the 'black box' view. This section discusses existing numerical models that have been developed to evaluate and improve existing constructed wetlands design criteria.

As mentioned already, in engineering practice, the design of constructed wetlands is often carried out using the 'black box' concept. Hence, important design factors, such as organic loading rate, hydraulic loading rate, aspect ratio, granular medium size and water depth are defined mostly from previous experience.[121] Other equally important parameters are the selection of the pre-treatment, inflow and collection systems, as well as the plant species to be planted.

Arguably, there exist as many models for constructed wetlands as there are types of wetlands, water pollutants and processes that take place within these systems. However, only the most recent numerical codes applied to simulate the treatment of wastewater, and those able to provide new insight into the functioning of constructed wetlands, are presented in this section. The models are based on articles by Campà[122] and Samsó et al.[123] Tables 9.3 to 9.6 compare the features of some of the models. From the numerical codes in the tables, it can be seen that the FITOVERT model is the only one that does not use either the biokinetics models CW2D or CWM1.

Table 9.3: General model description[124,125]

	FITOVERT	PHWAT	CWM1-RETRASO	AQUASIM	HYDRUS-2D-CW2D	HYDRUS-2D-CWM1	BIO_PORE	RSM_Sim
Simulation platform	MATLAB	PHWAT	Retraso Code Bright (RBC)	AQUASIM	HYDRUS-2D	HYDRUS-2D	COMSOL Multiphysics™	Open (MS Excel)
Biokinetic model	Their own	CW2D	CWM1	CWM1	CW2D	CWM1	CWM1	Their own
Commercially available	No	No	No	No	Yes	Yes	No	In preparation
Free of charge	No	For noncommercial uses	Yes	Yes	No	No	No	For noncommercial uses
Dedicated graphical user interface for CW modelling	Yes	No	No	No	Yes	Yes	No	No
Model dimensions	1D	1D, 2D, 3D	2D	0D	2D	2D	2D	1D
Calibrated	Hydraulics and hydrodynamics	Hydraulics and clogging	Yes	Yes	Yes	No	Yes	Yes

Table 9.4: Hydraulic and hydrodynamic description[126,127]

	FITOVERT	PHWAT	CWM1-RETRASO	AQUASIM	HYDRUS-2D-CW2D	HYDRUS-2D-CWM1	BIO_PORE	RSM_Sim
Hydraulic/ hydrodynamics	Richards/ transport equations	Darcy/ transport equations	Darcy/ transport equations	CSTR	Richards/ transport equations	Richards/ transport equations	Darcy/ transport equations	Series of CSTR
Saturation conditions	Variably saturated	Saturated	Saturated	Saturated	Variably saturated	Variably saturated	Saturated with variable water table	Variably Saturated
VF/HF CWs	VF	HF/VF	HF	CSTR	VF	HF/VF	HF	VF
Feeding strategy	Feeding-emptying cycles	-	Continuous	Batch (20 days incubation)	Batch	Continuous	Continuous	Even driven (CSO)
Evapotranspiration	Evapotran-spiration	-	No	Green conditions	Yes	Transpiration	No	In progress
Surface flow/ponding	Yes	No	No	No	Yes	No	No	Yes
Clogging	Yes	Yes	No	No	No	No	No	No

(-) data not available / not applicable / not specified by the authors

Table 9.5: Biokinetic model[128,129]

	FITOVERT	PHWAT	CWM1-RETRASO	AQUASIM	HYDRUS-2D-CW2D	HYDRUS-2D-CWM1	BIO_PORE	RSM_Sim
C	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P	No	Yes	No	Yes	Yes	No	No	In progress
O	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
S	-	No	Yes	Yes	No	Yes	Yes	No
Monod type	Yes	Yes (CW2D)	Yes (CWM1)	Yes (CWM1)	Yes (CW2D)	Yes (CWM1)	Yes (CWM1)	-
Functional bacterial groups	-	3	6	6	3	6	6	-
Bacterial growth	Yes	Yes	No	Yes	Yes	Yes	Yes	-
Biomass description	Attached	Attached/ suspended	Suspended	Suspended	Attached	Attached	Attached	Sediment accumulation
Growth limitations	Substrates	Temperature, substrates and logistic expression	-	Tem-perature and substrates	Tem-perature and substrates	Tem-perature and substrates	Temperature, substrates, logistic growth and accumulated solids	-

(-) data not available / not applicable / not specified by the authors

Table 9.6 Physico-chemical processes[130,131]

	FITOVERT	PHWAT	CWM1-RETRASO	AQUASIM	HYDRUS-2D-CW2D	HYDRUS-2D-CWM1	BIO_PORE	RSM_Sim
Atmospheric oxygen transfer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Gas transport	Yes	Yes	Yes	Yes	Yes	Yes	No	No
pH	No	Yes	No	No	No	No	No	No
Redox	No	Yes	No	No	No	No	No	No
Chemical equilibrium	No	Yes	Yes	No	No	No	No	Yes
Transport of particulate components	Yes	Yes	No	-	No	No	Yes	Yes
Filtration/ sedimentation	Filtration	Attachment/ detachment of biomass	No	-	No	No	Filtration	Yes
Sorption	No	-	No	Adsorption and desorption	Yes	Yes	No	Yes

(-) data not available / not applicable / not specified by the authors

CHALLENGES AND FUTURE PROSPECTS

Mathematical models have become very important tools for technology design, optimising performance and process trouble-shooting of wastewater treatment plants, as they are both time and cost efficient.[132] The subject has a rich history, intertwined with the development of statistics and dynamical systems theory; however, recent analytical advances, coupled with the enhanced potential of high-speed computation, have opened up new vistas and presented new challenges.[133]

For example, although a number of models of treatment facilities have been developed and applied extensively,[134] these state-of-the-art models usually implicitly assume that the chemical and physical processes can be described by relatively simple models compared to the biological processes (for example, the precipitation model in ASM2D).[135] However, these simplifications imply that the applications of these models have to be restricted to situations where the simplifying assumptions remain valid.[136]

Other key challenges involve finding ways to describe the dynamics of systems that are aggregates of heterogeneous units and to scale from small spatial regions to large ones.[137] For example, the most significant obstacle to developing realistic models for reactive transport flow is the need to incorporate the multitude of spatial scales that are characteristic of natural sub-surface environments.[138] However, the central issues – understanding how detail at one scale makes its signature felt at other scales and how to relate phenomena across scales – cut across scientific disciplines and go to the heart of algorithmic development of approaches to high-speed computation.[139] Major challenges also exist with the development of AMD generation and transfer models. For example, the transport of chemical constituents to, from and within micro-environments is an extraordinarily difficult problem to fully integrate with macroscopic transport.[140] A chemical micro-environment can be defined as a small region in space in which the chemical composition of the fluid differs from the bulk chemical composition. Micro-environments may or may not be physically isolated from the bulk solution. From a modelling perspective, a micro-environment is problematic because the processes take place at a scale well below the size of a typical computational grid cell. Therefore, one is faced with the daunting challenge of describing reaction rates in a chemical environment where the composition is difficult to probe or predict and of inferring how these reactions affect the chemistry of the bulk fluid.

Furthermore, mathematical models cannot solve the problem of the apparent discrepancy between laboratory and field rates (or data) by themselves; however, they can be used to rigorously evaluate the importance of individual processes, some of which can be constrained independently.[141] In other cases, the mathematical modelling can be used to narrow down the possible explanations for the overall rates observed in the field.

Despite some challenges, mathematical modelling continues to evolve with new interests and efforts being developed in AMD generation, transfer and treatment processes. However, there are several frontier research questions that have generally not been addressed by mathematical modelling. Examples are the oft-cited discrepancy between laboratory and field data and the issue of chemical micro-environments in the subsurface, especially with regard to their control of AMD migration. These questions present both special challenges and opportunities for mathematical modelling in the future. With past and future successes, it is possible for mathematical modelling to form the basis for a new research approach and perhaps even paradigm in the AMD sciences, which goes well beyond its narrower, but important, role as a tool. Nevertheless, the real role of mathematical modelling comes from its ability to integrate fundamental research and provide the dynamic glue that links fundamental processes in complex natural AMD environments.

CONCLUSION

Many of the ideas presented in this chapter emanate from the work pioneered by IWA in 1983[142] and the chapter has shown that mathematical modelling approaches can provide powerful tools that can guide empirical work and provide a framework for synthesis and analysis of mine wastewater treatment systems. Several computer programmes have been developed based on the mathematical models developed since 1983; however, the most commonly used ones are those of the ASM family. As already stated, due to the advantages, mathematical modelling and computer simulation have become more common tools used in the management of water quality systems. This has been achieved due to the joint efforts of consultants, universities and government agencies, including collaboration at the international level. However, further research is still needed to develop firm fundamental knowledge upon which numerical modelling must be based. Further field studies are also required, as there is a need for more site characterisation to be integrated into monitoring and modelling programmes.

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CHAPTER 10

The Role of Geospatial Technologies in Modeling Acid Mine Drainage

A Case Study of South Africa's Tweelopiespruit

Shingirirai Mutanga, Munyaradzi Mujuru, Keneilwe Hlahane and Mashilo D Moshobane

ABSTRACT

The last decade has witnessed an upsurge in the use of geospatial technologies. These technologies have been evolving at a fast pace, with new and more advanced technologies meeting growing needs and delivering precise and efficient solutions to serve various needs. Similarly, the scourge of acid mine drainage (AMD) has witnessed the use of geographic information systems (GIS) and remote sensing in providing location-based tools to monitor or predict the levels of pollution in the environment, and aiding in the decision-making process, i.e. in the identification of appropriate intervention technologies. This chapter demonstrates the application of GIS in tracing and predicting the spatial variation of AMD pollutants on the environment. Apart from the embedded ability of mathematical modelling discussed in the previous chapter, there is also the power of geospatial technologies in providing location-based analysis, complemented with visualisation capabilities, which help reveal the effect of contaminants on surface runoff pathways and surface and underground water quality, and quantify the magnitude and severity of damage on soil and vegetation. The array of tools available thus enables analysis of both short-term and long-term action with limited investment cost.

INTRODUCTION

The process of determining pollution concentration at contaminated sites can be costly,[1] given the number of samples required to identify areas with higher contaminant concentrations. Yet if pollution transport pathways can be found, then spatial variation of contamination levels can be detected with fewer samples.[2] Apart from the purely mathematical models described in Chapter 9, geospatial technologies in the form of GIS and remote sensing equipment provide location-based tools to monitor or predict the levels of pollution in the environment.[3] Equally, spatial modelling, using GIS, can contribute to the understanding of AMD generation and the subsequent design of treatment processes. Models built from geospatial tools are useful tools that allow rapid and varied evaluation of causes and effects and the principal advantage of providing exact location-based analysis[4,5] that could be used for long-term action plans with limited investment costs. This review chapter demonstrates the application of GIS in tracing and predicting the spatial variation of AMD pollutants in the environment. This broadens the understanding of AMD impacts on the natural environment. In particular, the chapter provides case studies that reveal the usefulness of geospatial technologies in mapping AMD contaminants on surface run-off pathways, surface and underground water quality, soil and vegetation. In order to appreciate the role of geospatial technology, the next section provides a brief overview of GIS and remote sensing and how the tools apply the model concept.

AN OVERVIEW OF GIS

Using GIS has become the modern way to carry out spatial examination of data within a geographical context.[6] GIS offers a computerised system that allows its user to store, analyse and display geographically referenced data.[7] GIS has the unique capability to effectively handle spatial data (data linked to a geographic map through coordinates or identifiers), as well as to attribute data (data not explicitly linked to the earth's surface through coordinates or identifiers).[8] A GIS allows the user to perform specialised spatial analysis operations, such as distance measurement, multi-layer analysis and advanced geo-statistical analysis,[9] in addition to more common database functions. How then is GIS relevant or especially useful for AMD remediation planning? One of the key reasons is that a GIS can store information about the nature of AMD contamination (such as the heavy metals like iron and aluminum concentrations as well as pH), and about the location of the source of the contamination. Such capabilities provide information to decision-makers about where the worst AMD contamination is coming from and can pinpoint the best places in the watershed to treat it, based on factors such as upstream or downstream location in the watershed and distance of stream impacted by a single discharge. Doyle and Gray[10] presented a protocol for monitoring and predicting the impact of AMD using GIS.

In essence, GIS models provide a visual representation of AMD impacts in a form of maps. These models can be classified into two key categories, namely static and dynamic.

GIS MODEL CLASSIFICATIONS

There are two main classifications of GIS models: static and dynamic models. A model is defined to be static if it represents the state of spatial data at a given point in time.[11] Maps and databases are examples of static models. Database models allow the user to create a representation of how the world looks, by storing the data in a table format, which is then stored in a spatial database.[12] This type of model provides various functions to operate on the stored data and the table can be queried to represent a process in the real world. This process is defined as spatial data modelling.[13] Spatial data modelling is applied in AMD projects to store and manage the collected contaminants data, and the data is then visually represented in the form of maps.

The second classification of GIS models is dynamic models. Dynamic models are used to represent time-dependent changes in the system.[14] Dynamic models are implemented through simulations. Simulation is a technique that can generate different states of spatial data over time.[15] As an example, dynamic models of stream flow can be used to predict AMD concentrations at un-sampled locations and how the concentration will change over time.

The utility of geospatial technologies requires consideration of certain major factors, including:

- Purchase or hiring of hardware and software: commonly used software includes ESRI products such as Arc GIS, Arc Info, Open Source software, ILWISS and Erdas Imagine; and
- Human capital: the availability of specialised personnel for advanced database design and advanced spatial analysis.

GIS was used to identify potential sources of AMD production and examine the effect of these sources on the surrounding environment. GIS proved useful for certain aspects of interpretation of the data collected during a detailed examination of the site. Apart from its use in cartography, GIS can be used for examining spatial data collected during the soil and vegetation study as well as the effects of mixing of the leachate from a deep audit in the river. Visualisation of the site in 3D can also be an important feature, as it provides the ability to examine the effect of physical remediation on the landscape of the site. The next section provides case studies that have successfully employed GIS in understanding the AMD challenge.

GEOCHEMICAL-GEOSPATIAL LANDSCAPE ANALYSIS OF AMD CONTAMINATION

Advances in GIS technology have ushered in tools for classifying elementary landscapes. Elementary landscapes can be used to define geochemical barriers. According to Szucs and Jordan,[16] elementary landscapes that are geochemically related by material transport (landscapes in a watershed, or areas at recharge and discharge regions of the same groundwater system, for example) form a geochemical landscape. Often, the characteristics of the geochemical landscape are dependent on the geochemistry of the area, which may have stream segments that are influenced by another landscape with up-slope mineralisation. The technology has provided the consideration of spatial relationships through surface and sub-surface matter flow in a way analogous to the soil catena concept of soil science. The spatial relationships could be classified based on matter transport direction at elementary landscape boundaries, and the geochemical character of landscapes determined by their acid neutralising capacity and redox conditions on either side of the barrier.[17] Szucs, et al.[18] delineated and classified elementary landscapes using GIS overlay of the hydrology layer and the slope break model derived from the digital elevation model (DEM). The study was premised on the assumption that in the case of eluvial landscapes, characterised by podzol soils underlain by granitic glacial till, groundwater is likely to be oxidising, and in the super-aqual mire landscape it is reducing, while active stream segments are also oxidising environments in the study area. The information was added to the attributes of elementary landscape polygons in the GIS database. As shown in Figure 10.1, the elementary landscape map was overlaid with the run-off model using GIS technology, in order to define flow direction at landscape boundaries. Relationships between landscapes were then analysed by matter transport models, such as run-off and watershed models that were also derived from the DEM (Figure 10.1). In this study, a run-off model derived from the DEM was used for calculating surface matter transport vectors. Findings showed that oxidising active stream sediment receives weakly acidic-reducing gley water (pH 3 to 6.5) from the neighbouring mire, and an oxidising barrier is likely to form in the receiving stream sediments with an expected element association of iron (Fe), manganese (Mn) and cobalt (Co).

Figure 10.1: The elementary landscape map overlaid with the run-off model using GIS technology, in order to define flow direction at landscape boundaries[19]

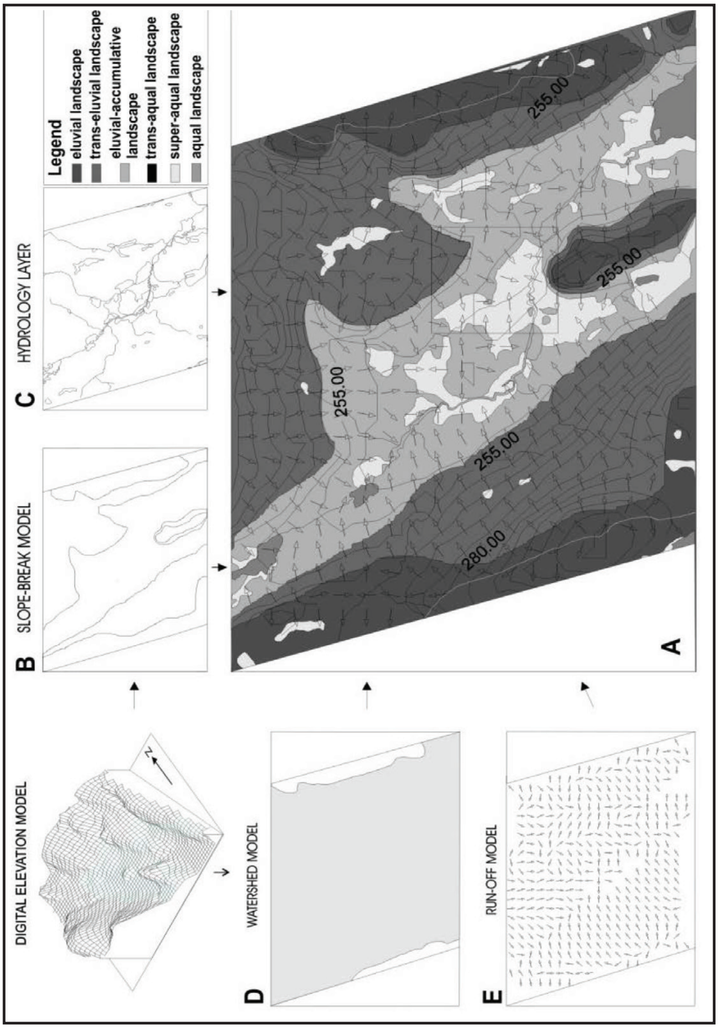


Figure 10.1A. Grey shading shows elementary landscapes derived from the hydrology layer (Figure 10.1C) and the slope-break model (Figure 10.1B). Geochemical landscape flow is also shown, derived from the watershed (Figure 10.1D) and run-off (Figure 10.1E) models. The map shows elementary landscapes and their relationships by matter flow lines. Solid box: area shown in Figures 10.1A, B and C. Slope-break model derived from DEM and hydrology layer, respectively. Figures 10.1D and E show watershed and run-off models derived from DEM, respectively.

THE ROLE OF GIS IN MAPPING, SPATIAL VARIATION OF ACID MINE DRAINAGE LOCATIONS.

Spatial evaluation and visualisation of pollutants improve our understanding of how the sources of risk, the receptors and the exposure pathways are distributed in the space.[20,21] This has been an important factor that has influenced the upsurge in use of GIS techniques in studies on the distribution of environmental pollution.[22,23] Delgado, et al.[24] analysed the spatial variation of heavy metals in the Guadiana Estuary sediments (SW Iberian Peninsula) based on GIS mapping techniques. The study demonstrates the usefulness of GIS techniques through enrichment distribution maps, which evidenced a distribution of natural origin elements (Al, Fe, Mn, Co, and Cr), distributed homogeneously along the basin, and anthropic origin elements (As, Cd, Cu, Pb, Ni and Zn) with clear punctual sources. The study showed that the enrichment factors for the anthropogenic group are indicative of the existence of a noticeable diffuse historical mining pollution associated with the AMD generated in the internal zones of the basin. This study corroborates Caeiro and Costa's study,[25] which identified and assessed heavy metal contamination in the Sado Estuary in Portugal. The study used interpolation surfaces per metal to compare and gauge the results of the developed indices and assessed the contamination per individual metal. From the 78 stations sampled in the main bay of the estuary, a set of heavy metals and metalloids was established, i.e. cadmium (Cd), copper (Cu), lead (Pb), chrome (Cr), mercury (Hg), aluminium (Al), zinc (Zn) and arsenic (As).[26] Key to GIS was the location of the sampling points, mapping and providing a comparative analysis and the spatial variation of contaminants indices, i.e. enrichment indices vs ecological risk indices for the sampling points, as well as spatial distribution of the metals.

ROLE OF EARTH OBSERVATION ON MAPPING FOREST CHANGE IN AN AMD AREA

Geospatial technologies in the form of satellite imagery or earth observation provide a unique approach for monitoring forest degradation in AMD areas. Numerous investigators have employed GIS and remote sensing data for assessing the effects of land use on stream ecosystems[27,28,29,30] and these have addressed a range of environmental scales, settings, and problems.[31]

A typical case study done by Walsworth and King[32] provides a clear demonstration of how the planar cellular transition model was investigated as a predictive methodology for modelling tree canopy dynamics along a chemical contamination gradient adjacent to an acid mine. Stochastic raster transitions were developed as a function of proximity to the tailings and the local stem density neighbourhood configuration. The results revealed significant forest degradation over a 40-year period nearer the tailings and within areas of mixed canopy types in the study area. Similarly, considering that vegetation chemistry is key in determining the potential of a wetland to remediate AMD, satellite application can equally be employed to monitor and retain AMD-resistant vegetation species compared to non-resistant and highly metallic accumulative species. For example, sphagnum has the ability to absorb iron until it reaches toxic levels, whereas typha (bulrushes) is more tolerant to AMD. Earth observation could therefore aid in monitoring the growth patterns of these species and provide reliable information for decision making in retaining vegetation species that can be used as neutralising agents of the AMD remediation option. This is an area that warrants more research. Yet another dimension of earth observation is the utility of GIS and remote sensing for mineral prediction,[33] which can then be used as a proxy for identifying AMD risk areas. The next section provides a demonstration of how geospatial technologies can be employed in the remediation of AMD. Kopačková[34] used a multi-range spectral feature fitting (MRSFF) technique to map certain pH ranges in the hyperspectral image datasets. This technique was found to be sensitive enough to assess differences in the desired spectral parameters (e.g. absorption shape, depth and (indirectly) maximum absorption wave length position). The study represents one of the few approaches that employ image spectroscopy for quantitative pH modelling in a mining environment, and the achieved results demonstrate the potential application of hyperspectral remote sensing as an efficient method for environmental monitoring.[35]

ROLE OF GEOSPATIAL TECHNOLOGIES IN AMD REMEDIATION OPTIONS

As described in Chapter 13 there has been growing interest in the use of wetlands as a passive and cost-effective remediation option to acid mine drainage and mining pollution in general.[36] However, most natural wetlands are being lost due to development, and, as such, construction of new ones as a means to control pollution from mines is desirable.[37] GIS plays a pivotal role in mapping and monitoring such aquatic environments. Selection of sample sites and mapping, using GIS, has been widely used in a number of studies.[38,39] The Machemer and Wildeman study[40] tested the processes for removal of metal from acid mine drainage on a constructed wetland in Colorado. The study confirmed competition for organic adsorption sites among Fe, Cu, Zn and Mn. Fe and Cu appear to be more strongly adsorbed than Zn and Mn. The study concluded that, over time, sulfide precipitation becomes the dominant process for metal removal from acid mine drainage. Similarly, the attenuation of Cu, Fe, Mn, Ni, Pb and Zn originating from acidic ore mine leachate was studied in a natural wetland stream environment in central Sweden.[41] GIS techniques, combined with statistical methods, provided an integrated and robust data model, depicting the spatial variability of metal retention in the stream sediments along the wetland. The analysis suggested that adsorption and co-precipitation with Fe oxy-hydroxide are major processes, apart from the adsorption of organic matter. Mn is probably specifically adsorbed on Fe oxy-hydroxides, and, besides Zn, it is least retained in the sediment. Pb, Cu and Ni are found in considerable quantities in the reducible fraction and it is suggested they are occluded in Fe oxy-hydroxides. The pH is one of the major chemical parameters affecting the results of remediation programmes carried out at abandoned mines and dumps, and one of the major parameters controlling heavy metal mobilisation and speciation.[42] Detecting and mapping pH levels using hyperspectral imaging, as described above, illustrate an effective use of geospatial technologies.

ROLE OF GIS IN EVALUATING POLLUTION LEVELS IN ABANDONED MINES

Geospatial technologies provide a plethora of tools that are useful in the evaluation of pollution levels in abandoned mines. Some notable studies [43,44] used sediment deposition to trace pollution levels caused by AMD. An integrated watershed analysis using GIS tools was undertaken to examine erosion and sediment transport characteristics in the watersheds.

Estimates of stream deposits of sediment from mine tailings were related to the chemistry of surface water, in order to assess the effectiveness of the methodology used to assess the risk of AMD being dispersed downstream of abandoned tailings and waste rock piles. Findings showed an improvement in the ability to predict streams that are likely to have a severely degraded water quality as a result of past mining activities. Similarly, an actual bathymetric map was created from the data pool of Mining Lake 111, Brandenburg, Germany, and that map was the basis for the selection of sampling sites where the study obtained sediment cores to describe the geochemistry of the lake sediments. With the fusion of Principal Component Analysis (PCA) to examine patterns and similarities between concentrations of different heavy metals, the study was able to depict the spatial variation in metal concentration from AMD.[45,46] Another example is the spatial distribution of pollutant concentrations evaluated with respect to the surface run-off pathways and locations of potential contamination sources.[47] The next section provides a demonstration of GIS application on monitoring surface water quality.

GIS APPLICATIONS IN ASSESSING AMD IMPACT ON SURFACE WATER QUALITY

AMD poses a major threat to surface and groundwater resources, especially in streams, as described in Chapter 4. Prior to the advent of GIS, GPS and RS, in particular during the mid-1970s to mid-1980s, opportunities for digital database construction with easy access by users, including data sharing capabilities relative to regional mining, as well as its impacts and extent remained extremely limited. EPA's BASINS (Better Assessment Science Integrating Point and Nonpoint Sources, EPA, 2001) is a multi-purpose environmental analysis system based on GIS for use by natural resource agencies to perform watershed and water-quality-based studies.[48] Although BASINS represents a good first step in providing access to a range of geospatial data on land use and water quality,[49] environmental information on AMD-impacted streams remains limited in comparison to other sources of aquatic pollution, especially 'permitted' (by regulatory agencies) sources of industrial pollution and effluents. Bio-monitoring techniques can be used in chemical analysis while geo-statistical tools are used to monitor river water quality in streams.

Another example is the mapping of the regional water quality of the Humber catchment area, which was mapped for key inorganic chemical determinants, using a GIS system and an extensive Environment Agency and LOIS monitoring database.[50] Delgado, Nieto's[51] applied geostatistical techniques in the form of Kriging is used to map the spatial variability of **enantiomeric fractions** (EF) of As, Cd, Co, Cr, Cu, Ni, Pb and Zn along the estuary of Guadiana. Findings indicated the environmental vulnerability of the estuary. Similarly, Tavares and Sousa[52] applied ordinary Kriging and indicator Kriging in the cartography of trace elements contamination at the São Domingos mining site.

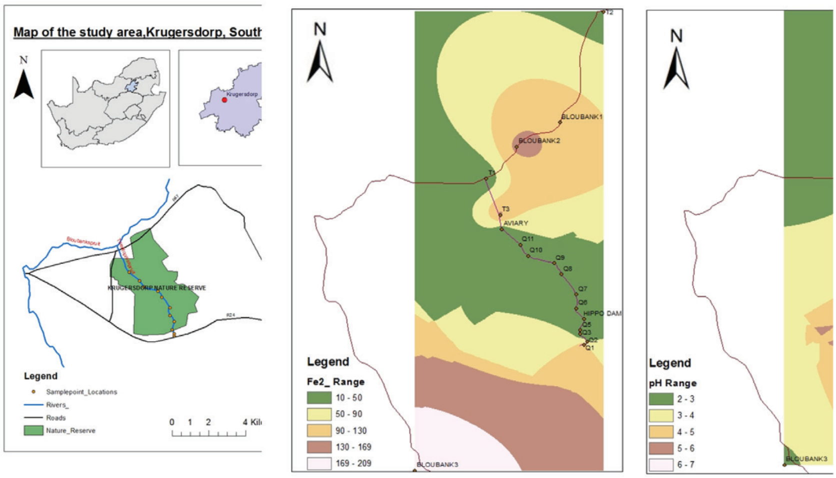
Several GIS-related watershed investigations have been consistent in their findings, even though a wide range have reported differing results. For example, Richards et al.[53] concluded that macro invertebrate 'biological signatures' could be used to assess landscape-scale influences on central Michigan streams, based on factors such as geology and land use. Johnson et al.[54] reported that relatively coarse spatial scale databases were able to provide useful descriptors of regional water quality in central Michigan streams. And multivariate analyses by Stewart et al.[55] indicated that agricultural land cover in riparian zones as well as forest land cover in whole watersheds were part of a suite of variables, with the greatest influence on invertebrate and fish communities in agricultural watersheds in eastern Wisconsin.

SOUTH AFRICA'S TWEELOPIESPRUIT CASE STUDY

The Tweelopiespruit is a stream located in the West Rand area of Krugersdorp, in South Africa. See Figure 10.2. It is the recipient of AMD decanting from the goldfields of this region. The volume of AMD decanting into Tweelopiespruit is currently alarming – 60 mega liters per day (Ml/day). The AMD water in the area is currently being treated through neutralisation. GIS modeling techniques were used as part of the stream remediation project, to show areas which were highly contaminated by AMD along Tweelopiespruit.

A spatial database was built, based on sampled borehole locations, and geospatial techniques were used to analyse variations in the concentration level of stream pollutant parameters. The pollutant parameters that were analysed are pH levels, Fe_2+ concentration, electrical conductivity, acidity and alkalinity. For demonstration purposes, the spatial database enabled queries to be performed on different pH levels and Fe_2+ concentrations. Surface models showing pollutant parameters were created using the Kriging GIS interpolation method. Kriging is a geo-statistical method based on models that include the statistical relationships among measured points. Kriging techniques have the capability of creating a prediction surface and an estimation of concentration values. They also provide a measure of accuracy of the predictions made. This method assumes that the distance and direction between sample points reflects a spatial correlation. The outcome was a series of static maps, showing pollutant location and variations in the concentration of pollutants along the stream as shown on Figure 10.2. The results indicated that along Tweelopiespruit, the tributary is characterised by a decline in pH levels values. The low pH can be attributed to untreated AMD water. Despitean AMD treatment pond at point Q9 which retains a relatively high pH, the treated AMD water is mixed with untreated water in the tributary; hence it is effective over a short distance, as depicted by the decreasing pH levels downstream, indicating high AMD contamination levels. Metal concentrations are high in the main stream, suggesting the impacts of AMD to the downstream surface water resources. This demonstration provides a unique example of how static maps are presented for GIS modelling.

Figure 10.2: Predicted pH and Fe_2 levels along Tweelopiespruit[56]



This method of modelling is effective for analysing and presenting visual spatial variations of pollutant concentrations. Highly contaminated areas along the stream, where AMD treatment should be prioritised, can easily be identified.

CONCLUSION

There has been a surge in applied geospatial technologies to enhance environmental protection recently – especially in water resources management. By and large, the management of surface and groundwater resources, especially in mine-dominated areas, could benefit from the use of geospatial technologies for geochemical-geospatial landscape analysis of AMD contamination, evaluating pollution levels on abandoned mines and decision making on AMD remediation options. This chapter highlights that GIS modelling techniques should be incorporated into AMD treatment projects, as they would enhance decisions regarding the selection of effective treatments in the future. Case studies reveal the usefulness of geospatial technologies in mapping AMD contaminants on surface run-off pathways, surface and underground water quality, soil and vegetation.

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CHAPTER 11

Financing Acid Mine Drainage Treatment in South Africa

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ABSTRACT

This chapter discusses one of the key requirements to deal with acid mine drainage (AMD) treatment: finance. One of the pertinent questions that this chapter attempts to respond to is: How does South Africa finance AMD treatment through public or private ventures? The chapter acknowledges that what compounds the challenge is the widespread proliferation of abandoned or disused mines. The unpalatable reality is that legacy, contemporary and future AMD generation challenges will persist for years to come and any intervention needs to be sustainably funded. The chapter also discusses current AMD remediation technologies in South Africa, their running costs and funding mechanisms, and explores some models that need to be considered to deal with contemporary and future AMD remediation challenges.

INTRODUCTION

This book addresses the complex issue of AMD treatment and how policy and practice could deal with the legacy and contemporary and future AMD incidence and proliferation in South Africa (SA). In this chapter, we discuss one of the key requirements to deal with AMD treatment: finance. How does SA finance AMD treatment through public or private ventures? What compounds the challenge is the widespread proliferation of abandoned or disused mines. For example, according to Mining Weekly,[1] of the 120 mining companies that historically operated in the Witwatersrand area, only six can be traced. The Witwatersrand area has approximately 6 000 ownerless abandoned mines, and about 270 tailings dams containing six billion tonnes of pyrite — a catalyst for AMD.

The unpalatable reality is that the legacy and contemporary and future AMD generation challenges will persist for years to come and any intervention needs be sustainably funded. In discussing finance and funding models, we are acutely aware that any intervention that seeks to deal with AMD treatment sustainably will need to engage with resource ownership, particularly of land and water. Ownership of land, as well as surface and ground water resources, will, to a large extent, determine the socio-economic and technology interventions, and negotiations between and amongst individuals, private organisations, and government at local, regional and national level. The remit of this chapter does not cover these complex issues, but we acknowledge that any intervention that involves market creation and entrepreneurship will require negotiation with the aforementioned and other parties.

The challenge is not peculiar to South Africa only; it is common in many countries with a mining history. As such, South Africa can draw contextualised lessons on systemic issues regarding sustainable funding of AMD treatment from countries such as the United States of America (US), Australia and Canada, which are also battling AMD. The policy and practice complexity of funding AMD treatment programmes emanates from the variety of technology and socio-economic interventions that can be applied to deal with legacy mining issues, balancing contemporary economic versus environmental well-being imperatives, as well as crafting policies and frameworks that would balance future investment without burdening the public with environmental risk. AMD generation from disused or abandoned mines, as well as tailings dams, aptly demonstrates the tension between short-term private profit (for mining entrepreneurs) and long-term environmental risk and social cost to the public who are then forced to fund remediation processes through public funds. Private enterprises generated private profits (after paying statutory taxes and tariffs), but left the long-term environmental remediation of what is essentially a public good to the public through tax or other levy payments. Mitigating contemporary and future AMD generation may be different, however, because mine owners can be traced and socio-economic frameworks can be designed that approach an equitable sharing of the long-term environmental risks. Government can craft policy and practice mechanisms that link short-term profits and corporate social responsibility with long-term environmental risk management responsibility.

In this chapter, we discuss current AMD remediation technologies in South Africa, as well as the running costs and funding mechanisms and explore some models that need to be considered to deal with contemporary and future AMD remediation challenges. As other chapters in this book have discussed the background and political economy of AMD generation and treatment, as well as the science and technology aspects in South Africa, we do not dwell on these factors in this chapter. We focus instead on current and possible future funding mechanisms for the legacy, and contemporary and future AMD generation by considering public and private financing institutional architecture. We discuss how current AMD treatment technological initiatives linked to and run mostly by universities, as experimental research projects, need to be sustainably scaled up to a large-scale level, which may include commercial activities. We discuss how AMD remediation can be linked to sustainable funding mechanisms that leverage downstream integration of AMD treatment process outputs with public, commercial agricultural, and industrial activities or business models.

What emerges from the discussion is that long-term and sustainable funding of AMD treatment will require multi-pronged public, private and public-private funding models. The rest of the chapter is structured as follows: the next section discusses treatment technologies and the cost factors, followed by a section which covers the extraction of benefits from AMD treatment. The fourth section discusses existing financing models, as well as envisaged new business models. The fifth section concludes the chapter.

TECHNOLOGIES TO TREAT AMD AND THE COST FACTORS

As discussed elsewhere in this book, various methods are employed to treat AMD, broadly classified as abiotic and biotic processes. Biotic processes use biological systems to treat AMD, whereas abiotic processes are based on chemical processes. Biotic and abiotic processes can be passive or active and the type of system chosen determines the treatment running costs. Various factors influence treatment costs, including terrain, aesthetics, land ownership and metals load or acidity. For example, in the US, the passive system, in certain instances, is deemed the most cost effective at 430 US dollars per tonne of acid per year.[2] Reliance on the passive treatment method can be driven by aesthetics, as property owners may not be keen on unsightly active treatment plants on their land (which may impinge on real estate value) and the total cost of the system. However, the major drawback of the passive system is its inability to treat larger areas without resorting to the construction of larger infrastructure, which, in turn, requires initially high infrastructure investment and subsequently higher maintenance costs and larger real estate utilisation. Scarcity and the cost of real estate in Gauteng province are among the reasons why the passive system is not popular.

Table 11.1: Cost comparison of proactive prevention techniques for collection and treatment for acidic mine drainage

Technique	Cost (US$/ha)	Technique	Cost (US$/ha)
Collect and treat	$26,900	Quicklime addition	$56,800
Lime addition	$32,900	Phosphate/apatite addition	$38,500
Clay cover and alkaline trench	$50,200	Controlled layering of acid-generating material	$31,400

Source: Expert Team of the Inter-Ministerial Committee[3]

AMD REMEDIATION COST ANALYSIS

The combined cost of setting up AMD pipelines and water pumping infrastructure is significantly higher than that of setting up AMD treatment plants. The capital cost of setting up a pump station and pipeline that can transport 25 Ml/day of water over a distance of 20 kilometres is estimated at R60 million and the electricity running costs at R5 million per annum.[4] Analysis of the costs in this section will mostly refer to AMD treatment processes.

Figure 11.1: Acid mine drainage going into Tweelopiespruit

Table 11.2 shows the running costs of AMD treatment technologies in SA. Most of these technologies were developed by South African institutions, which signifies a high level of technological development capability in the country. However, the technology is still under assessment in terms of scaling up for large-scale applications. The challenge, therefore, is that some of the technologies have not been proven on large-scale operations and thus translation and scale up still needs to be developed.

Table 11.2: Technologies available in South Africa and indicative running costs[5]

Technology	Running cost (million Rands)	Income (million Rands)
CSIR Alkali-Barium-Calcium	4.04	3.56
KeyPlan Hipro	9.12	3.35
AR technologies sodium carbonate reverse osmosis	12.79	4.29
Mintek SAVMIN	11.30	3.84
Biosure	3.80	0.0
Tshwane University of Technology (TUT)/ CSIR Magnesium-Barium-Alkali	2.22	5.58
Lime treatment for industrial water	5.50	0.70
Current treatment undertaken at Rand Uranium in the Western Basin	8.20	0.0

As shown in Table 11.2, various technologies have been deployed to treat AMD water, albeit on a small scale. The applicability of these technologies depends on cost and other issues, such as level of acidity of the AMD water.

REVERSE OSMOSIS (RO)

Multi-stage RO concentration and gypsum precipitation is a well-known process and several large-scale applications of this process exist for AMD treatment in South Africa. It is important to note that this desalination process requires the removal of metals present in solution before the RO process, in order to prevent the scaling of the RO membranes by precipitates (for example, iron and manganese). According to a report from the

Department of Water Affairs,[6] the RO process has been used in large installations in South Africa and abroad, and the quality of the treated water can meet all the required specifications; however, large quantities of sludge are produced, which requires large tailings storage facilities or dedicated sludge disposal ponds. The operating costs associated with this process are presented in Table 11.3. These costs exclude waste disposal and upstream limestone and high density sludge (HDS) processes.

Table 11.3: Operating cost summary for feed water quality at the 95th percentile[7]

Description	Operating cost for feed water quality at the 95th percentile		
	Western Basin	Central Basin	Eastern Basin
Chemicals and consumables - R million/year	31.412	63.309	56.655
Membrane replacement - R million/year	5.034	13.214	6 935
Electricity - R million/year	17.210	18.469	30.660
Operational personnel - R million/year	9.360	12.480	9.547
Maintenance provision - R million/year	5.750	12.116	7.636
Total annual operating cost - R million/year	68.766	99.242	131.780

Table 11.3 shows that the main cost drivers are chemicals and consumables and electricity costs. Operating personnel costs tend to be higher than maintenance or membrane replacement costs.

SELECTIVE URANIUM REMOVAL

The only technologies that are considered proven and viable at the scale required and that can be recommended currently include: Ion Exchange for the removal of uranium; HDS for neutralisation; and RO for desalination. All three basins contain uranium at levels exceeding the limits set by SANS241:2011. (Uranium tests were only done for the Central and Eastern basins, but it is believed that all three basins contain uranium.) A selective resin is used to remove the uranium from the AMD as an anionic complex. As the resin has a high capacity and the uranium concentrations are fairly low, the resin requires infrequent regeneration. The cost associated with this process is still very high when used for the Gauteng AMD problem; however, with the development of technology, this could be reduced when using cheaper raw materials.

TUT-CSIR MAGNESIUM-BARIUM-ALKALI

The research team at Tshwane University of Technology (TUT) estimates that the capital cost for pumping water in three basins to the recommended environmental critical levels of 150 meters for the Western Basin, 200 meters for the Central Basin and 400 meters for the Eastern Basin, will amount to R211.4 million per annum[8]. The associated alkali cost for Western Basin water, using the Sequence Batch Reactor (SBR) method (limestone is used for the removal of free acid and iron (II) and lime solely for the removal of heavy metals) amounts to R25.5 million per annum (R2.80/m^3), compared to R53.2 million per annum (R5.83/m^3) when lime is employed for both stages. The corresponding figures for both the Western Basin and Central Basin together amount to R60.3 million per annum for the SBR process, compared to R136.9 million per annum when using lime for both stages.

The alkali cost for treatment of 85 Ml/d acid mine water from both the Western Basin and Central Basin would amount to R60 million per annum in the case of limestone/lime treatment, compared to R136.9 million per annum if only lime were used. Secondly, the capital cost for the SBR system amounts to R3.5 million/(Ml/day). Limestone is the prime choice for acid water neutralisation, due to its widespread availability, non-proprietary nature, ease of application and cost effectiveness.

Capital cost and operational cost must be considered in water treatment, and therefore one of the operational costs that needs to be managed is electricity cost. While cost and ease of implementation may play major roles, a key driver that influences the selection and viability of a particular technology is the chemistry and volume of the acid water.

DESEI

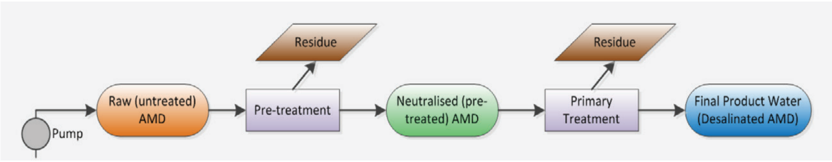
In a study done by Marinda de Beer[9] of a two-stage DesEl treatment process, it was shown that: sulphate concentration was lowered from 4434 mg/l to 100 mg/l; magnesium from 539 mg/l to 12 mg/l; calcium from 375 mg/l to

9 mg/l; manganese from 53.7 mg/l to 1.3 mg/l; and chloride from 77 mg/l to 2 mg/l. The energy cost was R1.21/m^3 of feed treated and R1.53/m^3 of pure water produced during the first stage. For the second stage, the cost amounted to R0.30/m^3 of feed treated and R0.32/m^3 of pure water produced.

COST FOR TREATMENT OF RESIDUE GENERATED FROM THE TREATMENT OF AMD

High costs are associated with the treatment of AMD, including residue treatment. This process is presented in Figure 11.2.

Figure 11.2: Treatment process of AMD



Source: [10]

The estimated cost of disposal of AMD in the Western, Eastern and Central Basins over a 50-year period is shown in Table 11.4 below. The estimated costs indicate that, over 50 years, about R3 billion will be required to build and maintain disposal sites for the residue products. As a result, it may be preferable to develop alternative technologies that require less AMD residue disposal. To this end, some stakeholders have suggested that commercial ventures be established to offset the high residue treatment costs.

Table 11.4: Summary costs for the disposal of sludge in the Western, Eastern and Central Basins[11]

Site	Capital cost (Year 0) (R million)	Operating cost over 50 years (R million)	Closure cost (Year 50) (R million)	Total cost (R million)
Western Basin	282	530	65	877
Eastern Basin	278	700	71	1049
Central Basin	398	650	67	1115

The estimated costs of AMD residue disposal show the extent of investment required. If other industries, such as the chemical and metal industries, could process the residue, then new activities or cheaper sources of metals and chemicals could gradually be introduced as inputs for existing or new enterprises. We will discuss this further under the section titled 'Extracting benefits from AMD'. In the next section we look at who has been funding AMD treatment in South Africa to date.

SOUTH AFRICAN GOVERNMENT DEPARTMENTS FUNDING AMD TREATMENT

To date, the bulk of funding for dealing with AMD treatment has come from government and research grants. Table 11.5 shows that the South African government (through the Department of Water Affairs, the Department of Mineral Resources and the Department of Trade and Industry) has contributed about R653 million. Some of these funds have been disbursed through government bodies and to academic sectors through the National Research Foundation.

Table 11.5: Government department allocating funds to treat and manage AMD in South Africa[12]

Government Department	Allocated Amount	Purpose
Department of Water Affairs	R225 million	R220 million to fund a short-term solution and R5 million to develop a long-term strategy to deal with acid mine drainage and to develop a funding model.
Department of Mineral Resources (DMR)	R328 million	Combat AMD (includes R200 million transfer to Council for Geoscience and Mineral Technology- Mintek).
Department of Trade and Industry (The dti)	R100 million from government and the private sector	AMD projects funded for several years through partnership between the National Research Foundation and the academic sector.

Mintek, South Africa's national mineral resource organisation, is working on new technology that could allow mining operators to process the hazardous components extracted from AMD into usable materials. In addition, a number of government entities are mandated to drive various aspects of dealing with the AMD challenge. Areas that will be addressed as highlighted in the Inter-Ministerial Report on AMD include:

- Environmental impact assessment;

- Identification of required infrastructure;
- Treatment plant maintenance costs; and
- Monitoring costs associated with treatment technologies.

Prior to the approval of the Inter-Ministerial Report, a number of projects had been funded by various government departments through their agencies. Consequently, the success of these efforts could not be consolidated because the interventions were characterised by poor coordination and a lack of cooperation between the implementing institutions.

In order to solve the uncoordinated approach of earlier interventions, a number of government entities are currently involved in funding and finding solutions to the AMD challenge, as shown in Table 11.6.

Table 11.6: The role of government entities involved in AMD funding and technology solutions[13]

Department/Organisation	Role in AMD
Development Bank of South Africa (DBSA)	Infrastructure funding
Independent Development Cooperation (IDC)	Infrastructure funding
Mintek	Development of technology
Council for Geoscience	Development of technology
Council for Industrial and Scientific Research (CSIR)	Development of technology

The D BSA and IDC are responsible for infrastructure development, whereas Mintek, the Council for Geoscience and the CSIR drive technology identification, development or acquisition and adaptation and improvement of the specific geochemical characteristics of the problem in South Africa. Given the techno-centric nature of project managers at the DBSA and IDC, it is envisaged that risk identification, amelioration and management will be enhanced as they deal with the technology development government bodies.

WHAT ARE OTHER COUNTRIES DOING AND WHAT CAN SOUTH AFRICA LEARN?

South Africa does not need to re-invent the wheel, so to speak. It can learn from other countries that are battling the AMD challenge. The US, for example, compels companies to contribute funding for treating AMD to a State Special Fund – the AMD Abatement and Treatment Fund – that is used to fund operations and maintenance of the 38 current AMD treatment systems. This fund is also used to fund the salaries of state employees tasked with AMD remediation work and to match other federal grant funding for the construction of new AMD treatment projects. All deposits to the AMD Abatement and Treatment fund come from annual Abandoned Mine Reclamation grants.[14]

The situation in Australia is similar to that in the US. An additional operational cost of managing AMD at Australian mine sites of about 60 million US dollars per year is charged to the Australian mining industry. This cost is a small proportion of the industry's total annual cost, but a significant proportion of the amount is spent on the environment.[15]

In New Zealand, there is no remediation fund reserved specifically for AMD treatment. Efforts toward remediation are completely funded by the mining companies. Although New Zealand has a strong clean-green image overseas and a strong green movement, regulations for AMD treatment and prevention are not clear and it is reported that there is poor enforcement.[16]

AMD is of major concern to the Canadian mining industry. The Canadian Mine Environment Neutral Drainage programme was established in 1989 to deal with this challenge. Mines in Canada were required to establish trust funds to cover the cost of treatment of AMD from mine wastes. It is believed that there are many operational methods in Canada that can be improved upon to reduce costs without compromising treatment efficiency. These include detailed plant optimisation, which often improves both cost and performance simultaneously. Major cost saving opportunities are often found in the maintenance of treatment plants.[17]

Back to South Africa, although there is strict regulatory enforcement, only small contributions are realised from the private sector, as the owners of many abandoned mines cannot be traced. Consequently, the government has to provide funding for addressing the legacy environmental concerns. What South Africa can learn from the US, Australia and New Zealand are the policy and practice options to deal with contemporary and future AMD generations. It is within the South African government's powers to design and implement regulatory frameworks and roadmaps that ensure sustainable funding of treatment interventions that do not propagate the public risk and private profit chasm currently facing the country on legacy AMD issues.

Some of the interventions will entail looking at ways of extracting value from AMD – the subject of discussion in the next section.

EXTRACTING BENEFITS FROM AMD

AMD treated water can be used for agricultural, industrial and residential purposes. South Africa currently imports potable water from Lesotho, which is a drain on the fiscus. If 500 Ml/day of treated AMD pumped from the Witwatersrand gold mines was channelled to agricultural use, over R2 billion per annum could be realised. It is estimated that the roll-on impact for job creation in peripheral activities could be as high as 100 000 jobs.[18] Metals claimed after AMD treatment could be industrial raw material inputs into the iron and steel industry.[19] Gypsum, a by-product of AMD treatment, could also be an industrial input for construction work. New industries in the chemical sector could create markets that leverage metal oxides from the treatment process.

The desalination process, as shown in Table 11.7, could produce water for domestic and industrial use. The option with the lowest capital cost and the second lowest operating cost is desalination to the river, but this option does not generate any income from water sales and has the highest unit risk value (URV), and therefore it is not recommended. The three remaining options are desalination for either domestic or local industrial use or remote use by Rand Water for industrial water. However, the distance to the platinum mines – the likely recipients of the industrial water – makes this option significantly more expensive in terms of upfront capital and operating costs. If local industrial users could be identified, then the higher selling price would make this the best option. It is clear that Rand Water's preference for not using fully treated AMD water for domestic use could incur additional capital costs of R404 million and additional operating costs of R11 million per annum, if local industrial users cannot be found.

Table 11.7: Western Basin – Comparison of selected options[20]

Option[4]	Capital[1] Cost (R mil)	O&M[3] (R mil /a)	URV[2] (R/m^3)	Income (R Mil /a)	Income (R/m^3)
Desalination by RO to river	1 058	142	20	0	0
Desalination by RO for: • domestic use • industrial use	1 158	139	21	42 67	5 8
Desalination by RO for remote industrial use	1 562	150	34	67	8

Option[4]	Capital[1] Cost (R mil)	O&M[3] (R mil /a)	URV[2] (R/m^3)	Income (R Mil /a)	Income (R/m^3)
Tunnel abstraction with biological treatment to river	1 380	96	18	0	0

Notes:

1. Cost base date is March 2012.
2. URV discounted at March 2012 rates at eight per cent p.a.
3. Energy tariffs estimated at 10 per cent above inflation for three years to 2015.
4. TOL = 1 585 m amsl.

For the Central Basin, a comparison of options (as illustrated in Table 11.8) shows that the option with the lowest capital cost and operating cost is the discharge of desalinated water into the river, but because this option does not generate any income from water sales, it has the second highest URV. The option of supplying water for domestic use to the nearest Rand Water reservoir has a higher URV, but lower operating and capital costs, which are R686 million lower than if it were supplied for industrial use. However, if this water could be sold for industrial use at a similar distance from the treatment works, then the higher selling price makes this a preferred option. The two tunnel options have the highest capital and operating costs and offer no benefits, even after allowing for possible income from water sales.

Table 11.8: Central Basin – comparison of selected options[21]

Option[4]	Capital[1] Cost (R million)	O&M[3] (R mil/a)	URV[2] (R/m^3)	Income (R mil/a)	Income (R/m^3)
Desalination to river	1 103	267	16	0	0
Desalination for: • domestic use • local industrial use	1 299	278	19	 84 134	 5 8
Desalination to EB for remote industrial use[5] plus share of pipeline to Secunda	1 420 565	276 33	19 4	134	
TOTALS	1 985	309	23	134	8

Option[4]	Capital[1] Cost (R million)	O&M[3] (R mil/a)	URV[2] (R/m^3)	Income (R mil/a)	Income (R/m^3)
Tunnel with desalination to river	1859	229	20	0	
Tunnel with desalination for: • domestic use • local industrial use	2 013	278	21	84 134	 5 8
Multiple boreholes to remote industria	2152	310	24	134	8

Notes:

1. Cost base date of March 2012.
2. URV at March 2012 at three per cent discount rate.
3. Energy tariffs estimated at 10 per cent above inflation for three years to 2015.
4. TOL = 1 454 m amsl.
5. Excludes pro-rata cost of transferring the water from the Central Basin to the Eastern Basin, which is shown separately, but includes the full revenue from Central Basin water.

Table 11.9 shows options in the Eastern Basin for desalination to river water quality for industrial and domestic use. The option with the lowest capital cost and operating cost is again desalination to the river, but because this option brings in no revenue, it has the highest URV. If industrial users nearer to the basin could be found, then that option would have the lowest URV, unless the distribution infrastructure is very expensive. That option would be preferable. However, the selection of an option must also take into account options for the Central Basin, because of the benefits of scale. The option with the second lowest URV, after deducting the cost of the Central Basin's share of the cost of transporting the water to Secunda and taking the income from the sale of water into account, is the option of supplying industrial water to Secunda, despite this option having the highest capital cost.

Table 11.9: Eastern Basin – Comparison of selected options[22]

Option[4]	Capital Cost[1] (R million)	O&M[3] (R mil/a)	URV[2] (R/m[3])	Income (R mil/a)	Income (R/m[3])
Desalination to river	1 624	279	14	0	0
Desalination for: • domestic use • local industrial use	1 627	286	14	 146 234	 5 8
Desalination for industrial use (includes full pipeline to Secunda) less CB pro-rata share of pipe to Secunda	2 917 -565	314 -33	20 -4	234	8

Notes:

1. Cost Base date March 2012.
2. URV at March 2012 at 3 per cent discount rate.
3. Energy tariffs estimated at 10 per cent above inflation for 3 years to 2015.
4. TOL = 1 280 m amsl.

RETHINKING BUSINESS MODELS FOR AMD TREATMENT

The examples given above of benefits that can be obtained from AMD treatment demonstrate the potential of re-imagining business models that link what are currently outputs that are not integrated into potable, agricultural or industrial use. Although we did not discuss extensively the potential benefits from sludge as inputs into the chemical and metal industries demonstrating potential revenue streams, nevertheless that possibility exists. In essence, the key outputs are water for domestic, industrial or agricultural use, as well as metals and other compounds for the chemical and metal processing industries. In as much as mining companies are not competent at being water treatment companies, opportunities may exist for the mining companies or even communities that are currently over-burdened by the AMD environmental risks. Therefore, as part of corporate social responsibility, mining companies could consider the water business or alternatively retrofit water treatment plants that harness AMD-treated water for water tower cooling processes. New entrepreneurs that are community or privately owned could come up with demonstrated design business models that link up with AMD treatment products and by-products. There is still a lot of work that needs to go into re-imagining business models that can be deployed to sustainably solve the AMD challenge. As already demonstrated by the work done by the government through universities, there is a need for concerted government, industry and university cooperation: the triple helix approach. Deploying the triple helix model (government, industry and academia) to build, enhance and sustain the science, technology and innovation infrastructure is required to achieve the above. A case in point is the Korean example where government policy drove science and technology as well as industrialisation. South Africa has the resource endowments in terms of finance, people, technologies and industrial capabilities to design long-term sustainable solutions for AMD treatment. The potential to generate a linked industrial complex that solves environmental challenges is not outside South Africa's reach.

FINANCING MECHANISMS FOR EXISTING AND NEW BUSINESS MODELS

In 2009, the Auditor General estimated that the cost of cleaning up existing and abandoned mines was approximately R30 billion. Looking at the AMD challenge in South Africa, it is estimated that R9 billion to R10 billion would be enough to 'neutralise the water and also desalinate it'.[23] Other sources estimated that a temporary solution for the Witwatersrand Basin would cost in excess of R1.5 billion. Some experts estimate that the cost of rehabilitation and eventual remediation is going to be way more expensive than what was envisaged initially.[24] A contribution of R500 million was reported by the mining companies in the form of available infrastructure.

It is inevitable that the burden of solving AMD legacy issues (see Table 11.10), because of the public goods nature of water resources, may fall on government and, where possible, industry, through the use of 'endowment type funds'. However, with contemporary and future AMD issues, policy and practice framework and roadmaps may be designed that align private profit with risk and thus collectively working towards sustainable environmental health management.

Table 11.10: Suggested financing mechanisms for AMD treatment[25]

	Financing Source	Ideal Candidate	Determinant	Lending Technology/ Fund Type
Private profit/ public responsibility for risk management	Public resources: local, regional or federal	Legacy contamination	Owners of mines can no longer be traced	Grants and budgetary allocation and, where possible, mining endowment funds
Private profit/ public responsibility linked to profit ventures	DFI (Development Financial Institutions)	Contemporary or future AMD generation issues: communities, private enterprises, local, regional or national governments bodies (parastatals)	A viable business case for linking AMD treatment product and by-products as inputs for agriculture and chemical or metals industries. Sale of treated water for domestic, agricultural or industrial use.	Loans, equity, hybrid funding instruments
	Commercial banks			
	Investment banks/venture capital			

Where a business case can be demonstrated and business models crafted, the profit-driven motive can be pursued, which can initially attract public or development financial institutions as the primary risk underwriters for the uncertain period (the valley of death). As the industry clusters mature, commercial funding streams progressively engage with the enterprises. At that time of maturity, development financial institutions or the public venture funding agencies can exit their initial investments if they had invested via equity.

CONCLUSION

As discussed earlier, long-term and sustainable funding of AMD treatment will require multi-pronged public, private and public-private funding models. We showed that most of the AMD treatment technology is being used by universities on a small scale and therefore concerted effort is required for technology scale-up and commercialisation through reimagined business models, where possible. We argued that funding may remain a problem unless there is clear demarcation of responsibilities for legacy, contemporary and future AMD generation. Roping in financial institutions is dependent on building an industry surrounding AMD treatment with demonstrable business cases that leverage value addition either through agriculture or industrial activities. This, in turn, calls for policy crafting that considers sectoral linkages and leverages with South Africa's finance, skills and technological capabilities in agriculture and the chemical and metal industries. The triple helix mode of innovation is critical at this stage. Universities have been dominant, but it is time for industry and government to work together to solve the issue on a multi-level basis. We are not advocating a techno-fix solution as being the silver bullet. We are, however, arguing in favour of a multi-factoral approach that includes technology, policy, practice and behavioural change for entrepreneurs, communities, industrial associations and public bodies, which need to work together to design and improve funding solutions through learning by doing. However, commercial financial institutions can only solve that portion of the challenge that has a sustainable business model with the ability to repay loans. The challenge therefore remains regarding those processes that cannot be linked to profitable business activities. These unprofitable processes for legacy issues may only be solved through public funding. But for contemporary issues, government, industry and industry associations have a responsibility to protect the environment and do no harm as a precautionary principle to the livelihoods of communities from which they derive economic value.

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CHAPTER 12

Acid Mine Drainage Treatment Technologies

Sehliselo Ndlovu

ABSTRACT

This chapter is a compilation of the various chemical treatment technologies that have been developed to date in South Africa and elsewhere. The chapter demonstrates that South Africa is a leading light that has invested a lot in the research and remediation of AMD. Most of the technologies in use today have been developed in South Africa. Amongst others these include CSIR-ABC, SAVMIN, and CESR. The chapter discusses in detail the internationally acclaimed HDS. A detailed comparison of the technologies giving advantages and disadvantages of each is given. The chapter ends by recognizing that there is no one size fit all for treatment technologies and in that regard provides useful criteria which can be used to decide which technology to use in a given AMD remediation circumstance.

INTRODUCTION

The effect of acid mine drainage (AMD) can occur indefinitely and as such its impact is not only felt by the existing mining operations but also on the environment and associated communities long after mining has ended. The processes responsible for its formation are autocatalytic and once it occurs on a large scale, it cannot be stopped. Remedial methods are a level of control that focuses on collecting and treating the contaminated water.[1] The ultimate objective of AMD treatment is to remove suspended solids, neutralise free acidity and remove iron and other metals, such as sulphates, so that the resulting effluent can meet permissible environmental discharge levels.[2] Sulphate – the major contaminant in mine water – tends to react with other available metal ions, forming a wide range of salts that contribute significantly to salinity in the vicinity of discharge.[3] Treatment to lower the sulphate content, in order to meet the discharge regulations, is therefore another necessity. The remedial control systems involved in the treatment of AMD can be classified into two distinct categories: active and passive treatment systems.

PASSIVE TREATMENT SYSTEMS

Passive treatment systems rely on natural physical geochemical and biological processes, generally require more land space and can function without tight control to effect acid water detoxification.[4] Most of the passive systems used for treating acidic waters tend to utilise materials that would normally be classified as waste products. These include industrial – and agroprocessing related waste that, in most cases, can be locally sourced, thereby reducing transport costs.[5,6] The passive treatment systems use treatment methods such as constructed wetlands, diversion wells containing crushed limestone or open ditches filled with limestone and bioreactors.[7,8] These systems can provide a potentially long-term solution to the AMD problem. However, their success is highly dependent on the volumes, iron loadings and acidic values of the streams encountered.[9,10]

ACTIVE TREATMENT SYSTEMS

According to Jennings, active treatment systems are engineered treatment facilities that apply a chemical amendment approach to the treatment of AMD in order to achieve a specified water quality standard in a discharge permit.[11] The active treatment systems are frequently used at mining sites that are still in operation, whereas passive systems are generally applied after mine closure. This is because active mines often have limited space for remediation systems and have drainage chemistry and flow rates that can change as mining proceeds. These factors are easily addressed by active treatment methods rather than passive treatment methods.[12] However, passive treatment is more economic in terms of a long-term solution and, if there is available land and chemistry and flow rates are not expected to change, then passive treatments would be the best option.[13,14]

The commonly used active treatment procedures for the remediation of acidic mine water streams include most abiotic methods such as chemical precipitation, ion exchange (IX), solvent extraction, electrolytic techniques, membrane technologies and adsorption processes.[15] Active treatment is characterised by ongoing high intensity flow of chemicals into and out of a treatment plant that requires continuous monitoring and maintenance by trained personnel. These systems generally require the construction of a treatment plant that is equipped with a variety of systems, such as agitated reactors, precipitators, clarifiers and thickeners, extraction columns, etc.

Active treatment processes have garnered a lot of interest, mostly due to their simplicity and ease of implementation. In addition, the precision in terms of process control makes them easy to engineer and operate to produce specific water chemistry.[16] The processes remove metals and sulphate to comply with regulations, produce clean water, meet strict criteria for reuse or safe discharge, recover value-added by-products from wastewater and deliver savings in both capital and operating costs.[17] These processes work either through metal precipitation via chemical dosing, precipitation of sulphates as insoluble salts or a reduced sulphide solid or separation of salts through a membrane and through water evaporation and brine saturation.[18]

This chapter looks at the developed and emerging active treatment technologies used in the remediation of AMD. This will cover technologies such as chemical precipitation, IX and membrane processes. The chapter includes a discussion on adsorption and electrochemical processes. Bioremediation technologies involved in AMD treatment are discussed in a subsequent chapter.

CHEMICAL PRECIPITATION

The chemical precipitation processes that include hydroxide and sulphide precipitation are the most commonly applied processes in industry, because of their simplicity and cost effectiveness of operation.[19,20,21,22] The fundamental chemical principles involved in the precipitation processes involve the conversion of ionic metal to an insoluble form through a chemical reaction between the soluble metal compounds and a precipitating reagent. The processes use the concept of pH control and, most often, an alkaline reagent is used to raise the solution pH so as to lower the solubility of the metallic components. Solubility is defined as the number of moles (or milligrams) of solid (precipitate) that will dissolve in a litre of solution (moles/l, mg/l, or g/l). This is an important concept, as it gives an indication of the residual concentration of soluble metal in the treated effluent after precipitation.

A solution that contains the maximum amount of a dissolved solute is said to be saturated. What is decisive for the precipitation of a compound from an aqueous solution is its solubility product constant typically denoted as K_{sp}. This is the product of the ion activities of the compound in a saturated solution and is a measure of the extent to which a compound will dissolve in water. Very small values of K_{sp} suggest that the compound is insoluble in water. Precipitation alters the ionic equilibrium of a metallic compound to produce a relatively insoluble precipitate. In other words, it induces supersaturated conditions, i.e. the solubility- product constant is exceeded. Thus, compounds of lower solubility have a higher probability of precipitating from a solution.

The general solubility expression for a solid precipitate, M_mP_n (s) can be written as:

$$MmPn = mM^{z+} + nP^{y-}$$

Where:

$$K_{sp} = [M^{z+}]^m[P^{y-}]^n$$

and [*M*] and [*P*] are in moles per litre.

K_{sp} represents the maximum value that the product of the molar concentrations of ions can have at equilibrium conditions for a given temperature.

Table 12.1: Solubility product values for some metal hydroxides and sulphides at 25°C[23]

Metal hydroxide	Hydroxides	Sulphides
Cadmium(Cd^{2+})	$4.47x10^{-15}$	$1.58x10^{-26}$
Chromium(Cr^{3+})	$1.58\ x10^{-30}$	*
Cobalt(Co^{2+})	$1.26\ x10^{-15}$	$5.01x10^{-22}$
Copper(Cu^{2+})	$4.79x10^{-20}$	$7.94x10^{-37}$
Iron(Fe^{2+})	$7.94\ x10^{-16}$	$7.94x10^{-19}$
Lead(Pb^{2+})	$1.2x10^{-15}$	$3.16x10^{-28}$
Manganese(Mn^{2+})	$1.58x10^{-13}$	$3.16x10^{-11}$
Mecury(Hg^{2+})	$3.9\ x10^{-4}$	$2.0x10^{-53}$

Nickel(Ni^{2+})	6.31 $x10^{-16}$	$3.98x10^{-20}$
Silver(Ag^{2+})	$1.95x10^{-8}$	$7.94x10^{-51}$
Zinc (Zn^{2+})	3.47 $x10^{-17}$	$2.00x10^{-25}$

Table 12.1 shows the solubility of selected metal hydroxides and sulphides at 25°C. It is important to note that, like all equilibrium constants, the Ksp is temperature dependent, as it increases with increasing solution temperature, but at a given temperature it remains relatively constant.

Supersaturated conditions must be present for precipitation to take place. A supersaturated solution contains more undissolved solute than the saturated solution and in a supersaturated solution the product of the molar concentrations of the ions is greater than the solubility-product constant. This can be shown as:

$$[M^{z+}]^m[P^{y-}]^n > K_{sp}$$

Under these conditions, precipitation will take place.

In industrial practice the observed removal efficiencies of metal ions from a solution will often differ considerably from calculated theoretical solubility figures. Incomplete reactions, poor separation of colloidal precipitates and the formation of soluble metal-complexes tend to give higher actual solubility figures compared to expected theoretical solubility figures. On the other hand, co-precipitation in some cases can also give rise to lower solubility values than those expected based on theoretical calculations.

The precipitates formed can be separated from the water by sedimentation or filtration and the resulting treated water then appropriately discharged or reused. The unit operations typically required in this technology includes neutralisation, precipitation, coagulation/flocculation, solids/liquid separation and dewatering. Factors such as the type and concentration of ionic metals present in solution, the reagents used for precipitation, the reaction conditions and environment and the presence of other constituents that may inhibit the precipitation reactions, have a huge influence on the effectiveness of the precipitation process.

Since AMD contains multiple combinations of acidity and metal ions, each AMD is unique to a site and, as such, the treatment processes applied tend to vary widely from site to site. The types and amount of metals in the water, therefore, play a significant role in the selection of the treatment system. The resulting metal precipitates generated during the treatment processes are identified as waste/sludge. This sludge must be disposed of in an environmentally acceptable manner. For most treatment operations, sludge disposal costs can be quite high and, in order to reduce the costs, most advanced processes minimise the sludge volumes by creating higher-density sludge. The long term sludge disposal and reagents costs usually justify a more significant and informed decision in the capital investment in order to minimise overall operating costs.

HYDROXIDE PRECIPITATION OR NEUTRALISATION

Hydroxide precipitation or neutralisation is the most commonly used chemical precipitation technique, due to its simplicity, low cost and ease of pH control.[24] Hydroxide precipitation also continues to be the number one process of choice when it comes to acid mine water remediation, because of its proven ability to achieve regulatory effluent limits to several metals. These processes can remove heavy metals, non-metal pollutants (such as soaps) and fluorides. However, enough alkaline reagents must be added to raise the solution pH and supply hydroxide (OH^-) ions so that the dissolved metals can form insoluble metal hydroxide precipitate. The conceptual mechanism of metal removal by chemical hydroxide precipitation is represented as:

$$M^{2+}(aq) + 2OH^-(aq) = M(OH)_2(s) \qquad (1)$$

Where: M^{2+} and OH^- represent the dissolved metal ions and the precipitant, respectively; $M(OH)_2$ is the insoluble metal hydroxide generated.

Although widely used, hydroxide precipitation processes have some limitations. One of the limitations of these processes is that the removal efficiency of different mixed metals cannot be achieved at a single precipitation pH level.[25] This is due to the solubility of metal hydroxides being strongly pH dependent and with the pH of the lowest metal solubility being different for the various heavy metals. As effluent metal discharge limits to the environment become stricter, it is becoming much more difficult for a simple lime plant as applied in the past to meet these regulations. Some metal hydroxides also tend to be amphoteric in nature,[26] indicating that the sludge products generated can also resolubilise under acidic conditions that led to the initial generation of AMD. Another drawback of the precipitation method is that the metal concentration of treated water cannot be reduced below the solubility of the precipitate.[27] For this reason, acid mine water has to be treated in multiple stages, which might not be cost effective.

Hydroxide precipitation generates large volumes of low density sludge, which can cause filtration- and disposal problems.[28] In addition, the presence of complexing agents in the wastewater tends to increase the metal solubility by forming stable complexes with metals under consideration. Whilst some weak complexing agents (such as citrate and tartrate) may not interfere with the hydroxide precipitation process, most ligands (especially chelating ligands) modify the precipitation process to yield unacceptable levels of metal effluent concentrations.[29,30] Thus, to achieve a more effective precipitation process, the complexing agents that could keep metal ions in solution must be destroyed prior to metal precipitating as hydroxides.

REAGENTS USED IN NEUTRALISATION PROCESS TECHNOLOGIES

A variety of basic reagents have been used to precipitate metals from acid mine water, with their use dictated by availability, cost and performance. The key considerations in selecting the appropriate reagent for neutralisation include:[31]

- materials handling;
- hazardous nature, if any, of the material and its impact on personnel safety;
- availability and reliability of supply;
- infrastructure and equipment investment costs of reagent handling, storage make up and dosing facilities; and
- cost of reagent and treatment objectives.

The most widely applied reagents include limestone ($CaCO_3$), lime (CaO), hydrated lime $Ca(OH)_2$, Magnesia (MgO, $Mg(OH_2)$), caustic soda ($NaOH$) and other reagents, such as soda ash and ammonia, acid consuming mill tailings and slags.

LIME

CaO, also known as quicklime, pebble lime, slaked lime or burnt lime, has been widely used for the treatment of industrial waste streams.[31] Lime is usually the preferred chemical in hydroxide precipitation at industrial settings, due to ease of handling and the low cost.[32] This reagent is often applied in the hydrated and slurried form for best efficiency. Hydrated lime ($Ca(OH)_2$) is very useful and cost effective in large flow, high acidity situations. In this case, a lime treatment plant with an aerator is constructed to help dispense and mix the chemicals with the water.[33] pH values in the range 6 to 12.4 can be obtained when lime is used as the neutralising agent. The main advantage of this reagent is the short reaction period, due to the high solubility nature of lime and the ease of pumping. The major disadvantage associated with the lime dosing process is the large volume of sludge – typically composed of $CaSO_4$ – which is generated.

LIMESTONE

Limestone or calcium carbonate ($CaCO_3$) is another well-established reagent that has been used for decades to provide an alternative means of neutralising the acidic water and precipitating metals in AMD. The main advantages of this reagent over lime are: it is inexpensive and it produces a smaller volume of sludge that must be disposed of.[34,35] Among the chemicals used for AMD treatment, limestone is known to have the lowest material cost and is the safest and easiest to handle. Unfortunately, its successful application has been limited due to its slow reactivity, low solubility and mild neutralising ability, i.e. pH above neutrality cannot be achieved (due to the production of H_2CO_3).[36] A second limitation is that the gypsum and ferric hydroxide precipitates tend to cover the limestone, thus further lowering its neutralising efficiency and increasing consumption and the process cost as a result.[37] Therefore, limestone tends to be used as a pretreatment step at the low pH ranges.

CAUSTIC SODA

Caustic soda is often used in remote locations, in low flow, high acidity situations and when the manganese concentrations in the AMD are high.[38] Caustic soda is highly soluble in water, disperses rapidly and raises the pH of the water quickly.[39] It is easy to store and deliver (as a solution), thus reducing capital costs. In addition, no significant sludge is produced during neutralisation with NaOH. However, NaOH is more expensive than other chemicals applied in the treatment of AMD. In addition, since NaOH is a strong base and does not have any buffering capacity, fine pH control is difficult to achieve and over-neutralisation to pH 13 is possible.[40]

MAGNESIA

Magnesia, which occurs as either the dry MgO or a slurry of $Mg(OH)_2$, can be used as a possible alternative to lime and caustic soda for hydroxide precipitation. It has the advantage that it produces a dense precipitate containing only the metal hydroxide.[41] Thus, the sludge volumes are smaller than those produced when using lime and caustic soda. Magnesium hydroxide also tends to be non-hazardous and non-corrosive when used properly, which makes handling safer and easier. Besides its ease of handling, additional benefits are its buffering ability, which provides the added benefit of excellent pH control. However, it is a costly reagent and the resulting effluent must be further treated with lime to remove sulphate as gypsum before discharge.[42]

OTHER NEUTRALISING AGENTS

Some of the neutralising agents that have been tried and tested in the recent past include slags, fly ash, soda ash and ammonia. Soda ash (sodium carbonate) is generally used to treat AMD in remote areas with low flow and low acidity and metals. It is less reactive and more expensive than other treatments and, as a result, the selection of soda ash for treating AMD is usually based on convenience, rather than chemical cost. However, it provides some buffering action, although carbon dioxide evolution can create some foaming problems.[43]

Ammonia, another neutralising agent, is extremely soluble and reacts rapidly in the gaseous state thus reducing residence time.[44] It behaves as a strong base and can easily raise the pH of receiving water to 9.2. At pH 9.2 it buffers the solution to further pH increases and therefore very high amounts of ammonia must be added to elevate the pH beyond 9.2.[45] It therefore works very well and is most cost effective for precipitation below this pH value. However, the disadvantage is the hazards associated with handling the chemical.[46] In addition, the nitrogen introduced into the water could make the system undesirable.

Various metallurgical slags are generated in metal extraction, refining and alloying processes and steel slags in particular have been shown to have potential for utilisation in AMD treatment. The use of slag for the treatment of AMD has been studied and described by various authors.[47,48,49] The key constituent in the slags is the various oxide phases that provide the neutralising effect for the acid component of AMD. The advantage of slag is the cost effectiveness associated with the raw material since slags are a waste material from another industry. Utilisation of slag not only helps in AMD neutralisation, but also reduces the disposal cost for slag producing companies. The application of the slag as a neutralising agent therefore, minimises not only the impact of AMD, but also that of the slag on the environment.

PROCESSES USING NEUTRALISATION

Traditionally, acid mine water has been treated by applying the neutralisation process with the aid of lime or, more recently, limestone or limestone and lime together, resulting in the precipitation of metal hydroxides. The lime neutralisation process generally involves a number of steps, such as:[50]

- Neutralisation of the AMD solution with lime.
- Oxidation of ferrous iron under alkaline conditions by aeration, followed by precipitation of ferric iron and base metals at pH 9 to 10. Ferric hydroxides are more stable in acidic water and for this reason aeration is often applied to oxidise the iron to the more stable form, as per the following equation:

  $$Fe(OH)_2 + \tfrac{1}{2}H_2O + \tfrac{1}{4}O_2 = Fe(OH)_3 \qquad (2)$$

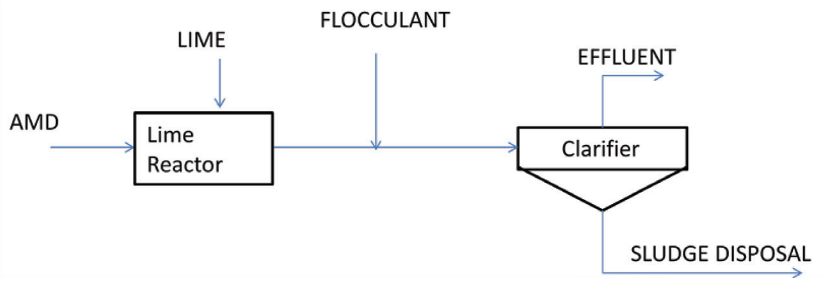
  Ferrous hydroxides also do not settle as well as ferric and can create a highly viscous sludge. It is, however, still possible to operate a successful treatment plant without aeration or even complete oxidation of iron.[51]
- Clarification following coagulant/flocculation addition. In this regard, the design of the settling unit plays a very important role, as it impacts greatly on the overall process throughput.

The following section gives a brief description of some of the neutralisation processes that have been developed for the treatment of acid mine drainage.

THE CONVENTIONAL NEUTRALISATION OR LOW DENSITY SLUDGE (LDS) PROCESS

The LDS process involves contacting the AMD in a mixing tank with a controlled addition of lime, in order to achieve a required pH. A typical flow sheet for the neutralisation plant is shown in Figure 12.1. A flocculant is added to the mixed slurry that is fed in at the solid/liquid separation step. In most processes, a clarifier is used for solid/liquid separation, although a settling pond is also commonly used. The clarifier produces an effluent ready for discharge into the environment and a sludge that can either be pumped to a storage area or pressure-filtered to increase its density before disposal. Part of the liquid effluent is recycled for reagent make up. This process generates a low density sludge, typically containing two to five per cent solids.[52,53,54] A low sludge density requires significant pumping and storage, particularly if the metal concentrations in the AMD are high. This process has not been used much in the recent past, as the introduction of a small additional step through the sludge recycle as described in the HDS creates significant advantages such as an increase in sludge density.

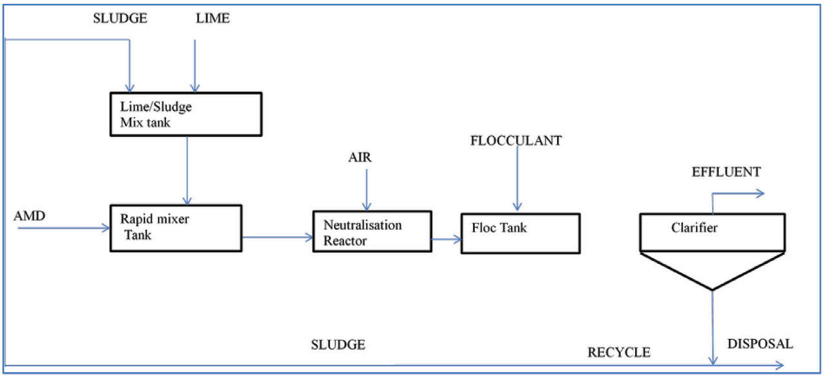
Figure 12.1: The conventional LDS process[55]



THE HIGH DENSITY SLUDGE (HDS) PROCESS

The HDS process is a modification of the low density treatment method and acts to substantially reduce the sludge volume by greatly increasing its density. It is now a standard in AMD treatment. A typical flow sheet of the HDS process is shown in Figure 12.2.

Figure 12.2: The conventional LDS process[56]



Instead of mixing lime directly with the AMD stream, this system contacts recycled sludge from a clarifier/thickener unit with sufficient lime to neutralise the AMD to the required pH level.[57] This is done in a lime/sludge mix tank. The mixture overflows to the rapid mix tank where the lime slurry is then contacted with the AMD stream. The neutralised slurry feeds into the lime reactor where the precipitation reactions are completed. Air is also added here, to help oxidise ferrous iron to ferric. The discharge from the lime reactor is then treated with flocculant in the flocculation tank to agglomerate all precipitates and promote settling in the clarifier.[58] The clarifier separates the treated effluent from the sludge, a portion of which is recycled to the sludge lime reactor. A portion of the thickener overflow can be used for reagent make-up. The remainder is discharged to the environment. The HDS process has a number of advantages over the basic lime precipitation systems, such as a substantial reduction in sludge volume, resulting from an increase in sludge density (an increase from two per cent to 30 per cent solids reduces the volume of sludge by over 95 per cent).[59,60] This leads to a reduction in sludge disposal cost. There is also an increase in sludge stability, both chemically and physically, and a high quality effluent is produced. The HDS process has been widely used on a commercial scale, albeit with a few modifications made to the original concept, in order to suit the different needs of different plants. Table 2.2 shows some of the plants that have been applied in the HDS process with some variations.[61]

Table 12.2: Differences in the commercial application of the HDS process[62]

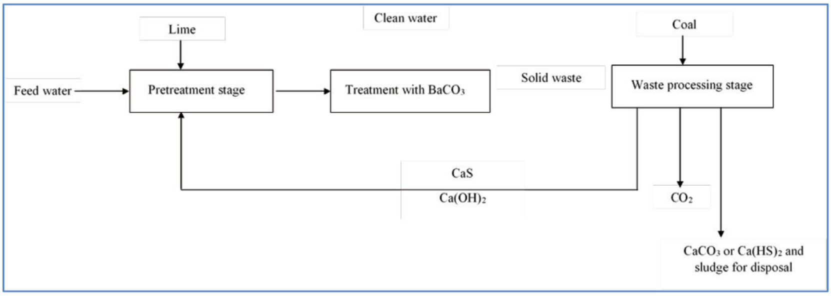
	Conventional HDS	Cominco Process	Geco Process	Tetra Process
ARD feed	Mix tank	Mix tank	Sludge conditioning tank	Sludge conditioning tank
Sludge recycle point	Sludge conditioning tank	Separate sludge/lime mix tank	Sludge conditioning tank	Sludge conditioning tank and separate sludge/lime mix tank
Lime slurry feed point	Sludge conditioning tank	Separate sludge/lime mix tank	Rapid mix tank	Separate sludge/lime mix tank
Aeration air injection	Neutralization reactor	Neutralization reactor	Neutralization reactor	Neutralization reactor
Polymer addition unit	Upstream of thickener	Upstream of thickener	Upstream of thickener	Upstream of thickener
Solid separation device	Gravity thickener	Gravity thickener	Gravity thickener	Gravity thickener

THE CSIR ALKALI-BARIUM-CALCIUM (ABC) PROCESS

The CSIR's ABC water treatment process is designed to achieve neutralisation as well as metal and sulphate removal from AMD by the optimal use of available and affordable chemicals. The process involves the use of barium carbonate to precipitate dissolved sulphate from mine water and comprises of three stages that involve pretreatment, followed by treatment with barium carbonate and then the waste processing stage. The process flow chart is shown in Figure 12.3.[63,64]

The feed water is initially treated with lime and CaS to remove any free acid and metals and to lower the sulphate content.[65,66] In the water treatment stage, barium carbonate is added to the solution to generate clean water and chemical sludge – the two end products. The water treatment stage is integrated with a sludge processing stage to recover the alkali, barium and calcium from the sludge through reduction in a coal-fired kiln. Good quality water, containing less than 100mg/l of sulphate, is obtained in a cost effective way, through the recovery of by-products.[67] The major limitation of this technology is the amount of sludge produced, which is expensive to dispose and the high capital and operating costs associated with thermal reduction of waste to produce CaS, gypsum and other solids for disposal.

Figure 12.3: Process flow diagram for the CSIR-ABC process[68]

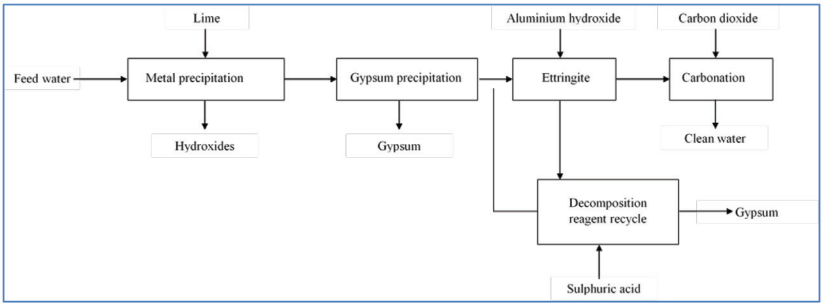


THE SAVMIN PROCESS

Wastewater from mining and mineral processing tends to contain high concentrations of sulphate. Calcium sulphate hydrates to become gypsum and has a solubility of approximately 2000 mg/l as sulphate. Sulphate reduction below 2000 mg/l has been possible in the past only through costly technologies such as reverse osmosis (RO) or IX. These processes also tend to generate large volumes of liquid waste, which typically create additional treatment and disposal costs. Sulphate removal through the precipitation of ettringite has been proposed by Smith[69] as the SAVMIN process. The SAVMIN process, developed by Mintek, is based on the selective precipitation of insoluble complexes at different stages during the process. It also involves recycling some of the reagents used in the process. Figure 12.4 shows the basic flowsheet of the SAVMIN process.[70] The main sequential treatment steps involved are: [71,72]

- Neutralisation, metals removal and gypsum crystallisation;
- Selective sulphate removal by ettringite precipitation; and
- Softening and pH adjustment by re-carbonation.

Figure 12.4: The SAVMIN process flow diagram[73]



In the neutralisation stage, lime is added to the solution to raise the pH to approximately 12. The dissolved metals and magnesium are precipitated and removed as hydroxides. After removal of the metal hydroxides, the water is seeded with gypsum crystals to catalyse the precipitation of gypsum from the supersaturated solution. In the third stage, aluminum hydroxide is added to remove dissolved calcium from the solution by the precipitation of ettringite (a calcium-aluminium sulphate mineral), as shown in Equation (3) below.

$$6Ca^{2+} + 3SO_4^{2-} + 2Al(OH)_3 + 38H_2O = Ca_6Al_2(SO_4)_3(OH)_{12} \bullet 26H_2O + 6H_3O^+ \quad (3)$$

The ettringite slurry is decomposed with sulphuric acid to regenerate aluminium hydroxide for reuse in the third stage.

$$3CaO \bullet 3CaSO_4 \bullet Al_2O_3 \bullet 3H_2O(s) + 6H_3O^+ = 6Ca^{2+} + 3SO_4^{2-} + 2Al(OH)_3(s) + 37H_2O \quad (4)$$

In the fourth stage, the wastewater stream is treated with carbon dioxide, resulting in calcite precipitation that can be removed through filtration.

The final products of the SAVMIN process are potable water and a number of potentially saleable by-products, such as metal rich gypsum sludge, relatively pure gypsum sludge and calcium carbonate sludge. The major advantage of the SAVMIN process is that high quality products can be obtained.[74] However, the major disadvantage is that a significantly large amount of the sludge is produced, which is expensive to dispose.

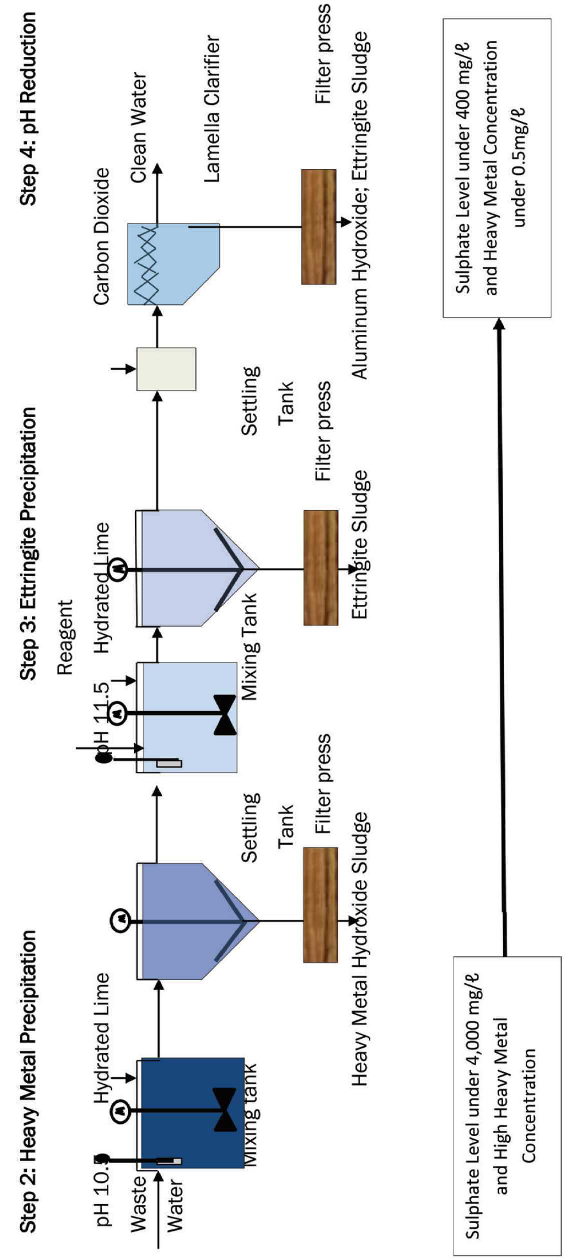
THE COST EFFECTIVE SULPHATE REMOVAL (CESR) PROCESS

The CESR process was developed to address the shortcomings of other technologies used for sulphate removal. The process, originally developed as the Walhalla process in Europe in the 1990s is an extension of the lime treatment process. This process provides better sulphate removal efficiency, reducing the sulphate concentration in most wastewater to less than 100 mg/l.[75] The process is similar to the SAVMIN process, the primary distinction being the reagent used in the removal of sulphate from the solution. Whereas the SAVMIN process uses aluminium oxide (aluminium trihydroxide in amorphous or gibbsite form) to remove the sulphate as ettringite, with recovery, the CESR process uses a proprietary Al-containing chemical obtained from cement production, without recovery of the aluminium source. A flowsheet of the process is given in Figure 12.5.[76]

The CESR process essentially consists of four steps, i.e.:[77,78]

- Initial precipitation of sulfate as gypsum;
- Precipitation of metals as hydroxides in a gypsum matrix;
- Additional sulfate removal via ettringite precipitation; and
- pH reduction using re-carbonation.

Figure 12.5: The CESR process flow diagram[79]



Addition of the CESR reagent to lime-treated water precipitates sulphate as a nearly insoluble calcium-alumina-sulphate compound, termed ettringite. Ettringite formation can also provide a polishing effect, allowing precipitation of metals such as chromium, arsenic, selenium and cadmium, which tend to be difficult to remove. Metals and other constituents that the ettringite removes are typically not leachable, allowing them to be disposed of easily as non-hazardous waste. The CESR process uses a sequential design to separate any metal hydroxide sludge from the other precipitates. Water treated using the CESR process typically meets or exceeds recommended drinking water standards for sulphate, metals and other parameters. The advantages of the CESR process include: low concentrations of sulfate in treated water, additional removal of metals and other parameters, no liquid waste generated and minimal volume of hazardous solid waste.[80]

THE MBA PROCESS

Bologo et al.[81] developed a process that uses a magnesium and barium-hydroxide (MBA) process for the treatment of mine water. In the process, magnesium hydroxide ($Mg(OH)_2$) is used for the neutralisation and removal of metals, while barium hydroxide (Ba(OH)2) is used for the removal of sulphate in the water, as well as magnesium ions (Mg^{2+}) that were added as $Mg(OH)_2$.[82] Ferrous iron is first oxidised to the ferric form before it is precipitated. Alternatively, ammonium hydroxide can be used for neutralisation and metal removal in place of magnesium hydroxide. One of the significant benefits of the process is the production of a lower sludge volume, when magnesium hydroxide is used for neutralisation, instead of calcium hydroxide. This is because of the high solubility of magnesium sulphate compared to calcium sulphate.[83] Another benefit is that the mixed product of barium sulphate and magnesium hydroxide can be separated with carbon dioxide.

THE SBR LIMESTONE/LIME PROCESS

Another process developed for neutralisation of AMD utilises both lime and limestone in a sequential batch reactor (SBR).[84,85] The plant design for the process includes stages such as SBR, clarifier, limestone handling and a dosing system.[86] Mine water sludge and limestone slurry are pumped into the SBR to allow for acid neutralisation, iron (II) oxidation and some gypsum crystallisation. Upon completion of iron oxidation, lime is added to precipitate metals and enable further crystallisation of gypsum.[84] SBR is a cost effective process, offering both: the neutralisation of free acid and providing conditions essential for the removal of iron (II), using limestone (the cheapest alkali), followed by lime treatment for removal of heavy metals, and partial sulphate removal (to levels lower than 2000mg/l) through gypsum crystallisation.[85] The SBR process was shown to be more cost effective than when lime is used for both stages.[87]

SULPHIDE PRECIPITATION

Metal sulphides are typically insoluble; therefore, metals can be precipitated and removed from solution by adding sulphide ions (S^{2-}):

$$M_mS_n = mM^{z+} + nS^{2-}$$

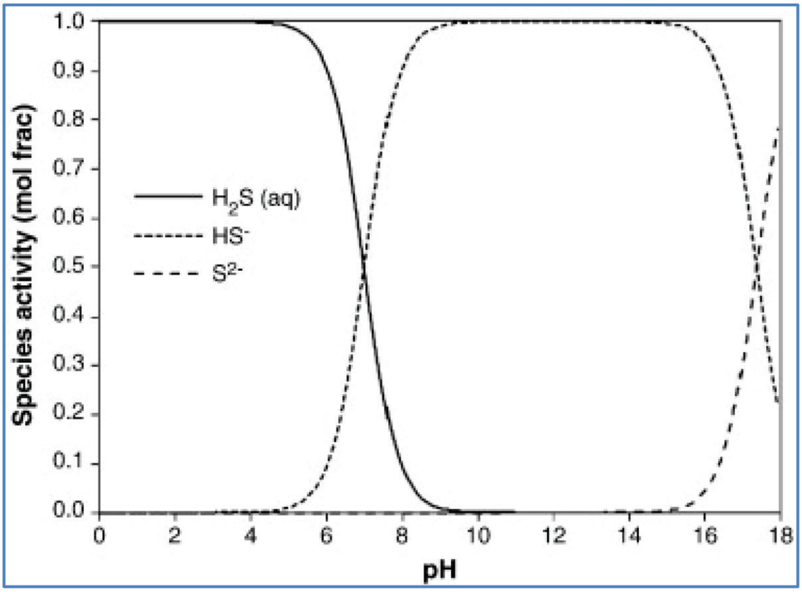
The quantity of metal ions remaining in solution at equilibrium mainly depends on the solubility product (K_{sp}) of the metal sulphide:

$$K_{sp} = [M^{z+}]^m[S^{2-}]^n$$

Sulphide precipitation has been demonstrated to be an effective alternative to hydroxide precipitation for removing various heavy metals from industrial wastewater.[88, 89] One of the major advantages of using sulphide is that the solubility of the metal sulphide precipitates is much lower than those of hydroxide precipitates. In addition, sulphide precipitates tend not to display the amphoteric behaviour commonly shown by metal hydroxides. As a result, the sulphide precipitation process can achieve a higher degree of metal removal over a wide pH range, when compared to metal removal by hydroxide precipitation. The metal sulphide sludge also exhibits better thickening and dewatering characteristics.[90] Lastly, unlike metal hydroxide precipitation, good metal removal is possible even with weak chelating reagents present and there is further potential for reuse of sulphide precipitates by smelting.[91]

However, sulphide precipitation is not as widely used as it could be, because the dosing of the sulphide is considered too difficult to control. This is due to the very low solubility of the metal sulphide and thus the sensitivity of the process to the dose.[92] In addition, the sulphide sludge generated is more prone to oxidation, resulting in resolubilisation of the metals as sulphates. The resulting sludge must therefore be stored carefully or recycled for metal recovery. The complexities of the system frequently result in higher capital and operating costs than cost involved in the simple lime treatment processes. In addition, there are potential dangers with the use of the sulphide precipitation process. As is known, heavy metals ionise often in acid conditions and sulphide precipitants result in the evolution of toxic H_2S fumes. Figure 12.6 shows the speciation of H_2S with changes in solution pH. H_2S is the dominant species under highly acidic conditions and the S^{2-} ion that plays a role in metal sulphide formation reactions only becomes dominant at very high pH (~14).

Figure 12.6: pH dependence of sulphide speciation[93]



Hence, by adding a sulphide salt, equilibrium is generated, resulting in only the partial formation of the S^{2-} ions actually used in precipitation. It is essential that this precipitation process be performed in a neutral or basic medium to promote the formation of the sulphide ion and to prevent the release of toxic H_2S gas. Since AMD solutions are highly acidic, neutralisation might need to be effected first, before sulphide precipitation can take place. This will ultimately have an impact on the total operational cost.

PRACTICE OF SULPHIDE PRECIPITATION

Sulphide processes are defined according to the means of introducing the sulphide ions into the wastewater: soluble sulphide precipitation (SSP); and insoluble sulphide process (ISP). In the SSP process, the sulphide is added in the form of a water-soluble sulphide reagent such as sodium sulphide (Na2S) or sodium hydrosulfide (NaHS). The addition of a sulphide reagent that is highly soluble in wastewater will yield a relatively high concentration of dissolved sulphide. This high concentration of dissolved sulphide causes rapid precipitation of the metals dissolved in the water as metal sulphides, leading to the formation of small particulate and colloidal particles that have poor settling and filterability characteristics. In addition, due to rapid process kinetics, the potential for excess sulphide dosage is high.[94]

The ISP, patented as the Sulfex Process,[95] has proven to be effective in separating heavy metals from waste streams, particularly those of plating processes. The process uses freshly prepared ferrous sulphide slurry (prepared on site from sodium sulphide and ferrous sulphate) as the source of the sulphide ions needed to precipitate the metals from the wastewater. The process operates on the principle that FeS will dissociate into ferrous ions and sulphide ions to the degree predicted by its solubility product: [96]

$$FeS = Fe^{2+} + S^{2-} \qquad (5)$$

$$M^{2+} + S^{2-} = MS \qquad (6)$$

The consumption of sulphide ions results in the additional dissociation of FeS, in order to maintain the equilibrium concentration of sulphide ions. In alkaline solutions, the ferrous ions will precipitate as ferrous hydroxides:

$$M(OH)_2 = M^{2+} + 2OH^- \qquad (7)$$

$$Fe^{2+} + 2OH^- = Fe(OH)_2 \qquad (8)$$

Because most heavy metals have sulphides that are less soluble than ferrous sulphide, they will precipitate as metal sulphides. An advantage of the ISP is the absence of any detectable hydrogen sulphide (H_2S) odour, a problem historically associated with SSP treatment systems. Because of the low solubility of FeS, using excess amounts will prevent the formation of toxic H_2S.[97] However, the use of an excess amount adds significantly to the operational cost involved. In addition, due to the addition of the ferrous ions into the waste stream, and their subsequent precipitation as ferrous hydroxide, a large volume of sludge is generated. Although the solubility of FeS is low, residual sulphide levels could be high.

Calcium sulphide is another reagent used for sulphide precipitation.[98, 99] The use of CaS has the advantage of minimising the formation of toxic H2S and excess reagent requirements – two problems associated with ISP and SSP processes. There is also the possibility of using the degeneration reaction of sodium thiosulphate ($Na_2S_2O_3$) as a source of sulphide for metal precipitation.[100]

In a different, but more recent approach, industrial effluents that contain high sulphate and metal concentrations have be treated using a combination of sulphate reducing bacteria to generate sulphide, followed by removal of the metals as metal sulphide precipitate.[101] Adams et al.[102] proposed a process that uses biogenic generation of hydrogen sulphide by reduction of elemental sulphur. The biogenic sulphide so generated is then used in an anaerobic-agitated contactor to selectively precipitate the metals in the solution as sulphides. The particular advantage of this technology is that it can be used for profitable operation in cases where the solutions are too low grade for solvent extraction-electrowinning.[103]

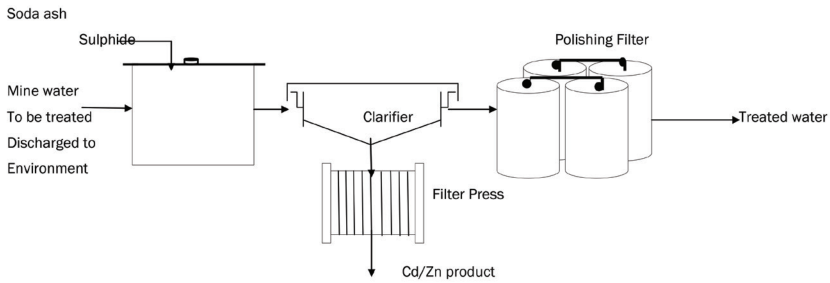
PROCESSES USING SULPHIDE PRECIPITATION

THE CHEMSULPHIDE™ PROCESS

The Wellington Oro Mine in the US (non-operational) has successfully applied sulphide precipitation to cost effectively remove dissolved metals from an acid mine solution stream, in order to meet strict effluent discharge targets for zinc and cadmium.[104, 105, 106] The plant uses a process developed by BioteQ Environmental Technologies of Vancouver, known as the ChemSulphide™ Process. This is a robust and efficient process technology for the treatment of mine impacted water. The process meets objectives that include compliance with stringent discharge limits and the reduction or elimination of waste sludge. The technology has been applied at multiple sites (Canada, the US, Australia and China) with different site conditions and requirements.

The process can also be integrated with lime neutralisation plants (HDS), as in the Dexing Copper Mine, for the recovery of valuable metals, control of iron and sulphate and the production of value-added construction materials from waste sludge. Figure 12.7 shows an overview of the sulphide treatment process used in the remediation of AMD at the Wellington Oro Mine to recover zinc and cadmium as metal sulphide.

Figure 12.7: Wellington Oro ChemSulphide™ process flow diagram[107]

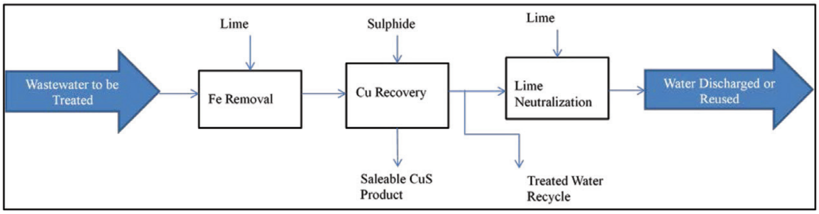


In this process, sodium hydrosulphide (NaHS) is used as the precipitating reagent for the removal of cadmium and zinc from contaminated wastewater.[108] The pH range for optimal sulfide precipitation is achieved by the addition of a small amount of soda ash. Dosing of NaHS is carefully controlled, so that zinc and cadmium are removed to discharge limits, and also to ensure that excess hydrogen sulfide gas is not created (nor too much iron precipitated).[109] The precipitated solids settle to the bottom of a clarification tank, while the treated water flows off the top.

The underflow solids from the clarifier are contained in a liquid sludge and are pumped to a plate and frame filter press for dewatering.[110] The precipitated metal sulphides can be sold to offset some of the process costs.

Dexing Copper Mine in China (operational) has successfully combined the conventional HDS lime neutralisation process with the ChemSulphide™ process to treat AMD and recover copper.[111, 112] The process flow sheet (Figure 12.8) consists of a ferric iron removal stage, followed by the recovery of copper. The ferric iron is removed to reduce the NaHS consumption associated with ferric to ferrous iron reduction. The Fe removal is performed by oxidation of ferrous iron to ferric using hydrogen peroxide, then by addition of limestone to raise the solution pH to 3.5.[113] At this pH level, most iron and some aluminum will precipitate as hydroxides and these solids are removed in a clarifier and sent to the HDS lime plant. The downstream HDS lime plant is used to remove zinc, aluminum and iron, prior to final discharge. The plant currently recovers only copper, but the operating conditions of the plant also remove arsenic and cadmium to ultra-low levels, which is deported to the copper concentrate – hence preventing them from being discharged into the environment. The treated water is reused on site.

Figure 12.8: Dexing ChemSulphide™ process[114]



THE ION EXCHANGE TECHNOLOGY

IX is a well-established process applied in the concentration and purification of solutions. More recently, IX processes have been developed and applied to reduce the metal and sulphate concentrations in wastewater. The process is a reversible chemical reaction, in which an ion in the solution is exchanged for a similarly charged ion attached to an immobile solid particle. The process takes place on the surface of the IX material, commonly called a resin, which is in contact with the solution. It is an adsorption phenomenon in which the mechanism of adsorption is electrostatic. Electrostatic forces hold ions to charged functional groups on the surface of the IX resin. The adsorbed ions replace ions that are on the resin surface on a 1:1 charge basis, i.e. stoichiometric action takes place.[115] The ions taken up from the solution have a greater preference than the ones existing on the resins and the existing ones are released into the solution as the preferred ones are taken up by the resin.[116]

During the IX process, the metal bearing solution is passed through a bed of solid organic resins in a particular form, wherein the adsorption of the metal ions on the resin takes place by IX reaction.[117] The most common type of contactor used in the IX process is the fixed bed column in which a static bed of resin is placed in a vertical column and the solution is pumped down through the bed. After adsorption, the resin is contacted with an eluant of suitable composition and volume. This results in the metal ions being released from the resin back into the solution. Purification and separation is achievable if the resin is selective or specific with respect to the metal ions of interest in comparison to the impurity ions present in solution.

They are two types of ion exchangers:

- Natural: protein, soil, lignin, coal, metal oxides and aluminosilicates (zeolites); and
- Synthetic zeolite gels and organic resins beads.

Synthetic organic resins are generally preferred, as they can be designed for specific applications and are thus effective in removing nearly all the heavy metals from the solution.[118] IX resins consist of two principal parts, a porous polymeric organic network (polystyrene-divinyl benzene copolymers) and an ionised functional group with specific IX capability placed inside the pores of the polymer backbone. The resins perform the extraction process by means of IX and coordination through attached functional groups. The resins are classifed according to their functional groups, which are formulated to provide the desired exchange and physicochemical properties.[119] There are two classes, namely cationic exchangers that exchange positively charged ions (cations) and anionic exchangers that exchange negatively charged ions (anions). The most common functional groups used in the resin IX beads include amines, carboxylates, phosphonates and sulphonates. The ions realeased into the solution are generally: hydrogen or sodium for the cation and hydroxyl, sulphate or chloride for anion exchange.[120]

Besides synthetic resins, aluminosilicate minerals (such as natural zeolites) have been widely used to remove heavy metals from aqueous solutions, due to their low cost and abundance. Zeolites contain exchangeable alkaline earth metal cations (normally Na, K, Ca and Mg) in their structural framework, as well as water. The physical structure is porous, enclosing interconnected cavities in which the metal ions and water molecules are contained.[121, 122] Zeolites have high IX and size selective adsorption capacity, as well as thermal and mechanical stability.[123] They are able to lose and gain water reversibly and to exchange extra framework cations, both without change of the crystal structure.[124] In addition, zeolites can also be modified by introducing functional groups on its surface in order to improve its selectivity for the substance to be removed.[125] This is usually done by alteration of temperature or pH and surface modification with organic compounds and yeast types.[126, 127, 128] They have been used as water softeners,[127] chemical sieves and adsorbents [129, 130] for a long time and have also been found to be highly selective for heavy metal removal from wastewater streams.[131]

The excellent cation-exchange capacity of zeolites for heavy metal ions under different experimental conditions have been demonstrated by a number of researchers.[132, 133, 134, 135, 136] In general, developing countries do not have the financial ability to invest in conventional water treatment techniques that are expensive. The employment of natural resources (such as clinoptilolite, bentonites and zeolites) provide a cheaper and simpler alternative to traditional costly methods.

The uptake of heavy metal ions by ion-exchange resins is affected by certain variables, such as pH, temperature, initial metal concentration and contact time.[137] Zeolites become unstable at high pH;[138] for this reason, chemicals are added to adjust the pH, making this process expensive. Furthermore, the use of zeolites does not reduce the level of most organic compounds.[139] In general, ion-exchangers become ineffective by obstruction, i.e. their pores become blocked by suspended particles or inorganic residues, such as iron compounds. The latter are regularly flushed out, but with time, more pores become progressively blocked and finally the bed has to be replaced.

IX processes have been proposed for the extraction of several metals from AMD and for the conversion of AMD to potable water.[140, 141] The IX resin can remove potentially toxic metals (cationic resins), or chlorides, sulphates and uranyl sulphate complexes (anionic resins) from mine water. Acidic and basic reagents are generally used to regenerate the exchange sites on the resins, following adsorption of the contaminants. This generally generates a brine solution that contains the pollutants in a concentrated form.[142] In the water recovery process, all the dissolved solids are removed, so that water is produced that is suitable for domestic or industry applications. In order to apply the IX method effectively, cheaply and without producing toxic material, knowledge of optimum conditions (such as pH and types of resins) is required.[143]

The application of IX processes for the removal of copper, cobalt and nickel from AMD solutions are the most studied of all applications. In addition to their high value, these metals can be extracted directly from solution without any modification. The affinity of most resins for copper is very high, and they will extract this metal at low pH.[144, 145] The affinity for cobalt and nickel is smaller, but still favourable at the natural pH of most AMD solutions. Figueroa and Wolkersdorfer[146] stated that 99 per cent of copper can be recovered from AMD using IX in a two-column fixed bed: the first column consisted of cation resins and the second column constisted of anion resins. In the first column, metal ions are exchanged for cations attached to the resins. In the second column, the heavy metal-free water from the first column is contacted with an anion resin, so as to neutralise the acid. These are OH^- type ion exchangers.[147] The used cation resins can be regenerated by an acid (HCl) and the anion resin regenerated with NaOH.

The removal of copper and other metals from AMD solutions using sulphonic cationic resins has also been studied.[148, 149] The separation of nickel from cobalt in a sulphate medium with picolylamine was reported by Rosato et al.[150] Prisbrey et al.[151] were able to reduce the copper and cobalt concentration to acceptable levels at Blackbird Mine using a fuidised IX system. Uranium and thorium have also been recovered from AMD.[152, 153] The recovery of these metals from AMD is facilitated by their unique ability to form stable complexes with sulphate ions. These two metals can then be extracted and separated with anionic resins that will not extract other metals. Zinc, cadmium and lead are generally not easily separated by IX resins.[154] This is because chelating resins are usually applied for extraction of these metals. However, these resins also have a high affinity for ferric iron and, as a result, it is unlikely that these metals can be removed by IX from a previously untreated AMD solution.

IX treatment has also been used in combination with chemical precipitation processes. Papadopoulos et al.[155] reported the use of ion-exchange processes individually, followed by chemical precipitation, in order to remove nickel from wastewater streams. They found that the individual application of IX resulted in up to 74.8 per cent of the nickel being removed, while a combination of IX and precipitation processes gave removals above 94 per cent. Treating acid mine water by the precipitation of heavy metals with lime and sulphides, followed by IX, were also applied in the removal of heavy metals from a South African gold mine.[156] This process resulted in the production of potable water. Gypsum of good quality can also be recovered using this process.

According to Gaikwad et al.,[157] the IX method is thought to be an efficient and economically feasible option. The IX process is suitable for removing low concentrations of metals from large flows of wastewater without high power consumption and without prior treatment to remove other water constituents (as in the use of membrane technology). IX is capable of reducing metal ion concentration to parts per million levels. A point worth noting, however, is that most IX resins are too expensive to discard once they have been loaded with heavy metals. The resins must, therefore, be regenerated and regeneration again yields a solution of heavy metals that are hard to dispose of.[158, 158] One of the major disadvantages with the IX technique is disposal of the regeneration liquid. Alternatively, one may look for a resin that is cheap and can be discarded without much overall economic impact. Regeneration with highly concentrated acids or bases has been recommended, in order to reduce the volume of regeneration liquid that must be disposed of.[160]

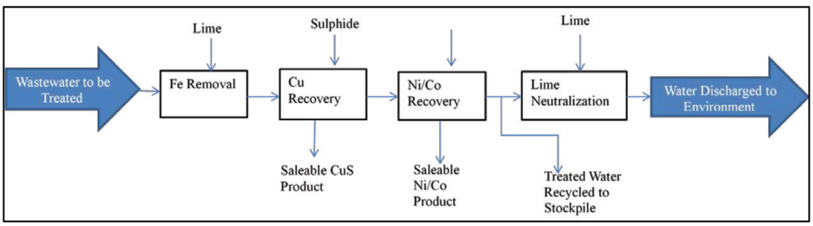
PROCESSES USING ION EXCHANGE TECHNOLOGY

THE BIOTEQ SULF-IX™ PROCESS

BioteQ Environmental Technologies of Vancouver developed the Sulf-IX™ process to remove sulphate from water high in hardness and at near gypsum saturation levels.[161] The development of the technology was based on the South African GYP-CIX technology.[162] The Sulf-IX™ process overcomes the difficulties experienced with the GYP-CIX process associated with: limited process flexibility for varying feed chemistry, mechanical entrainment of gypsum in the regeneration stage and limitations regarding sulphate removal when magnesium is present in significant concentration in the feed water.[163]

The Sulf-IX™ process (Figure 12.9) is designed to selectively remove calcium and sulphate from water, so as to achieve effluent compliance with sulphate discharge limits. The process applies two IX stages – one cationic and one anionic – to partially demineralise the feed water.[164] The cationic and anionic resins are regenerated using sulphuric acid and lime, respectively, to generate non-toxic solid gypsum (the only by-product of the process); this can provide added-value as a construction material[165] or be safely disposed of in a conventional land-fill.[166] The treated water product from the plant can be discharged directly to the environment or recycled. The first commercial plant to use this technology has been operating in Arizona since 2011.[167]

Figure 12.9: The BioteQ Sulf-IX™ process[168]

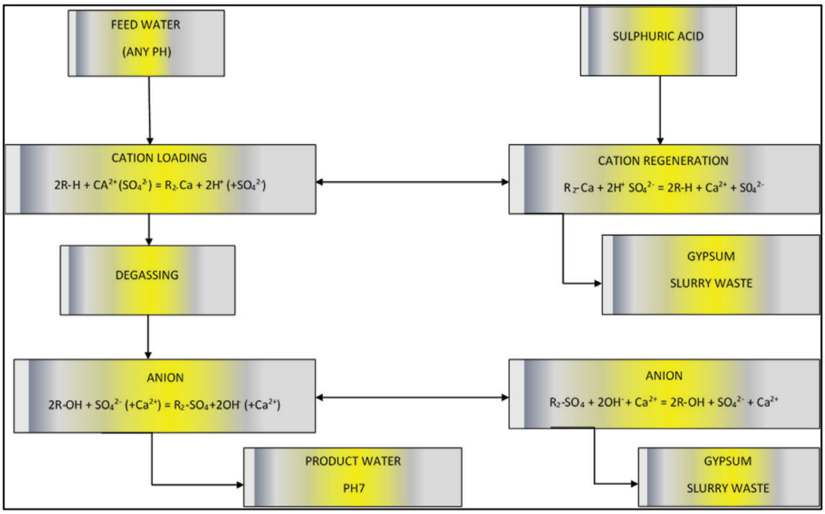


THE GYP-CIX PROCESS

The gypsum ion exchange (GYP-CIX) process (Figure 12.10) is a fluidised bed IX process developed in South Africa to remove sulphate from water that is close to gypsum saturation, so that it could be used as a polishing step after lime precipitation.[169, 170] It is a historic predecessor to the Sulf-IX™ process and is based on IX resins that use low-cost chemicals (such as sulphuric acid) to regenerate the cation exchange resin, while the lime slurry is used for anion resin regeneration.[171] The resins are designed to target calcium and sulphate, in order to reduce gypsum levels in the effluent, thereby reducing the total dissolved solids and the corrosion potential.[172, 173] The gypsum generated is the result of both cationic and anionic exchange and can be sold commercially, thus off-setting treatment costs, whilst the treated water meets standards for reuse. The benefits of this process are the use of low cost chemicals and high water recovery yielded.[174] However, the major disadvantage is the production of large volumes of gypsum sludge in the regeneration of the ion-exchange resins, which presents disposal challenges.

Figure 12.10: Simplified Process flow diagram of the GYP-CIX process for treatment of mine water[175]

LOADING SECTION **REGENERATION SECTION**



EARTH (ENVIRONMENTAL AND REMEDIAL TECHNOLOGY HOLDINGS) ION EXCHANGE PROCESS

Environmental and Remedial Technology Holdings (Earth) (Pty) Ltd developed an ion-exchange based process to recover uranium and sulphate ions from AMD.[176] The process involves the use of a proprietary IX technique to significantly increase eluate concentrations and eliminate waste. The key enabling features of the treatment are the use of nitric acid and ammonia as regenerants in the IX circuit to produce saleable products directly and good control over the product mix. The sulphate ions recovered are reacted with ammonia gas to form a 20 per cent ammonium sulphate solution.[177] Metal cations are also recovered by use of cationic exchange resins, which are later eluted with nitric acid to form a mixed metal nitrate solution that can be sold. The products generated by eluting the cation and anion columns are saleable in the form produced; thus, the process has no significant effluent other than a small volume of solid waste from backwashing the sand filters that are used for clarification of the feed solution. The overall cost of the process varies, depending on the quality and composition of the feed water.[178]

THE ACID RETARDATION PROCESS

Of growing interest is the recovery of heavy metals and sulphuric acid, which could be due to their appreciable market value as well as the environmental benefits derived from their recovery, given that these are the most toxic components of AMD. The acid retardation processes a form of IX and has become popular for acid recovery in the metal finishing industry owing to its simplicity and high acid recoveries. The acid retardation process was initially introduced by Hatch and Dillon.[178] The process is based on the adsorption of the undissociated acid as it passes through a bed of IX resins, while dissolved metal salts are rejected. The resin has a greater affinity for the acid than for the salts, resulting in chromatographic separation of salts from the acid, as its movement is retarded by the greater affinity.[179] In backwashing with water, the adsorbed acid is released. Gulbas et al.[180] suggested that the reason for acid retardation is the different rates of diffusion of metal ions, dissociated acids and acid molecules. Sheedy and Parujen[181] proposed that the process is driven by the acid concentration difference between the interior of the resin phase and the surrounding fluid. Agrawal and Sahu[181] mentioned that the release of the acid from the resins by water is a result of the difference in osmotic pressure.

The reason for the wide application of the acid retardation process in the metal finishing industry is its low cost, simplicity of use and superior performance.[182,183] Although effective in reducing ionic contaminants to acceptable levels, the resins used in the process normally suffer from a lack of selectivity. Research has therefore been directed towards improving selectivity and efficiency. The primary appeal of the acid retardation process, unlike the conventional IX process, is that no chemicals are required for the regeneration of the resins – only water is used.[184] Regenerant chemicals not only represent an economic cost, but since they report to the waste in the form of neutral salts, along with the original contaminants, an additional load of salt is discharged into the environment. Application of this technology in AMD remediation is therefore expected to reduce the amount of sludge produced and to significantly reduce the cost of the remediation process by producing a saleable sulphuric acid product.

The drawback of this process, however, is the production of a diluted solution that adds to the solution volume. This problem could be eliminated by concentrating the solution to obtain water of reusable quality in addition to the concentrated acid. However, this could be costly.

MEMBRANE TECHNOLOGIES

Membrane treatment technologies show great promise for heavy metal removal, due to their high efficiency, ease of operation and savings in land space. Membrane separation processes have increased dramatically since their development in the 1950s.[185] A membrane is a semi-permeable barrier through which selected chemical species can migrate from one region to the next. The membrane processes used to remove metals from the wastewater are RO, nano-filtration, diffusion dialysis and electrodialysis.[186,187] Traditionally, membranes have been used for the desalination of brackish water and the recovery of table salt from sea water. They have also been used commercially to recover dissolved metals from aqueous waste generated through electroplating or metal etching processes.[189] However, pretreatment of the wastewater is necessary in order to remove suspended and dissolved solids and so ensure an acceptable lifetime for the membrane.

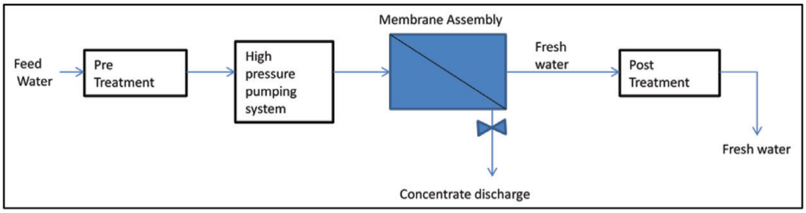
The major driving force for the popularity of the membrane technology for wastewater treatment is its unparalleled ability to meet rigorous requirements for the generation of high quality water that is suitable for reuse. The other significant advantage of the process is the low-energy consumption rate, high proton permeability and strong salt rejection.[190,191] Membrane processes require much less land area than competing technologies, making them comparatively more economic, since a single unit process can be used, instead of several unit treatment processes. However, these technologies tend to be expensive in terms of capital and operational costs for single contaminant removal, but can be cost effective and provide substantial benefit when multiple contaminants are present in a water source. The biggest technical challenge with the use of membranes for wastewater treatment is the high potential for fouling.[192,193] Membrane fouling is usually caused by colloids, soluble organic compounds and micro-organisms that are typically not well removed with conventional pretreatment methods. This is especially true for most mine water that has a high sulphate content. Although frequent membrane cleaning can be done in the short-term, the overall effect of membrane fouling is reduced efficiency and a shorter lifespan. The membrane sensitivity to solids therefore makes it imperative that a pretreatment stage is involved. Other technical barriers may include the complexity and expense of concentrate (residuals) disposal from high-pressure membranes.[194] There is also a problem with highly-charged ions being attracted to sites in the membrane and reducing separation efficiency.

Recent studies done by several researchers have shown the successful application of membrane technology in the treatment of AMD.[195,196,197,198] The most important examples of membrane processes applicable to inorganic wastewater treatment include RO and electrodialysis.[199] For RO, pressure difference is employed to initiate the transportation of solvents across a semi-permeable membrane; electrodialysis relies on ion migration through selective permeable membranes in response to a current being applied to electrodes.[200]

REVERSE OSMOSIS

RO or ultra-filtration is a process that uses high pressure pumps to force water through a semi-permeable membrane. Ionic solutions have a significant osmotic driving force for acquiring additional solute molecules. The pathway for additional ion transfer can be a membrane; membranes have small pores that selectively allow ion molecules[201] to pass through, while the solute molecules or contaminants are rejected. Consequently, high pressure is required to reverse the osmotic process and expel solvent molecules through membranes. Thus, this process is also called ultra-filtration, because solvent is filtered from the solution.[202] Membranes are made of materials such as cellulose acetate but they exhibit tremendous resistance to flow. High resistance makes it necessary to increase the surface area to enhance flow.[203] Figure 12.11 shows the basic components of a RO plant.

Figure 12.11: Basic reverse osmosis[204]



This process is capable of achieving strict discharge criteria and producing high quality water, whilst providing high efficiency, easy operation and space saving.[205] The process has received considerable attention for the treatment of inorganic effluent, since it is capable of removing suspended solids and organic compounds, as well as inorganic contaminants such as heavy metals. RO can be used to recover trace metals (except for boron) from AMD. This can be done feasibly and the water produced is of a high enough quality for it to be reused as process water.[206] Heavy metals are separated by a semi-permeable membrane at a pressure greater than the osmotic pressure caused by the dissolved solids in wastewater.[207] Mortazavi[208] reported that RO has the potential of removing 90 to 99 per cent of total dissolved solids.

The two most important factors that determine the operating cost of the RO treatment system are the efficiency of the membrane and energy usage. The process is energy intensive, which adds significantly to the operating cost. In order to prevent membrane fouling and improve the life-span of the membrane, the feed water must be pretreated. The pretreatment step generally involves filtration and chemical treatment to minimise mineral precipitation and microbial growth[209] and can add to the process cost. Process improvements in the past years have reduced the operating cost of the RO process.[210] Modified processes (including seeded reverse osmosis (SPAR-RO), which uses a suspension of salt crystals to promote precipitation) have been developed to improve the efficiency of RO applications. It is important to note that the concentrate stream from RO processes will contain high levels of rejected species, including brine and will require proper management and disposal. The disposal of the brine stream is quite challenging and can include incorporation into a mine waste or tailing stream or further concentration by conventional evaporation/crystallisation. This is capital intensive and requires substantial energy. Alternatively, solar evaporation ponds, possibly with some wind-assisted features, can be established (INAP, GARDguide).

ELECTRODIALYSIS

Previous studies have shown the recovery of water and acid from industrial effluents using electrodialysis (ED).[211, 212, 213] The principle of ED involves a cell arrangement consisting of a series of anion-exchange and cation-exchange membranes that are placed in an alternating pattern between an anode and a cathode to form individual cells.[214] The process utilises an electrical potential difference as a driving force for moving salt ions in solutions. The process is based on the principle that most salts that are dissolved in water are ionic, being either positively charged cations or negatively charged anions. The membrane is selective, in that it will only permit the passage of either anions or cations. This process can be used to separate differently charged molecules of similar sizes. In the effluent, anions are attracted to the positive electrode and can only pass through an anion selective membrane, but not through a cation selective membrane — and they are thus concentrated. The reverse is true for cations. Through the arrangement of ion-selective membranes relative to the electrodes, cations and anions become trapped in the concentrate stream flow, while water molecules are left behind in the product stream.[215] Thus, a solution treated by ED generates two new solutions: one that is concentrated and one that is diluted. By use of current reversal, electrical dialysis reversal (EDR) the process is greatly improved. The anode and cathode can be changed periodically, as can the effluent and clean water channels.[216] This reduces the potential for membrane fouling and facilitates regeneration of the membrane by self-cleaning. A major advantage of this process over RO is that it is not sensitive to effluent temperature and pH, leading to a reduction in capital and operating costs.[217]

ED can be used to obtain valuable products, such as sulphuric acid and water, from AMD.[218,219] The sulphuric acid can be used as a resource to off-set the cost of treatment and make ED technologies more feasible than typical treatments using lime. Cattoir et al.[220] found that 90 per cent of the sulphuric acid present in stainless steel decontamination waste could be recovered using the electrodialysis method. Sulphuric acid recovery from waste in an acidic nickel sulphate solution, [221] copper containing solutions[222] and recently AMD[223] have also been studied. Martí-Calatayud et al.[224] found that effective recovery of sulphuric acid with no Fe^{3+} species present was obtained in the anodic compartment, as a result of the co-ion exclusion mechanism in the membranes. Buzzi et al.[225] found that more than 97 per cent of ions can be removed from AMD by utilising a five-chamber electrodialysis cell. They[226] reported that Fe should be removed from AMD before this process is used, because the cation-exchange membrane may be blocked by the Fe precipitates. This might result in the need for a gradual increase in membrane voltage, which will decrease the efficiency of the process.

In spite of its limitations, ED offers advantages for the removal of heavy metals from wastewater, such as the ability to produce a highly-concentrated stream for possible metal recovery and the elimination of unwanted impurities from water. However, since ED is a membrane process, it requires clean feed, careful operation and periodic maintenance in order to prevent damage.

PROCESSES USING MEMBRANE TECHNOLOGY

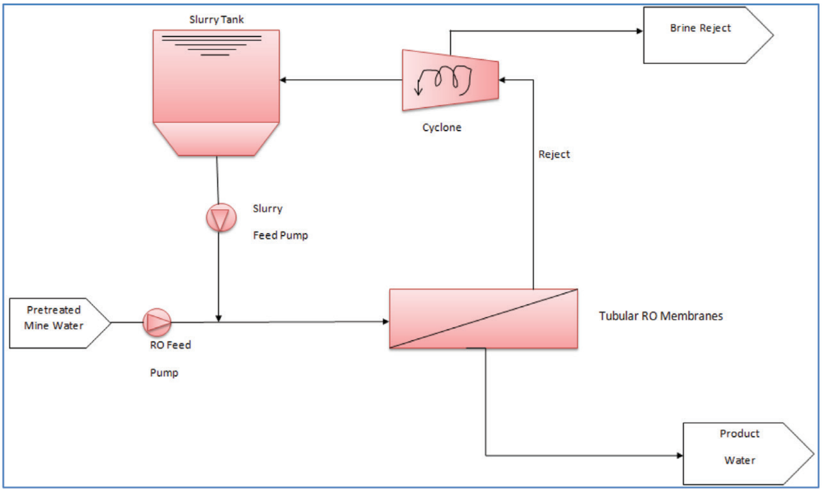
THE HIGH PRESSURE REVERSE OSMOSIS (HIPRO™) PROCESS

This process was applied successfully at the eMalahleni Water Reclamation Plant (Anglo American Thermal Coal and BHP Billiton).[227,228] The process produces the highest quality drinking water (i.e. to the South African National Standard (SANS) highest standard) and has a very high water recovery rate, usually in excess of 98 per cent fresh water recovery.[229] The HiPRO™ process, developed by Aveng Water, achieves its high water recovery rate through the use of multiple stages of ultra-filtration (UF) and RO membrane systems that operate in a series, with inter-stage precipitation of low solubility salts. The process also produces a liquid brine solution (less than three per cent of the total feed) that is expensive to dispose. The solid waste products are calcium sulphate of saleable grade, as well as a calcium and metal sulphates product.

THE SLURRY PRECIPITATION AND RECYCLE REVERSE OSMOSIS (SPARRO) PROCESS

The SPARRO process developed in the US is a membrane desalination process designed to treat calcium sulphate scaling mine water and it is a hybrid of conventional RO technology. Figure 12.12 shows the basic flow chart of the SPARRO process. The process was developed in the late 1970s by Resources Conservation Company in Seattle, US.[230] The SPARRO process is based on the protection of the membrane surface by providing a slurry suspension onto which precipitation products can form.[231] The SPARRO process incorporates three major treatment improvements over the conventional RO processes: lower power consumption; independent control of gypsum seed and concentrate blow down; and utilisation of a novel pumping system. The pretreatment stage incorporates the use of pH adjustment. This is followed by the removal of suspended solids through coagulation, settling and filtration. The resultant feed water is then pumped into a storage tank,[232] from which it is mixed with recycled gypsum seeds from the reactor, before being pumped to the RO membrane module bank.

Figure 12.12: Concept SPARRO process flow diagram[233]



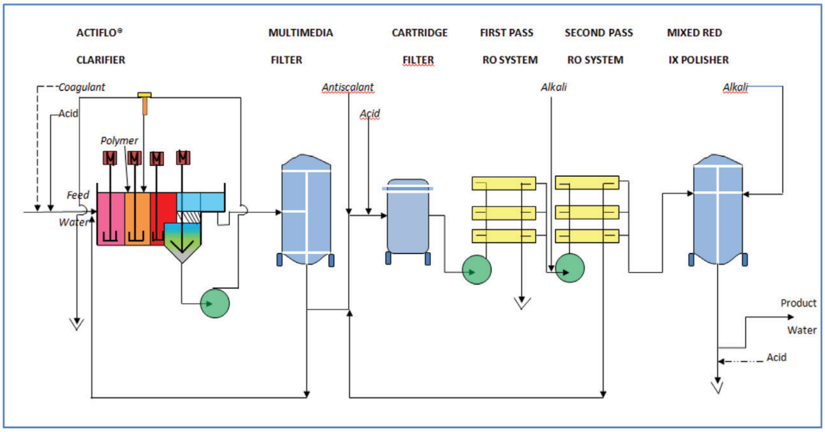
As the water is concentrated along the membranes, calcium sulphate (CaSO4), silicates and other scaling salts are preferentially precipitated on the seed material, rather than on the membranes. The treated water from the module is stored. The flow concentrate from the hydro-cyclone is further subdivided, with one part returned to the reactor and the other blown up as brine (overflow) and as seeds (underflow).

The SPARRO technology can treat a wide range of wastewater, producing good quality water at variable water recovery rates.[234] However, the disadvantage is that the life of the membranes is greatly reduced (due to fouling) by the quality of the feed water.[235] Improvements in membrane performance will greatly increase the economic viability of the SPARRO treatment process.

THE ACID MINE DRAINAGE REVERSE OSMOSIS AMDRO™ PROCESS

AMDRO™ is a patented process that utilises a high-rate clarification process with filtration, RO and IX, in order to generate high-quality effluent with minimum pretreatment requirements. This technology, developed by Veolia Water Group, is an ideal solution for meeting increasingly stringent requirements for the reduction of total dissolved solids in discharges to the environment. The process flow chart is shown in Figure 12.13.

Figure 12.13: The AMDRO™ process[236]



The process has three stages: pretreatment, RO for AMD treatment, and polishing. The pretreatment processes are designed to reduce the particulates and retain the scale-forming contaminants, such as metals and calcium salts in solution, preventing scaling of the membranes upon concentration. According to Zick,[237] the RO process is operated in double-pass mode. The first pass is operated under acidic conditions, which effectively help to control scaling due to metals and calcium salts. The second pass is undertaken at neutral pH conditions to further remove dissolved inorganic compounds.

Polishing is then applied as the last AMD treatment step, if water of high purity is required. In this case, a mixed bed IX demineralisation system is applied to ensure low total dissolved solids (TSS).

The advantages of the AMDRO™ technology is the reduced pretreatment costs associated with chemicals and sludge disposal as compared to the conventional approaches. The technology also offers a lower capital cost and incorporates effective scaling control to minimise the cleaning frequency for the RO membranes. This also helps in extending the working life of the membrane. Other additional benefits of the technology are high salt rejection and low maintenance requirements.

SOLVENT EXTRACTION

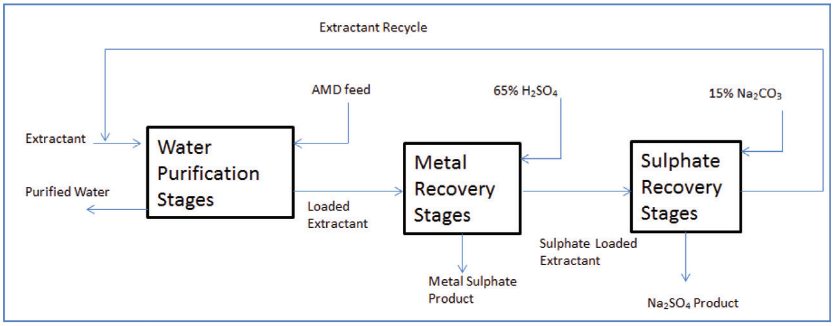
Solvent extraction involves extracting the metal of interest by contacting the metal laden solution with an organic reagent that will react with the metal ion and result in its conversion to a form that is soluble in the solvent. The extractant has a chemical reaction with the metal and forms an organic-metal complex that is soluble in the organic phase. With the proper choice of extracting agent, this technique can achieve group separation or selective separation of trace elements with high efficiency.

Although solvent extraction of metals is widely employed for selective recovery of metals from a wide range of solutions, it has not found much application in the treatment of AMD. This is because it is energy-intensive for low metal concentrations and has the potential of producing organic contaminants in the residual effluents, which can be toxic to humans or to aquatic life.[238] This method is quite effective when operated in the presence of high initial metal ion concentrations in the solution to be treated. However, the environmental standards for acceptable metal levels in the discharge water cannot be met with this method alone.

PROCESS USING SOLVENT EXTRACTION: THE AMDVEP PROCESS

Battelle, together with Pennsylvania Department of Environmental Protection, has developed a technology to remove sulphate ions and metal cations from AMD. The acid mine drainage value extraction process (AMDVEP) uses solvent extraction to treat AMD and recover purified water and saleable products such as potasium sulphate and iron sulphate. The result is a cost effective method to purify AMD from metals as well as sulphate without generating sludge. Figure 12.14 is a schematic flowchart of the process. The process has three major stages: the water purification stage, the metal recovery stage and the sulphate recovery stage.[239]

Figure 12.14: The basic AMDVEP process[240]



In the water purification stage, the AMD water is sequentially contacted (in a counter-current flow path in a series of mixer settlers) with an extractant solution formulated to remove these ions from the aqueous phase and load them onto the extractant.[241] The raffinate, made up mostly of the purified water, exits the process and can be discharged to a stream, reused as clean process water or fed to a municipal drinking water plant. The loaded extractant, now containing the iron, other metal ions and the sulphate ions, flows to the metals recovery stage. In the metals recovery stage, the extractant is stripped of iron and other metals using a sulphuric acid solution. A concentrate containing iron and other metal sulphates is produced and the products can be harvested for reuse. The metal ion-depleted extractant is then sent to the sulphate recovery stage of the process. In the sulphate recovery stage, sulphate is removed from the extractant, which again flows through a series of mixer-settler tanks in a counter-current fashion. The extractant is contacted with potassium carbonate – a basic aqueous solution – to produce a potassium sulphate concentrate. The extractant exits the last mixer-settler of the sulphate recovery section regenerated and is ready to contact a new stream of AMD feed water. The potassium sulphate concentrate is collected and stored for sale or reuse.

The advantage of the process is that it generates purified water that can meet drinking water standards. The process avoids the generation of large quantities of sludge associated with other concentional treatments and generates saleable products that can off-set process costs. The other significant advantage is the recyclability of the extractant used, which also lowers the process cost.[242]

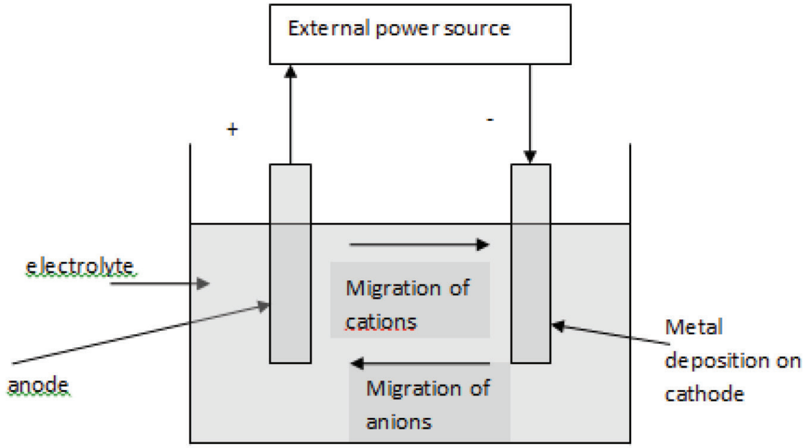
ELECTROCHEMICAL TECHNOLOGY

With the ever-increasing standard for drinking water and the stringent environmental regulations regarding wastewater discharge, electrochemical technologies such as electro-coagulation, electro-flotation and electro-deposition have regained importance worldwide during the past two decades.[243] In some situations, electrochemical technologies may be an indispensable step in treating wastewater that contains refractory pollutants. Not only are they process efficient, but they are also more compact compared to other technologies.[244]

Electrochemical recovery of metals using electrolytic cells (Figure 12.15) has been practised in the form of electro-metallurgy for a long time. The process utilises an applied potential to drive electrochemical reactions in the desired direction. To engineer an electrolytic reaction, electrodes must be connected electrically through an external circuit. An electrolyte or ion-conducting medium must exist between the anode and the cathode. The electrical power supply included in the external circuit then controls the conditions and extent to which electrons are transferred from anode to cathode. In this way, control is exerted on the half-reactions occurring in the cathodic and anodic compartments. The most important of these occurs at the negatively charged electrode, the cathode, resulting in the formation and deposition of elemental metal (M) through the transfer of electron to metal ions (M^+), as shown in Equation (9).

$$M^{n+} + ne = M \qquad (9)$$

Figure 12.15: The electrolytic cell[245]



The advantage of this technique is that it is a clean treatment, because no external reagents are used – only a supply of electrons are needed for the process. The standard effluents can be met, water consumption can be reduced and saleable products can be produced. The recovery of metals further results in the volume reduction of metal-containing hazardous sludge generated at the wastewater treatment plant, additionally minimising the disposal cost. One of the disadvantages of the process is the initial cost of purchasing the equipment, which may be prohibitive. Furthermore, the process cannot differentiate between various types of metals for selective recovery. The process is also unable to provide a complete solution to the industry's waste management problems, because it cannot treat all the metals both technically and economically.[246] In such instances, an integrated process involving other techniques (such as IX or precipitation) can make it more economical to recover less noble metals.[247,248]

Research on the application of eletrolytic processes in the treatment of AMD has been undertaken.[249,250] The AMD solution is made the electrolyte and the dissolved metal cations in the solution migrate towards and become deposited on the cathode. The anode is selected to reduce its oxidation but promote the oxidation of water. Figueroa and Wolkersdorfer[251] suggested that in order to use this process, certain aspects (such as economic and technical aspects) need to be considered. Dinardo et al.[252] and Gorgievski et al.[253] suggested that instead of using plates as electrodes, porous carbon fiber can be used as a cathode, because it increases the exposed surface area. In this process, AMD is fed to the carbon fiber and the metal ions are extracted. The carbon fiber can be recovered by anodic stripping of the accumilated metal ions. The metal ions are then deposited onto a stainless steel sheet and the metals can then be stripped from the sheet as saleable products.

Ubaldini et al.[254] proved a process involving the use of electrowinning and selective sequential precipitation to recover metals from AMD. Electrowinning was first used to recover Zn and MnO2 and the remaining metals were then removed by selective sequential precipitation. Selective sequential precipitation applied both sodium hydroxide and hydrogen sulphide, generated from sulphate-reducing bacteria (SRB), so as to precipitate metals. Sodium hydroxide resulted in the precipitation of metal hydroxides (Fe, Al, As and Mn), whilst hydrogen sulphide resulted in the precipitation of Cu and Zn sulphides.[255] This approach resulted in high metal removal effiency (90 to 99 per cent) and the Zn produced was of high purity. The products produced by selective sequential precipitation could be used for pigment production or processed further in other metallurgical processes.[256]

One electrochemical process developed for the treatment of AMD is the EcoDose process. This is an electrochemical sulphate removal process based on electrical charging of mine water under specific environmental conditions. The process involves the dosing of an electric current via suitable electrodes through an electrolyte that is constituted by the effluent. These metal electrodes release electrode products such as electrons, cations and hydroxyl anions, in the particular effluent. The electrode products can be selected and engineered to precipitate contaminants from the effluent, neutralise the effluent and render the effluent less noxious. The process is effective for acid mine water treatment and will remove a fraction of the feed sulphate, depending on the mine water composition.

ADSORPTION PROCESSES

Most active treatment methods discussed earlier are ineffective when applied for purposes of treatment of solutions streams of low contaminant concentrations. In such cases, low metal removal efficiency and high treatment cost are observed.[257] Over the last few years, adsorption has been shown to be a preferred alternative method for removing metal ions in wastewater, due to its simplicity, cost effectiveness, ease of scale-up and, most importantly, the ability to remove low concentration substances with high efficiency, even at part per million levels.[258] The adsorption process offers flexibility in design and operation, will produce high-quality treated effluent and the adsorbents can be regenerated using a suitable desorption process.[259]

Adsorbents such as activated carbon, silica gels and molecular sieves have been successfully used.[256] However, the financial constraints associated with these adsorbents have limited their application. Hence, much research in recent years has focused on finding alternative low-cost adsorbents. According to Bailey et al.,[257] an adsorbent can be considered as cheap or low-cost if it is abundant in nature, requires little processing and is a by–product or waste material from another industry. Dead biomass (such as cassava peel, tree bark, etc.), natural clays (such as bentonite, attapulgite, etc.) and alumino-silicates (such as zeolites) have been identified as potential alternatives to existing adsorbents.[256,257,258,259,260] The utilisation of low-cost adsorbents is an attractive option, since they can be used to remove toxic heavy metals from AMD and produce water with significantly less harmful impact on the receiving environment at a reasonable cost. Furthermore, the adsorbents can be regenerated and the metals recovered from them. This, in turn, increases the financial viability of the adsorption process, since valuable heavy metals can be recovered and the income generated used to compensate for the treatment cost.

The commonly applied adsorbent used in wastewater treatment is activated carbon. Activated carbon (AC) is an excellent adsorbent, and it has proven to be effective in the removal of both inorganic and organic compounds from wastewater. Carbon is particularly adept at removing low levels of dissolved ions.[261] Activated carbon has been widely used in water treatments because of its well-developed porous structure, large active surface area and good mechanical properties. It has high specific surface area ranging between 500 and 1500 m^2/g and widely different surface functional groups.[262] Its utilisation for metal adsorption relies greatly upon surface acidity and special surface functionality,[263] where the removal mechanisms may comprise ion-exchange, basal plane cation interaction and coordination to functional groups.[264]

SUMMARY OF THE PROCESSES

Table 12.3 gives an overall summation of the established and recognised processes discussed in the preceding sections and highlights the advantages and disadvantages of each.

Table 12.3: Summary of the AMD treatment processes[265]

Process	Process technology	Pre-treatment?	Advantages	Disadvantages	Possible improvements
Lime/ limestone	Chemical precipitation	No	Inexpensive; Low maintenance Removes trace metals Produces water quality suitable for irrigation or reuse in the mine Can be used as a cost effective pretreatment method to other processes HDS process proven technology	Limited sulphate removal High amount of sludge produced Costs associated with handling and safe disposal of potential unstable sludge	Reduction in the production of waste or recycling of sludge
CSIR-ABC	Chemical precipitation	No	A portion of the sludge produced is processed as reusable or saleable by-products, thereby reducing the total waste sludge volumes to be disposed of The pretreatment steps (neutralisation and gypsum precipitation) are widely applied and mature technologies. The risks associated with these processes are well understood	High costs associated with the thermal reduction of waste The feasibility of this process relies on the recovery of BaCO3 and Ca(OH)2, and the production of elemental sulphur	High energy demands; alternative and cost effective routes for recovering the reagents and saleable by-products
SAVMIN	Chemical precipitation	No	Reduce sulphate to very low levels High quality water even at fluctuating feed sulphate levels	High amount of sludge produced Success depends on high level of gypsum crystallisation Process can be complicated to control	Reduction in the production of waste or recycling of sludge
CESR	Chemical precipitation	No	High quality water obtained Low levels of residual sulphate Trace metals removal	High amount of sludge produced Relatively expensive	Reduction in the production of waste or recycling of sludge

PROCESS SELECTION CRITERIA

It is generally recognised that early avoidance of AMD problems is the best practice approach, as this is more effective and economic at reducing the environmental impact of mining than cleaning up at a later stage. This implies that, in terms of AMD control, preventive measures should be considered in preference to remedial activities when planning new mining activities.[266] Currently, the best practice for AMD management involves the integration of AMD prevention and minimising and controlling mining processes. In most cases, resources spent on preventing and minimising AMD are returned many times over through lower control and treatment costs.[267] In cases where AMD is unavoidable, suitable long-term control and treatment technologies should be implemented. Whilst there is a wide range of technologies available for treating AMD before discharge, evaluation and selection of an appropriate technology for a specific application requires consideration of many factors. The most suitable treatment depends on the overall treatment performance compared to other technologies,[268] technical factors (such as fitting into the life-cycle of the mine), operational factors (such as utility requirements and maintenance), environmental impact (such as waste disposal), as well as economics parameter (such as capital investment and operational costs). Above all, the chosen treatment option should be: reliable, in order to constantly meet the objectives of the treatment process; and sustainable, so that it can be applicable in the long-term and can be adapted to any changes in wastewater characteristics and properties.

One of the best approaches in the treatment of AMD is to consider it as a valuable resource and look at the recovery of water to satisfy the needs of a variety of mining and non-mining users and other valuable and saleable by-products such as metal sulphides and hydroxides that could be used to offset some of the operational costs. For example: iron oxide sludge recovered from a drainage channel at an abandoned coal mine in Pennsylvania has been used to manufacture burnt sienna pigment in a commercially successful venture;[269] base metals recovered by active biological treatment of AMD from metal mines provided some financial return on investment and running costs of sulfidogenic bioreactors; and metal sulphide production from closed mines, as in the Wellington Oro Mine case, can also help off-set AMD treatment costs. Thus, processes with the most likelihood of producing recyclable products and minimising waste products, so that safe disposal can be sustained, should generally be preferable. This approach can provide a sustainable business model that generates revenue from waste, reduces corporate liability for customers and delivers overall improvement of the environment.[269] It is also becoming increasingly essential to recycle as much water as possible on mine sites, in order to close the water circuit.[270] There are an increasing number of mine drainage treatment projects aimed at supplying treated mine water to neighboring communities and industries located near mines. A typical example is the Emalahleni Water Reclamation Plant, which was designed and built to recover potable water from AMD from several mines in the Emalahleni (Witbank) area. The plant uses the HiPRO™ process to desalinate rising underground water from Anglo Thermal Coal's Landau, Greenside and Kleinkopje collieries, as well as from BECSA's defunct South Witbank Mine. The project has resulted in a bulk supply agreement with the water-stressed Emalahleni Local Municipality.[271]

Since the chemical composition of AMD varies significantly from site to site, the effectiveness and feasibility of acid mine water treatment is highly variable, depending on the treatment methods employed and the unique site characteristics of the water. An appropriate treatment method for a given site is based on the quality and quantity of mining water, the type of parameters that require reduction or removal, the treated water quality objectives and capital and operational costs.[272] The quantity of chemicals required for the treatment of water can be estimated based on the chemical analysis of the water, the concentration of metal ions and total acidity. The quantity of sludge to be generated can also be calculated with the help of data on metal ion concentration, TSS, acidity and sulphate ion content. During the project planning stage, cost benefit analysis should be conducted for potential alternative treatment methods, in order to determine the most appropriate process for a given site.[273] Table 12.4 shows the criteria for selecting an appropriate mine water treatment method.

Most of the treatment methods discussed in this chapter have limitations because: they are only economically viable at high concentrations of metal ions; require the use of costly chemicals and specialised equipment; have a tendency to generate high volume sludge; or have a high equipment-wear rate. For example, precipitation and ion-exchange – the two remedial techniques that have found wide-spread application – require the use of chemicals and synthetic resins, which can be expensive. Membrane processes have a high membrane fouling rate, which can add to operational costs. Precipitation processes also result in a large volume of sludge that requires containment facilities or alternative disposal processes, which can impact further on the environment. The effluent produced by such neutralisation systems often contains more sulphate than is acceptable for either discharge into the environment or for many other uses.[274] The characteristics, advantages and limitations shown by the processes indicated in Table 12.4 suggest that process integration should be considered for more effective AMD treatment. Integrating processes helps to minimise the limitations that usually arise when treating AMD using only one technology. Hence, one of the best approaches to a sustainable solution for the AMD challenge is to consider integration of existing technologies as well as those under development, so as to come up with a solution that has the potential to address the problem in a more holistic and sustainable manner.[275]

Table 12.4: Criteria for selecting AMD treatment technology[276]

Mine Drainage Technology			
Selection Criteria	**Chemical Precipitation**	**Membrane**	**Ion Exchange**
Proven technology on scale	Proven with many demonstration scales, large commercial plants	Proven with several large commercial plants	Proven with a limited number of commercial plants
Specialised application	General application to high metals, high SO4 mine water	General application, but with appropriate pretreatment	Demonstrated for CaSO4 type waters, with appropriate pretreatment
Water recovery	High water recovery > 95%	High water recovery > 90%	high water recovery
Waste sludge/brine production	Large waste sludge production	Sludge and brine production	Large waste sludge production
Potential by-products	Potential for CaSO4 recovery	Potential, but not demonstrated	Potential for CaSO4 recovery and sulphuric acid production
Chemicals dosing	High chemicals dosing	Limited chemicals dosing	High chemicals dosing
Energy usage efficiency	Moderate energy usage	High energy usage	Moderate energy usage
Reliable and robust performance	Robust process	Process good performance, but sensitive to pretreatment	IX process performance and resin recovery subject to interference
Operations and maintenance costs	Low capital cost, simple operation Extra operational costs for sludge disposal	High operational costs due to membrane fouling and energy consumption	High operational costs associated with resin regeneration

CONCLUSION

There is still a tremendous need for further technical research and innovation of processes that can be applied in the treatment of AMD. The information presented in this chapter suggests that satisfactory processes for the treatment of AMD would be those that are technically sound and offer a cost-competitive approach to achieving the goal of toxic metal removal from wastewater, with the generation of potable water and near-zero waste or saleable products and allows for the reuse of treatment chemicals. A reduction in the production of waste would reduce the associated disposal problems that would have a major impact on the economics of the operation. A long-term and financially sustainable solution to the problem requires adequate research, not only into the negative impacts of acid water, but also into the opportunities that can be found if the water is treated as a potential resource. Although it is highly unlikely, in most cases, for the by-products to be the sole driver for the installation of a water treatment facility, the recovery of saleable products can be used to off-set some of operational costs of the project. This would make an expensive treatment plant a more economic option. In view of the limitations of some of the active AMD technologies discussed in this chapter, future development should also focus on processes involving integration of existing technologies, in order to take advantage of the positive aspects of each, thus eliminating/ minimising the challenges currently being faced with AMD treatment.

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CHAPTER 13

Acid Mine Drainage Bio-Remediation and Techniques

South African Perspective

Memory Tekere and Ilunga Kamika

ABSTRACT

Biological remediation of acid mine drainage is applied as a mild environmentally friendly method. Bioremediation is a unique method of remediation in that the diversity of organisms involved is wide, with ongoing discovery and their bioremediation capability not yet exhaustively exploited and their amenability to genetic modification for accelerated bioremediation established. Bioremediation involves passive and active systems. Active processes require continuous input of resources to sustain the process, while passive systems require relatively little resource input once they are in operation. Passive processes include packed bed iron-oxidation bioreactors, anaerobic wetlands, compost reactors/wetlands, aerobic wetlands and permeable wetlands; active systems are mainly offline sulfidogenic bioreactors. Several innovative bioremediation investigations have been carried out in South Africa and elsewhere to deal with the persistent environmental challenges posed by AMD from mining activities. While several research papers, academic theses and technical reports have been published, only a few of the bioremediation innovations are in full operation, such as the BioSURE® and THIOPAQ® processes. This chapter will give an overview of AMD bioremediation processes, including the organisms involved, the process designs and bioremediation cases in South Africa.

INTRODUCTION

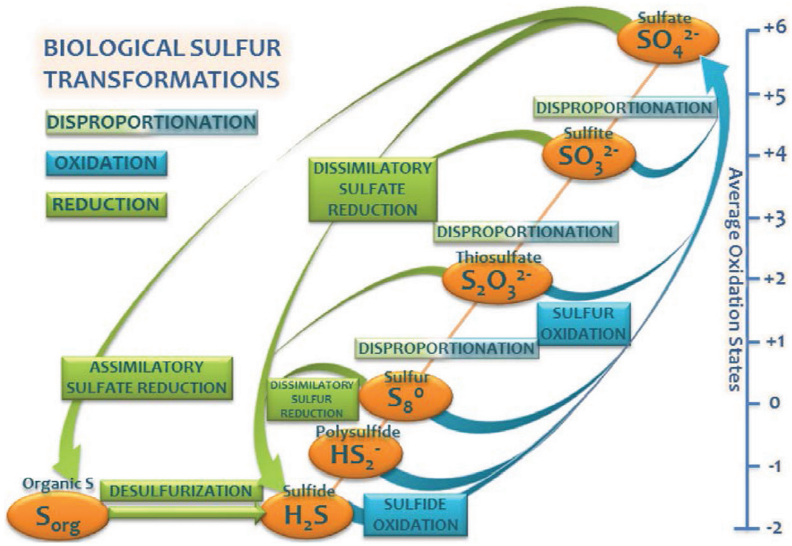
The South African mining sector is one of the critical drivers of the South African economy.[1] Despite such benefits, large-scale closure of mining operations on the Witwatersrand since the 1970s and the subsequent termination of efforts to extract underground water from mines, have become important national concerns. As elsewhere in the world, environmental pollution through acid mine drainage (AMD) is one of the main impacts cited in relation to South African economy dependence to mining.[2]

As described in preceding chapters, AMD is produced when sulphide minerals such as pyrite (FeS_2) are exposed to both oxygen and water and accelerated by micro-organisms.[3,4,5,6] AMD is prominent in both operating and inactive or abandoned mining sites, in underground tunnels and shafts, open pits, waste rock piles and mill tailings. Abandoned and active mines and mining tailings are the major sources of AMD.[7] The process of AMD generation is extremely complex, involving chemical, biological, and electrochemical reactions that vary with environmental conditions.[8] AMD chemistry is determined by the geology of the area, the micro-organisms present, the temperature and the availability of water and oxygen.[9]

Remediation measures for AMD can either be abiotic or biotic. Abiotic methods depend on chemicals to neutralise AMD and remove metals and salts from a solution, while biotic methods depend on biological mechanisms.[10] Abiotic and biotic systems include those that are classified as active (i.e. require continuous input of resources to sustain the process) and passive (i.e. require relatively little resource input once they are in operation).[11] Active treatment technologies often include aeration, neutralisation, metal precipitation, metal removal, chemical precipitation, membrane processes, ion exchange and biological sulphate removal.[12,13,14] Abiotic approaches are discussed in detail in Chapter 12.

This chapter explores the bioremediation of AMD, describing biological methods that have been researched, piloted or implemented, with specific reference made to South African cases. Bioremediation refers to the application of biological/living organisms (micro-organisms, fungi, algae and plants) to remove or neutralise pollution. Microbial remediation (makes use of micro-organisms) and phytoremediation (makes use of plants), will be covered in this chapter. Microbial bioremediation is a unique method of remediation, in that the diversity of organisms involved is wide, with ongoing discovery and their bioremediation capabilities not yet exhaustively exploited and their amenability to genetic modification for accelerated bioremediation established. A diversity of micro-organisms exist in AMD and a number of studies have reported this.[15,16,17,18,19,20] From this diversity of micro-organisms, some are involved in AMD formation, while others are involved in helping to reduce the acidity and precipitate metals.[21] Among these microbial species, bacteria such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* are ubiquitously present in sulphide mineral bearing ore deposits, mine tailings and abandoned mines and catalyse biochemical reactions that produce acid under natural conditions. These bacteria use ferrous iron and sulphur compounds as their energy source and reproduce through binary fission up to 108 cells/ml in water.[22] This results in the dissolution and mobilisation of toxic metals such as copper, iron and zinc in abandoned mines, mine wastes and tailing dumps.[23] On the other hand, sulphur-reducing bacteria have the ability to reduce acidity and immobilise metals. Figure 13.1 shows the different reactions involved in the biological transformation of sulphur.

Figure 13.1: Biological sulphur transformations[24]



MICROBIAL REMEDIATION OF AMD

Microbial treatment utilising sulphate-reducing bacteria (SRB) is an attractive option to treat AMD and to recover metals and has been used in several passive and active processes.[25] Native micro-organisms play an important role in AMD bioremediation by producing alkalinity, while simultaneously neutralising AMD and immobilising the metals.[26,27,28] These organisms are able to grow in environments highly polluted with heavy metals, iron and sulphate, and at concentrations higher than 5000 mg/l, since they have a respiratory metabolism in which sulphates, sulphites and other reducible sulphur compounds serve as the final electron acceptors, with the resulting production of hydrogen sulphide.[29] The use of mixed cultures of SRB, obtained from natural sources, has several advantages, namely their easy availability and environmental adaptation ability.[30, 31, 32] SRB oxidise simple organic molecules using sulphate ions as electron acceptors, resulting in hydrogen sulphide (H_2S) and bicarbonate ions (HCO_{3-}).[33] The H_2S formed reacts with heavy metal ions, immobilising them and forming metal sulphides (see Equation (1)) and bicarbonate ions, providing buffering activity by raising the pH and improving the water quality.[34]

The processes attributed to microbial remediation of AMD are proposed to involve: the oxidation of iron sulphide and enhanced oxidation of sulphide minerals by ferric iron; oxidation of ferrous iron (equation (2)); and hydrolysis and precipitation of ferric iron and other minerals (equation (3)).

$$MSx + (2X - 0{:}5)O_2 + H_2O \xrightarrow{\text{bacteria}} Mx + XSO_{-4}^{2} + 2H+ \quad (1)$$

$$2Fe^{2+} + 0.5O_2 + 2H+ \xrightarrow{\text{bacteria}} 2Fe^{3+} + H_2O \quad (2)$$

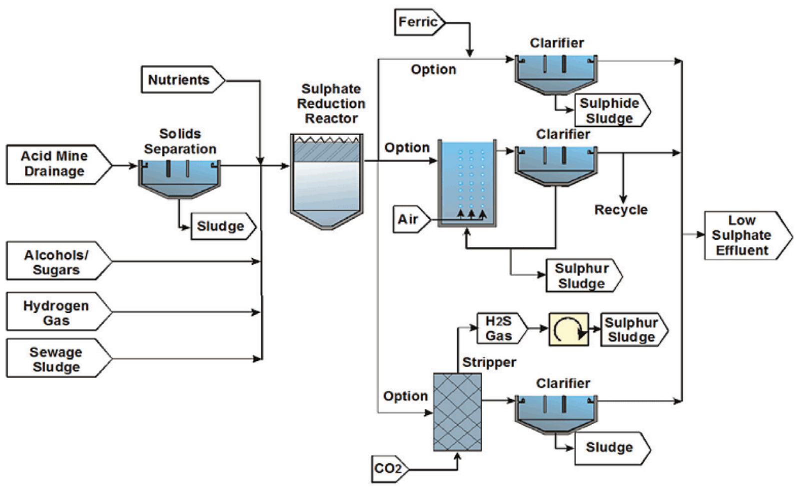
$$S^0 + 1{:}5O_2 + 2H_2O \xrightarrow{\text{bacteria}} SO_4^{2-} + 2H+ \quad (3)$$

Where M is a metal and X is a whole number.

The capacity of SRB to generate H_2S has been used in different treatments for heavy metal-contaminated waters/drainage.[35]

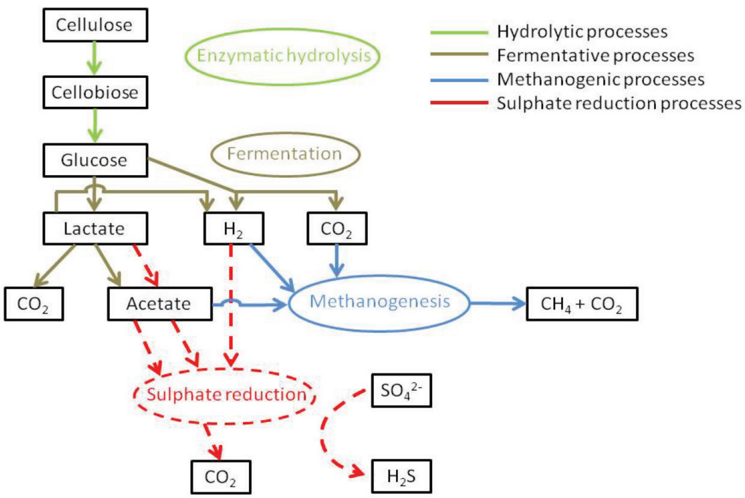
Microbial reductive processes that result in an increase in pH of the AMD include denitrification, methanogenesis, sulphate reduction, iron and manganese reduction and ammonification.[36] Figure 13.2 is an illustration of a generic biological sulphate removal system.

Figure 13.2: Generic biological sulphate removal process[37]



In the microbial reduction of sulphur, a carbon source such as compost and some limestone is added so as to aid in the bacterial metabolism and generation of alkalinity, respectively.[38] Figure 13.3 shows how a cellulose based carbon source, such as compost, is used to facilitate sulphate reduction, as illustrated by Wildeman and Gusek.[39]

Figure 13.3: An illustration of the breakdown of cellulose to facilitate the microbial sulphate reduction[40]



MICROBIAL POPULATIONS IN AMD

Several micro-organisms have the ability to colonise an extraordinary range of environments, and are directly or indirectly involved in many chemical alterations and mineral decompositions and have been found in AMD. The microbial population diversity is, however, influenced by the prevailing harsh physical and chemical conditions of the AMD and they are restricted to a fewer prokaryotic species.[41] Extensive investigations have been carried out on the microbiology of various abandoned mines and tailing dumps.[42,43,44,45] The metabolisms in these communities include organoheterotrophy, autotrophic iron and sulphur oxidation, anaerobic sulphur oxidation and ferric iron reduction.[46] Communities of autotrophic and heterotrophic archaea and bacteria catalyse iron and sulphur oxidation and can therefore determine the rate of release of metals and sulphur into the environment.

The SRB are generally classified into the following four taxonomic groups:

- The δ-Proteobacteria sub-division contains Gram-negative mesophilic SRB, including the genera *Desulfovibrio, Desulfomicrobium, Desulfobulbus, Desulfobacter, Desulfobacterium, Desulfococcus, Desulfosarcina, Desulfomonile, Desulfonema, Desulfobotulus,* and *Desulfoarculus*. These bacteria have optimal growth temperatures ranging from 20 to 40°C.
- The Gram-positive spore-forming SRB, mainly represented by the genus *Desulfomaculum*, form heat-resistant endospores.
- The bacterial thermophilic SRB group contains the genera *Thermodesulfobacterium* and *Thermodesulfovibrio.* These bacteria have optimal growth at 65 to 70°C and inhabit high-temperature environments, such as geothermal vents.
- Archaeal thermophilic SRB belonging to the genus *Archaeoglobus* thrive at temperatures above 80°C and have been found only in marine hydrothermal vents.[47,48]

PHYTOREMEDIATION OF AMD

Phytoremediation is defined as the use of plants to mitigate environmental pollution. In contrast to microbial bioremediation, in phytoremediation, plants are responsible for the degradation and immobilisation of the contaminants through physical and chemical processes. Due to the high potential of plants to immobilise heavy metals and radionuclides, and the ability of plant species to tolerate extreme contamination, increasing interest has been observed among scientists regarding the use of this technique as a cost-effective alternative method to conventional ones.[49] Plants used for phytoremediation of AMD in wetlands are beneficial in that they: ensure the aesthetic quality of the wetlands, encourage microbial population establishment, help to stabilise the AMD effluent/substrate and encourage a more uniform flow of effluent in the wetland system.[50] Even though phytoremediation appears to be cheaper than conventional options, it is not an easy method that simply involves the planting and growing of hyperaccumulating plants in the environment polluted with metals. It is, in fact, a highly technical strategy that requires expert project designers with good field experience and the ability to choose the proper species and cultivars for particular metals and regions.[51]

Phytoremediation involves the following processes: phytosequestration, rhizofiltration, phytoextraction, phytodegradation, and phytovolatilisation.[52,53] All, or a combination, of these processes are generally prevalent in the phytoremediation of AMD in wetlands, depending on the type of pollutants and the type of media affected (soil or water), as well as on the clean-up goals, which typically include stabilisation or sequestration, reduction, assimilation, detoxification and degradation. Due to the complexity of pollution linked to AMD, the most useful phytoremediation techniques for mining waste are phytosequestration, rhizofiltration, phytovolatilisation and phytoextraction, which are defined in Table 13.1.

Table 13.1: Type of phytotechnology mechanisms used for AMD treatment[54]

Mechanism	Description	Clean-up goal
Phytosequestration	The ability of plants to sequester certain contaminants: in the rhizosphere through exudation of phytochemicals; and on the root through transport proteins and cellular processes. This reduces the mobility of the contaminant and prevents migration to soil, water and air.	Containment
Rhizodegradation	Degradation of contaminants in the rhizosphere via microbial activities and exuded phytochemicals.	Remediation by destruction
Phytohydraulics	The ability of vegetation to evapotranspire sources of surface water and groundwater through the plant.	Containment by controlling hydrology
Phytoextraction	The ability of plants to take up contaminants from both soil and water via the transpiration stream.	Remediation by removal of plants
Phytodegradation	Uptake and break down of pollutants via internal enzymatic activity and photosynthetic oxidation/reduction.	Remediation by destruction
Phytovolatilisation	Refers to the uptake and transpiration of volatile contaminants by plants in the transpiration stream.	Remediation by removal through plants

PLANTS FOR PHYTOREMEDIATION OF AMD

During phytoremediation, plants serve as a medium either alone or in association with micro-organisms. AMD phytoremediation is almost always applied in natural and constructed wetlands. The plant species used in the remediation of AMD differ in their abilities to take up and accumulate various trace elements in their tissues. Metal hyperaccumulators have the ability to take up very high concentrations of metals into their system. Several studies have been conducted that examined the ability of some plant species to accumulate metals in their biomass.[55,56,57,58,59,60,61] In a study that evaluated some local water plant characteristics for phytoremediation of AMD, *Eleocharis dulcis* was found to reduce iron best, while *Pistia Stratatiotes* was effective at reducing manganese levels.[62] *Ipomea aquatic* was good at reducing acidity.[63] The most studied aquatic plants applied in wetlands are classified into four groups, namely: emergent plants, surface floating plants, free-floating rooted leaves and submerged macrophytes.[64] In emergent and surface floating plants, metal uptake occurs through the roots, whereas in free-floating rooted leaves and submerged macrophytes, metal uptake occurs through roots and leaves. Examples of plants used in AMD phytoremediation are listed in Table 13.2.

Table 13.2: Examples of plants used in AMD remediation

Plant used	**Metals removed**	**Reference**	**Remarks**
Duckweed (Lemna gibba L.)	U and As	65	Tailing ponds
Glyceria grandis	Cd,Cu,P,Pb,Zn	66	Laboratory studies
Scirpus validus	Cd,Cu,P,Pb,Zn	67	Laboratory studies
Spartina pect	Cd,Cu,P,Pb,Zn	68	Laboratory studies
Eichhornia crassipies	Cd	69	Laboratory studies
J. effuses	Fe and Al	70	Constructed wetlands
M. aquaticum	Fe and Al	71	Constructed wetlands
N. odorata	Fe and Al	72	Constructed wetlands
P. cordata	Fe and Al	73	Constructed wetlands
Imperata cylindrica	Fe	74	
Erica andevalensis	Fe and Al	75	Natural wetland
Erica australis	Fe and Al	76	Natural wetland
Zea mays L.	Pb and Zn	77	Laboratory studies
Brassica spp.	Cd, Cu and Zn	78	Laboratory studies
Typha latifolia	Mn, Fe, Mg and Al	79	Natural wetland

Solidago sp.	Mn, Fe, Mg and Al	80	Natural wetland
Glycine max	Mn, Fe, Mg and Al	81	Natural wetland
Phragmites australis	Mn, Fe, Mg and Al	82	Natural wetland
Alyssum bracteatum	Ni	83	Laboratory studies

PROCESS DESIGNS FOR AMD BIOREMEDIATION

As previously stated, process designs for AMD treatment can be either active or passive. According to Trumm,[84] active processes are mostly used in operating mines, while passive treatment processes are more suitable in abandoned mine sites in the absence of a responsible entity and remote locations which require the use of a long-lasting, low cost and environmentally sustainable treatment option with no artificial energy requirement.[85]

Active processes are characterised by ongoing high intensity flow of chemicals into and out of a treatment plant that is maintained continuously by trained personnel. [86] Even though they are regarded as more reliable and suitable than passive systems (due to the highly precise process control), their main disadvantage is that they are more expensive, due to operational and maintenance costs.[87] On the other hand, the management of AMD through passive treatment processes makes use of low-cost management options that rely on biological, geochemical and physical process.[88,89] Passive systems offer advantages such as high metal removal at low pH, stable sludge, very low operation costs and minimal energy consumption. Passive systems usually require large areas of land, and are more suited to operating alongside active systems or at closed mines.[90,91,92] The potential limitations of passive systems include vulnerability to high flows and high contaminant concentrations, seasonal variation in performance, large space requirements, technical challenges due to the need for periodic maintenance or renovation and the relative lack of technical experience for the management of these systems.[93]

Given the variability between the different mines, in terms of water quality, topography and other site characteristics, treatment process selection is critical, as a combination of different technologies is usually required for the treatment of AMD.[94,95,96] Table 13.3 provides a list of active and passive biological methods for AMD remediation. While an effort has been made to indicate all these methods, literature will provide possible other names for processes designed under the cluster given here.

Table 13.3: Biological methods for remediation of AMD[97]

Active	Passive
Offline sulphur reducing bioreactors	Aerobic wetlands
	Packed bed iron oxidation bioreactors
	Permeable reactive barriers
	Compost reactors/wetlands
	Anaerobic wetlands

PASSIVE BIOREMEDIATION PROCESSES

Passive biological treatment systems that include sulphate-reducing passive bioreactors, packed bed iron oxidation bioreactors and permeable reactive barriers are used in AMD bioremediation. Some of the perceived advantages and disadvantages of passive treatment of AMD with SRB are listed in Table 13.4.[98]

Table 13.4: General advantages and disadvantages of passive treatment with SRB[99]

Advantages	Disadvantages
Low cost	Limited to low flows or concentrations
Fewer site visits	Less control of some parameters
Little or no power required	Require some maintenance or renovation
May utilise waste material as C sources	Potentially high space requirement
Effective for multiple contaminants	Less technical experience
Effective in neutral, acidic or alkaline conditions	Potential odour problems
Little sludge generation	Low effectiveness for Mn
Inconspicuous or natural appearance	Need for polishing after treatment
Easily combined with other passive treatments	H_2S production

WETLANDS

Wetlands, commonly known as 'biological filters' appear to be a practical option for the remediation of AMD.[100,101] Remediation in wetlands is achieved through complex interactions between plants, microbes and sediments. For decades, research efforts on wetlands, as an alternative cost-effective way to remove heavy metals from AMD, have increased and processes have been successfully implemented worldwide.[102,103,104,105,106] The use for the treatment of AMD found its apogee during the 1970s to 1980s when it was revealed that the natural Sphagnum bog wetland systems could remove high concentrations of pollutants from AMD through natural biological and chemical reactions.[107] In comparison to other AMD passive treatment methods, wetlands are the most acceptable treatment method, because they are self-sustaining once established, and thus become cheaper in the long-run.[108] Wetlands used for AMD treatment are either natural or constructed wetlands. Natural wetlands are characterised by permanent or temporary water-saturated soils or sediments, which support plants adapted to reducing conditions in their rhizosphere, while constructed wetlands are man-made ecosystems designed to mimic their natural counterparts. Constructed wetlands often comprise shallow excavations containing flooded gravel, organic matter and soil to support wetland plants, such as cattails (*Typha* spp.), rushes (*Carex* spp.), reeds (*Phragmites* spp.), sedges (*Juncus* spp.) and bulrushes (*Scirpus* spp.).[109] Furthermore, the purification process in constructed wetlands occurs in a controlled environment, where plants, microbial populations, soil, sediments, speed of water and other parameters are set to maximise the efficiency of the water treatment process.

Constructed and natural wetlands have been successfully used for the removal of metals (for example Zn, Ni, Cu and Pb) in several mining sectors in the United States of America (US) and Europe.[110,111,112] A study conducted in Santee, California indicated that Cu (99 per cent), Zn (97 per cent) and Cd (99 per cent) were removed from wetlands via the precipitation-absorption phenomena caused by the wetland metabolism that increased the pH to near neutrality.[113] The construction of treatment wetlands has also been observed in South Africa in the last two decades, as a result of favourable aesthetics, capital cost, operation and maintenance costs and the positive experience that has been gained.[114] Since many candidate sites for treatment are remote, without easy access to power, and also linked to their self-sustaining and cost-effectiveness in the long run, passive wetland treatment options are more preferred to active treatments.[115,116,117]

AEROBIC SURFACE-FLOW WETLANDS

Aerobic wetlands are generally shallow, to ensure aerobic conditions and include plants that assist in the immobilisation and precipitation of heavy metals. Aerobic wetlands are designed to provide sufficient residence time to allow the metal oxidation and hydrolysis that lead to precipitation and physical retention of iron and manganese hydroxides.[118] Based on their accumulation of precipitates over time, the wetland bioremediation ability is usually affected and reaches saturation point. Periodic removal of precipitates through flushing or dredging of the area is thus a necessity.[119]

It has been reported that aerobic wetlands can be used to treat post-mining ground water seeps with pH higher than five.[120] However, Brodie[121] stated that staged aerobic wetland systems can remove: Fe loads of up to 21 grams/m2/day, even in the absence of excess alkalinity; and Mn loads up to 2 grams/m2/day, if alkalinity is present. In evaluating the performance of six aerobic wetlands, Skousen and Ziemkiewicz[122] found the performance to be highly variable, at between 0.1 and 27 t/yr of acid, at costs ranging from $23/t/yr to >$7,000/t/yr over an expected lifetime of 20 years.

Even though the aerobic wetlands approach has been found to be very efficient in terms of Fe uptake, the techniques face several drawbacks for the removal of other metals, such as Mn, which has been reported to leach in the effluent.[123] In order to improve the efficiency of this technology, a pretreatment stage (anoxic limestone drain or oxidation basin) is usually added to the system. Some systems also include a final polishing pond, which improves long-term capacity and minimises storm event flushing of Fe and Mn precipitates from the wetlands.

ANAEROBIC COMPOST WETLANDS

Anaerobic wetlands are water retention ponds that rely on organic matter substrates to generate reducing conditions and limestone aggregates for acid neutralisation.[124] In anaerobic compost wetlands, the water passes through a 30 to 40 cm thick organic rich substrate material.[125] These technologies are used to treat acidic and high sulphate AMD.[126] The SRB's activity is able to raise pH and thereafter remove metals, as sulphides, hydroxides and carbonates precipitate.[127] *Desulfovibrio* and *Desulfotomaculum* are some of the most dominant SRBs in anaerobic wetlands and appear to be capable of using sulphate as an electron acceptor for growth, while raising pH by producing bicarbonate alkalinity.[128] The anaerobic wetlands are similar to sulphate reducing bioreactors, where the AMD is drawn through organic substrates that host micro-organisms, in order to promote oxidation and reduction reactions.[129] Equations (4), (5) and (6) illustrate the process of immobilisation and precipitation of metals (for example Fe) mediated by micro-organisms in an anaerobic wetland:

$$4Fe(OH)_3 + CH_2O + 8H^+ => 4Fe^{2+} + CO_2 + 11\,H_2O \qquad (4)$$

$$3CH_2O + 2N_2 + 3H_2O => 4NH_3 + 3CO_2 \qquad (5)$$

$$SO_4^- + 2CH_2O => H_2S + 2HCO_3 \qquad (6)$$

Where, CH_2O is used as a representative of organic matters in these reactions.

According to Gusek,[130] AMD with moderate to high acidity water can be treated successfully in anaerobic wetlands at a flow ranging from 4 to 4,800 l/min. Another study, done by Faulkner and Skousen,[131] also reported acidity and iron reduction of up to 76 per cent and 80 per cent, respectively, from AMD with 110 to 2400 mg/l acidity and a flow rate of 4 to 98 l/min. In an evaluation of the performance of the 17 anaerobic wetlands, Skousen and Ziemkiewicz[132] showed a wide variation in acid removal of 0 to 67.9 t/yr of acid load treated, and that treatment costs varied from $341/t/yr to $4,762/t/yr. Anaerobic wetlands are generally accompanied by some bioreactor in order to control pH. Passive bioreactors, which involve the use of lined trenches and pits containing organic matter, can be used in conjunction with the wetland so as to raise the AMD pH and establish the desired micro-organisms.[133]

SULPHATE-REDUCING PASSIVE BIOREACTORS

Lately, much attention has been reported regarding the use of sulphate-reducing passive bioreactors as an effective technology for the treatment of AMD.[134,135] The activities of the SRB in the sulphate-reducing passive bioreactors require the presence of a mixture of organic carbon source, and several studies have focussed on finding the best natural organic substrates.[136,137,138,139] The studies showed that a combination of organic carbon sources is preferred to single specific substrates. Similar to anaerobic wetlands, metal sulphide precipitation, adsorption and precipitation of metal carbonates and hydroxides also occur in passive bioreactors and different designs can allow the flow to be either in upward or downward modes.[140] Bioreactor systems vary from small to large vessels, and may be in barrels or tanks in a series. In the US and Canada, highly efficient removal of sulphate and metals was noted for periods of up to five years, when using these technologies at pilot- and field-scale with mixtures of organic and cellulosic wastes.[141] However, additional investigations are still needed in order to properly assess the efficiency of reactive mixtures in the long-term and also to ascertain the mechanisms of metal removal.

PACKED BED IRON-OXIDATION BIOREACTORS

Due to the interest in improving iron oxidation during biological processes, an attempt has been made to fix bacteria in fixed-film applications, in order to provide a large surface area for iron attachment for efficient oxidation process of ferrous iron during AMD treatment.[142] According to Stumm and Morgan,[143] oxygen and pH are important parameters for fast ferrous iron oxidation to ferric iron. Contrarily, Lu et al.[144] stated that oxygen can accelerate the ferrous iron oxidation without improving the removal efficiency of total iron. Several experimental systems, using batch and continuous flow modes of operation, have been tested and various reactor configurations designed to obtain better results.[145,146,147] Oxidation rate and pollutant removal efficiency also depend on the type of matrix used. Studies have also been orientated in finding the best and most suitable materials to be used as a support matrix in iron oxidation bioreactors.[148,149] Grishin and Tuovinen[150] revealed that activated carbon particles are good packed beds due their roughness and porous matrix surface, and their ferrous adsorption ability. Furthermore, Mesa et al.[151] reported that, due to lower diffusion resistance to substrate transfer and low cost, polyurethane foam could also be considered as a good matrix to immobilise viable *Acidithiobacillus ferrooxidans* cells. The disadvantages of using this technique include bacterial cell wash-out at high liquid flow rate and detachment of cells from support media.[152] Recently, researchers have been trying to address these issues by developing other fixed-film approaches through integration with several configurations of packed-bed iron-oxidation bioreactors.[153,154,155] It is known that matrix preference among iron-oxidising micro-organisms differs,[156] as each has a different affinity for ferrous iron, based on suitable optimum environment conditions.

PERMEABLE REACTIVE BARRIER WETLANDS

These technologies involve the installation of a permeable zone against the flow path of the plume, in order to create a reactive treatment area oriented to remove metals and generate alkalinity by promoting sulphate reduction.[157] Permeable reactive barrier wetlands are seen as alternatives to conventional pump-and-treat approaches and operate on the same basic principles as compost bioreactors.[158] These techniques remove pollutants through a combination of physical, chemical and microbiological processes.[159] However, the systems take advantage of the SRBs populating the barrier to enhance the effectiveness of the removal process. SRBs reduce sulphate to sulphide in the acidic water by using the electrons present in the barrier. Organic substrates and zero-valent iron (Fe^0) are important during the process, as they stimulate sulphate reduction.[160] The barrier's permeability and reactivity are significantly governed by the reactive mixture selected,[161] which is a prerequisite for the success of this bioremediation process. Skinner and Schutte[162] reported that mixtures of gravel and organic matter can increase the permeability of the barrier, while additional alkalinity is provided by the addition of limestone. However, these processes suffer from some drawbacks, as they often rely on the flow of groundwater for the transfer of the pollutants to the treatment zone, resulting in long treatment times, depletion of organic substrates and clogging of the barrier as a result of metal precipitation. The reactive barriers can be constructed as horizontal or vertical layers to intercept and treat AMD. Even though these processes are considered to be quite expensive during their installation, they are still seen as cost-effective, since they can operate for a decade or more with very little maintenance and operational cost. According to Gibert et al.,[163] there are approximately 200 permeable reactive barrier wetlands installed worldwide, but only five for the treatment of AMD. This situation clearly shows that these techniques are not yet widely applied and are still in their early stage of application.

ACTIVE PROCESSES

Active processes have been very successful techniques for AMD treatment and exhibit long-term performance advantages over passive biological systems.[164,165] Unlike the passive treatments, which can be used as walk away solutions to the mining industry,[166] active techniques are more suited to application on operational mine sites. Disadvantages of active systems include high capital and operational costs, failure to significantly reduce the metal contamination to streams, requirement for proper sizing of the systems to account for seasonal variation in acidity loads and ensuring AMD is fully treated prior to discharge.[167] Similar to chemical processes, this technology involves high operating costs, as intricately engineered systems are carefully managed to maintain optimal conditions for the microbial communities by the continuous addition of expensive chemicals.[168]

OFFLINE SULPHUR REDUCING BIOREACTORS

Offline sulfidogenic bioreactors represent a different approach for remediating AMD,[169] but they also rely on SRB activities for hydrogen sulphide production, which, in turn, is used to increase the pH and remove metals via precipitation.[170,171,172] SRB activity in bioreactors is very important for the performance of the system, as these micro-organisms provide a good environment for neutralising hydrogen ion acidity.[173] Several SRBs have been reported as being sensitive to the shock of AMD acidity and this has led to the design of appropriate reactors to protect micro-organisms from direct exposure to the inflowing AMD.[174]

Even though these techniques are not cost effective when compared to other biological techniques, they offer three major advantages: they can selectively remove and recover metals from AMD; the control of their performance is easy and predictable; and they deliver significant sulphate removal.[175] In South Africa and elsewhere, developments have focused on harnessing very high rates of SRB in what are effectively active treatment systems.[176] Continuous upflow fixed film bioreactors were investigated and used as pilot reactors for uranium reduction and a 99.95 per cent reduction was achieved after 35 days, until the reactor was terminated after 82 days.[177] Also, at least two technologies using offline sulfidogenic bioreactors have been described and are being used commercially: the Biosulfide and the THIOPAQ® processes, as discussed later.

FACTORS AFFECTING AMD BIOREMEDIATION SULPHUR REDUCING BIOREACTORS

In sulphur reducing bioreactors, as well as in the natural environment, micro-organisms have key preferences for optimum performance and adaptation to particular environmental conditions. These limiting factors or specific environmental requirements affecting bioremediation are of major consideration when deciding on the design of bioreactors (or wetlands) for AMD mitigation. Important factors to consider in the biotechnological application of SRB include the inocula, the pH of the process, substrates, hydraulic retention time, AMD metal concentration and the reactor design.[178] Acid tolerance is beneficial in bacteria used to treat acidic drainage. It has been reported that SRB are able to survive in a large range of pH conditions, but can become less active below a certain pH.[179] For suitable survival and nourishment, SRB requires narrow pH ranges of 5 to 8.[180] It has also been proven that changes in pH outside of this range can affect the charges on the microbial membrane, which impacts the microbial sulphate reduction rate and metal removal capacity.[181] Low pH (<5) normally inhibits sulphate reduction and increases the solubility of metal sulphides.[182] At high pH, some metals are predominantly found in the form of insoluble mineral phosphates and carbonates.

Apart from pH, operating temperature is also regarded as one of the most important parameters, because of its ability to depress, activate, restrict, stimulate, control and kill bacteria. Operating temperature can also affect the kinetics of organic substrate decomposition, as well as hydrogen sulphide solubility. In general, micro-organisms such as SRB can grow at temperatures from below freezing point up to more than 100 °C.[183,184,185] Low temperatures slow SRB activity down and thus reaction rates are slower. According to Tsukamoto et al.,[186] AMD was not efficiently treated at temperatures as low as 6°C. It has also been recorded that low temperatures can affect the ability of SRB to acclimate.[187] In contrast, winter freezing of a well-established SRB population had little to no effect on their activity.[188,189] Cold-adapted species are able to function at temperatures as low as 4° C and increased populations may offset lower activity.[190]

Substrates, solid support (for example sand and/or gravel), Hydraulic Retention time (HRT) and hydraulic conductivity have also been reported as parameters affecting the bioremediation of AMD. Lyew and Sheppard[191] pointed out that sand and gravel are the best supports for SRB, onto which they can establish micro-environments for their survival in the presence of extreme conditions such as low pH or high oxygen concentrations. The rates of sulphate reduction are higher only if SRB has access to a porous surface, when compared to suspended bacteria.[192] Short HRT has usually been reported as not being adequate for SRB activity to neutralise acidity and precipitate metals and may result in biomass being washed out of the bioreactor.[193,194] Furthermore, a longer HRT may result in depletion of either the available carbon source or the sulphate source for SRB.[195]

The choice of carbon source, based on cost, availability and degradability, is key to the performance and cost effectiveness of the treatment system. Coetser et al.,[196] noted that the chemical composition of the substrate critically influences its ability to drive SRB, noting in particular that high protein content encourages SRB, whilst high fibre content restricts it. Gibert et al.,[197] investigating the substrates compost, sheep manure, poultry manure and oak leaf, found that substrates with the least lignin content and highest 'easily available substances' (EAS) are the most effective at encouraging sulphate removal.[198] Waste sources of carbon are generally preferred to the use of laboratory chemicals, as they offer cheap and sustainable carbon sources in the long-term of AMD treatment. Where substrates are cellulose based, the hydrolysis of cellulose becomes a rate-limiting factor in hydrogen sulphide production by SRB, when more labile carbon sources are absent.[199] Boshoff et al.[200] successfully used dried microalgal biomass as a sole carbon source for bacterial sulphur reduction in an upflow anaerobic digester.

Acclimation of microbial inocula was also found to be important for the SRB reactors, with pre-acclimated SRB being more ideal for use.[201] Sources of SRB inocula range from enriched mine sediment to wastewater treatment plant sludge.[202] In order to enhance their abilities, the microbial communities for inocula can be pregrown for several weeks on a rich-nutrient medium and thereafter inoculated into the reactor once the community is enriched and acclimatised.[203] The initial acclimation period should be minimised, however, as it can affect the pregrown inocula initiating the sulphate-reduction process on time.[204]

Table 13.5 summarises some of the problems that can arise during the operation of an SRB, and some possible solutions to these problems.

Table 13.5: Potential problems and solutions in SRB treatment systems[205]

Problem	Proposed solution
Clogging/channelisation	Use more porous, non-degradable material; flushing
Seasonally high flows	Apply storage or diversion

Carbon source depletion	Replace; use excess C and mixture of materials
Low pH stresses SRB	Use more acidophilic species; alkalinity addition; recirculation
Low temperature	Below-ground installation; impermeable covers
Little or no Mn removal	Add aerobic rock filter
High BOD, solids; low DO	Aeration/polishing pond or rock filter

AMD BIOREMEDIATION TECHNIQUES AND APPLICATIONS

A variety of reactor sizes and configurations exist and no specific design is suitable for every site. Careful bioreactor design selection needs to take into consideration the treatment site and objectives. In principle, the variety of bioreactors for AMD treatment include: tubular, stirred tank, different types of columns (fixed bed, expanded bed, fluidised, bubbling column, air-lift column and plate column) and special designs such as loop reactors, solid substrate reactors and heap reactors with different types of columns.[206] AMD remediation using SRB has been described in fluidised-bed reactors,[207] upflow packed bed reactors,[208] the Linear Flow Channel Reactor for sulphur removal in acid mine wastewater treatment operations[209] and upflow anaerobic sludge blankets.[210] In principle, elected reactors need to provide a large surface area for microbial growth and attachment, good mixing and contact between substrate and biomass, high mass transfer and substrate utilisation rates, high organic loading rates and greater resistance to inhibitors.[211,212]

AMD BIOREMEDIATION TECHNOLOGIES IN SOUTH AFRICA

A number of industries and research and academic institutions have been actively involved in AMD remediation studies in South Africa, as is the case in the rest of the world.[213,214,215,216] However, a significant number of research studies are non-biological, as described elsewhere on the technologies used in AMD.[217,218,219,220,221] Table 13.6 indicates some of the bioremediation research studies done on AMD. Bioremediation research studies undertaken and that are discussed in this chapter are at different stages of application, ranging from bench studies to pilot studies and full scale operations.

Amongst the most publicised AMD bioremediation processes in field application in South Africa are the THIOPAQ® and BioSURE® processes.

Table 13.6: Published South African reports relating to AMD bioremediation

Nature of research	Scale	Reference	Institute
Integrated algal sulphate reducing high rate ponding process (ASPAM) for the treatment of AMD.	Pilot scale	222	Rhodes University
The Rhodes BioSURE® process Part 1: Biodesalination of Mine Drainage Wastewaters	Pilot plant	223	Rhodes University
The Rhodes BioSURE® Process. Part 2: Enhanced hydrolysis of organic carbon substrates – development of the recycling sludge bed reactor (Report 10)	Laboratory scale and pilot plant	224	Rhodes University
The Rhodes BioSURE® process Part 3: Sulphur Removal Unit Operations investigation and development of the biotechnology of sulphur biofilms in the beneficiation and treatment of wastewater	Laboratory and pilot scale	225	Environmental Biotechnology Research Unit, Rhodes University
A biological process for sulphate removal from industrial effluents	Laboratory-scale plant	226	Council for Scientific and Industrial Research
The potential utilisation of indigenous South African grass types for AMD remediation	Laboratory-scale plant	227	University of the Witwatersrand
Development of integrated biosorption systems for the removal or recovery of heavy metals from mining and other industrial wastewater, and determination of the toxicity of metals to bioremediation processes	Laboratory-scale and pilot plant	228	University of Cape Town
Investigation of sulphide oxidation kinetics and impact of reactor design during passive treatment of mine water	Laboratory-scale plant	229	University of Cape Town

Addressing the Challenges Facing Biological Sulphate Reduction as a Strategy for AMD Treatment: Reactor stage - raw materials, products and process kinetics	Laboratory-scale plant	230	University of Cape Town
Towards passive treatment solutions for the oxidation of sulphide and subsequent sulphur removal from acid mine water	Laboratory-scale plant	231	University of Cape Town
Investigation of carbon flux and sulphide oxidation kinetics during passive biotreatment of mine water	Laboratory-scale plant	232	University of Cape Town
Cellulose fermentation products as an energy source for biological sulphate reduction of acid mine drainage type wastewater	Laboratory-scale plant	233	CSIR Natural Resource and the Environment, Pretoria

BIOREMEDIATION TECHNOLOGIES IN FULL-SCALE APPLICATION

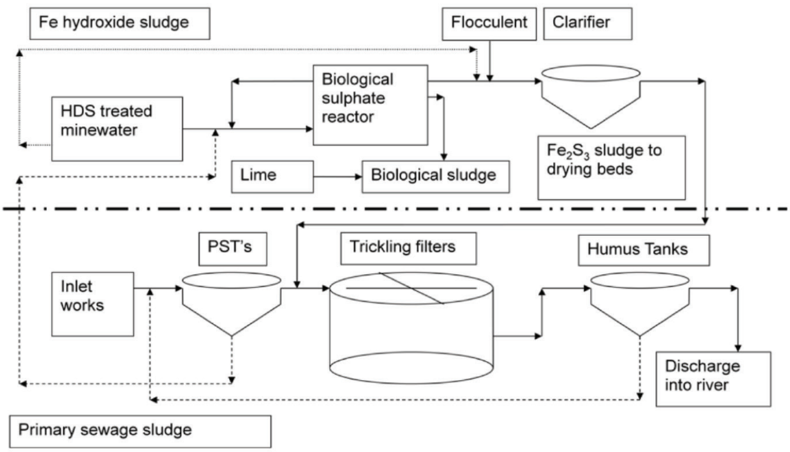
THIOPAQ® PROCESS

The THIOPAQ® process is a biological process developed by the PAQUES Company (Netherlands); it integrates gas desulphurisation with sulphur recovery in a single unit.[234] This process involves a sequential pre-chemical treatment process for the precipitation of carbonate and hydroxide, followed by a sulphate reducing bioreactor which precipitates metals as metal sulphides. The THIOPAQ® process has been successfully used in industry, especially at the ground water treatment plant of Budelco Zinc Refinery in The Netherlands.[235] In South Africa, this technology has been seen as the best option for AMD treatment and commissioned and piloted at the AngloCoal mines in Mpumalanga to treat approximately 3 Ml/d of AMD.[236] Furthermore, the successful application of this technology for the treatment of AMD has been noted in Utah, where 99 per cent of copper present in the Kennecott Bingham Canyon copper mine was selectively removed from AMD in a pH of 2.6.[237] However, the use of ethanol or butanol as carbon source and electron donor has been seen as a limitation of the acceptability of this method, due to the increased cost.[238]

THE RHODES BIOSURE® PROCESS

The Rhodes BioSURE® process is an innovative and cost-effective process developed by the Environmental Biotechnology Group (EBRU) of Rhodes University for the treatment of AMD.[239] This process was commissioned by the South African Water Research Commission and is a biological sulphate reducing process, in which sulphate-polluted water is mixed with the primary sewage sludge, in order to allow the removal of heavy metals and acidic sulphate by the SRB activity. This process was conceptualised based on the microbial ecology and sulphur cycle in tannery ponds, using a recycling sludge bed reactor (RSBR) as the main operating unit, followed by a second sulphate-reducing digester and sulphide-oxidising reactor.[240] The RSBR's main role is the solubilisation of primary sewage sludge to soluble organic matter, such as short chain volatile fatty acids (VFA), which are later used by sulphate-reducing bacteria in the sulphate-reducing digester (Figure 13.4). Based on the success of this process in the lab-scale, a pilot-scale plant has been built by the East Rand Water Care Company (ERWAT) for the treatment of underground mine water from Grootvlei Gold Mine, in order to treat 10 Ml/d.,[241]

Figure 13.4: Process flow diagram of the Rhodes BioSURE® system for AMD treatment[242]



CSIR SYSTEM

The CSIR system is more of a chemical process than a biological one as more emphasis is on the chemical part. This process comprises of sequential chemical and biological stages where lime or powdered $CaCO_3$ is utilised during the chemical stage to raise the AMD's pH for its neutralisation, followed by a ferrous (Fe^{2+}) oxidation and hydroxide precipitation that is caused by simultaneous aeration.[243] A second chemical stage where lime is added to raise the pH for sulphate and metal precipitation is also needed. In this process, a biological sulphate reducing reactor is incorporated for only partial oxidation of sulphide resulting in elemental sulphur (So) by the action of sulphide oxidising bacteria (SOB).

FUTURE OUTLOOK

Biological treatment of AMD is undoubtedly a promising sustainable way for AMD treatment of which, although it is being applied to some extent, the potential contribution it has is yet to be fully realised. In South Africa, when compared to other countries, particularly those in the developed world, application of full scale bioremediation field applications is limited. A lot of research at universities and research institutions, in particular the CSIR, and different mining houses has gone into AMD treatment.[244,245,246,247,248,249] The research results need to be aggressively moved to full-scale environmental application. Only two bioremediation processes (the BioSURE® and THIOPAQ® processes) have been implemented at a commercial scale. A noted and acceptable notion is that AMD treatment is and has to be an integrated approach, in which a combination of treatment approaches (biological, physical and chemical) and designs are required, as well as consideration of economic and environmental factors. AMD beneficiation as coupled to biotreatment is very attractive and needs to be fully investigated and applied to make AMD bioremediation economically viable. Even though the use of bioremediation for the treatment of AMD in South Africa is rather limited, extensive scientific research on AMD bioremediation (compared to other African countries) is commendable, as most, if not all, AMD bioremediation attempts in Africa have been carried out in South Africa. Recently, the South African government has pledged to provide funds for innovative processes to deal with the looming problem of decanting of water and undoubtedly some of the research will centre on evaluation of biological treatment of AMD.[250,251,252]

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CHAPTER 14

Deriving Benefits From Acid Mine Drainage

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ABSTRACT

This chapter reports on the possibility of recovering valuable products (such as drinking water, metals, electricity, pigments and sulphur) from acid mine drainage (AMD) in South Africa. A lot of effort has been put into AMD remediation using different technologies; however, each of the proposed technologies has advantages and disadvantages that tend to limit their use. To compensate for the limitations of the proposed technologies, researchers should focus on AMD remediation, with subsequent recovery of valuable products from such efforts. With 360 Ml/day of AMD being generated from gold mines in South Africa, this issue should not be considered a mining challenge, but rather a resource that could be used as the basis for a new value-added beneficiation industry.

INTRODUCTION

While there are a wide range of technologies available for treating AMD before discharge, the sustainability of any remediation system is a factor that is becoming increasingly critical in decision making.[1] This is because the available and proposed AMD treatment technologies are characterised by various limitations, such as high capital and operational costs, low efficiency, sludge disposal challenges and being inappropriate for removing a wide range of contaminants. For example, popular technologies, such as reverse osmosis and chemical precipitation, result in the generation of secondary waste materials that are environmental pollutants on their own. AMD treatment by chemical precipitation generates huge quantities of metal-rich sludge, while reverse osmosis results in huge volumes of brine being generated (among other limitations). Cognisant of the inevitable generation of secondary waste materials from these processes, the focus should be on recovering valuable products from such endeavours. This approach does not only have the benefit of generating income through the recovery of saleable by-products and thereby reducing the operational cost of treatment, but also allows generation and re-use of recovered products, in some cases. When the value of treated water and by-products exceeds the treatment cost, it is feasible to create enterprises that could provide economic benefits while solving environmental problems. In general, the recovery of valuable products from AMD treatment processes and other uses could include:

- recovery of drinking water;
- recovery of metals;
- recovery of saleable products, such as calcium carbonate and sulphur;
- the production of electricity;
- recovery of agricultural use products (for example, fertilisers);
- adsorbents used in municipal and industrial wastewater treatment;
- pigments, such as ferrihydrite; and
- building- and construction-related materials, such as gypsum and cement.

These products are discussed in detail in the succeeding sub-sections of this chapter.

RECOVERY OF WATER

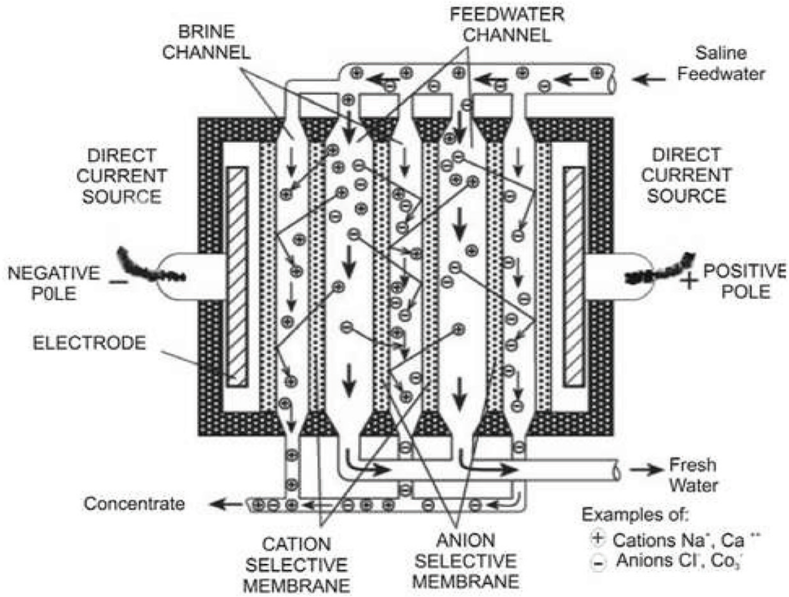
As stated, AMD is acidic water that is laden with sulphates and heavy metals, such as Fe, Mn, Al, Zn, Cu, Ca, Mg, and Cr, making it unfit for any application, be it industrial, agricultural or recreational use. However, the removal of all contaminants from AMD, using various treatment technologies, results in the recovery of clean water, with some of the technologies having the potential to treat AMD to drinking water standards. The CSIR has reported on the recovery of drinking water from gold mine effluent when using the Alkali-Barium Carbonate (ABC) de-salination process.[2] Another example is the Emalahleni water reclamation plant in Mpumalanga, which treats 25Ml/day of AMD water generated by coal mining and restores it to drinking water standards.[3]

Recovered water can also be utilised for agricultural purposes. Du Plessis[4] hinted at the possibility of utilising lime-treated AMD for agricultural crops. Jovanovic et al.[5] went a step further by demonstrating lime-treated AMD being used on a 20 agronomic and pasture crop species in Landau Colliery Kromdraai Open Cast section near Witbank, Mpumalanga Province, South Africa. The researchers monitored crop response and changes in soil chemical properties following sprinkler irrigation with lime-treated AMD. The results of the research were favourable, with considerable increases in the yield of irrigated crops being recorded, compared with rain-fed crops. The potential utilisation of lime-treated AMD water for agriculture is significant, considering that South Africa has low and variable rainfall, with 66 per cent of the country being classified as semi-arid to arid.[6]

Amongst the different membrane technologies, electro-dialysis (ED) has been tested and proven to be an effective technology for clean water recovery.[7,8] ED is an electrochemical separation process that involves the selective migration of aqueous ions through ion selective membranes as a result of an applied electrical potential difference.[9] Researchers, such as Buzzi et al.,[10] reported that electro dialysis is suitable for recovering water from AMD, with contaminant removal efficiencies as high as 97 per cent being recorded. The authors noted, however, that precipitation of iron at the surface of the cation-exchange membrane caused a blockage of the membrane system, thereby reducing efficiency of the process. Consequently, the elimination of iron from AMD prior to the electro-dialysis process would facilitate high contaminant removal efficiencies. The down-side of electro-dialysis is that membranes have a limited lifetime before fouling or failure of adhesive bonds necessitates replacement, thereby making the technology costly. The other disadvantage with ED is the constant electricity requirement to ensure maintenance of pre-heated feed-water; this, in turn, entails a more expensive energy process.

A schematic representation of the ED process is shown in Figure 14.1.

Figure 14.1: Principle of electro-dialysis. Scheme of an electrodyalizer with cell pairs: migration of ions caused by the action of an electric field[11]



Fortunately, the recovery of clean water from AMD is more applicable to water-stressed nations like South Africa that are currently making up the shortfall by purchasing additional expensive water from the Lesotho Highlands Scheme. South Africa currently sources over 10 billion cubic meters of water per year from the Lesotho Highlands Scheme. If the approximately 360 Ml/day of AMD that is being generated from gold mines in South Africa were beneficiated, South Africa would save millions of rands. Such beneficiation efforts are good news for the rest of the African continent, where shortages of drinking water are experienced.

RECOVERY OF METALS

The removal of metal contaminants from AMD is mandatory, owing to their devastating effects on the natural and human environment. However, the removal of metal contaminants from AMD is a costly undertaking that exerts enormous pressure on mining companies – hence the recovery of some of the valuable metals (such as iron, manganese, copper, zinc and aluminium) could help to off-set the treatment cost. Some of the metals that have been removed and purified on an industrial scale by means of ion exchange include:[12] uranium, thorium, rare earth metals, gold, silver, platinum group metals, chromium, copper, zinc, nickel, cobalt and tungsten. Aube and Zinck[13] noted that acid mine drainage sludge can contain as much as 22 per cent zinc. Accordingly, various technologies (such as selective precipitation, ion exchange and selective adsorption) could be used to recover heavy metals from AMD. Depending on the method employed for AMD treatment, chemical precipitation results in the generation of metal-rich sludge that is normally rich in iron content (20–30 per cent).[14] Many attempts were made to recover metals from AMD sludge, with the processes being reported to be difficult and economically unfriendly in some cases. Selective precipitation of AMD (which involves adding alkaline reagents to increase the solution's pH level and which results in dissolved metals being precipitated as hydroxides) appears to be attractive. Macingova and Luptakova[15] reported on the selective recovery of Fe, Cu, Al, Zn and Mn from AMD in a selective sequential precipitation process. On the other hand, Chen et al.[16] demonstrated the practicality of recovering metals from AMD using the fractional precipitation process. Sludge rich in Fe, Mn, Cu and Zn was generated in the process. The metal recovery efficiencies of Fe, Mn, Cu and Zn were 99.51 per cent, 79.71 per cent, 86.09 per cent and 87.87 per cent, respectively; the four corresponding types of sludge generated had metal grades of 45.91 per cent, 7.95 per cent, 11.58 per cent and 31.06 per cent, respectively.

Ion exchange methods have been employed for the recovery of several metals from acid mine drainage. Earth Metallurgical Solutions Company, based in Johannesburg, South Africa, has demonstrated the ability to recover valuable products from AMD effluent on a commercial scale using ion exchange processes. Howard et al.[17] reported that Earth Metallurgical Solutions recovers uranium and sulphate ions from AMD effluent. The uranium-bearing solutions could be sold to uranium processors. The sulphate ions recovered are reacted with ammonia gas to form a 20 per cent ammonium sulphate solution.[18] Metal cations are also recovered by use of cationic exchange resins, which are later eluted with nitric acid to form a mixed metal nitrate solution that can be sold. They also used metal nitrates extracted from AMD in explosive testing.

RECOVERY OF CALCIUM OR BARIUM CARBONATE AND SULPHUR

One of the technologies with the potential to solve the AMD treatment problem is the South African Council for Scientific and Industrial Research's (CSIR) Alkali-Barium Carbonate (ABC) process.[19] The barium carbonate used in this process is recyclable by barium sulphate calcining in the presence of coal and subsequent CO_2 treatment of the BaS. Masukume et al.[20] reported on the technical feasibility of recovering barium carbonate and elemental sulphur from barite sludge on a pilot scale. Likewise, the production of elemental sulphur and calcium carbonate ($CaCO_3$) from gypsum waste can be achieved by thermally reducing the waste into calcium sulphide (CaS), which is then subjected to a direct aqueous carbonation step for the generation of hydrogen sulphide (H_2S) and $CaCO_3$. Figure 14.2 shows the block flow diagram for the production of $BaCO_3$ and elemental sulphur. The H_2S produced was oxidised by ferric iron to elemental sulphur, while the resultant ferrous iron was re-oxidised in a biological reactor. The experiments were carried out on a Tshwane University of Technology (TUT) pilot plant. The TUT sulphur recovery pilot plant is shown in Figure 14.2. The barite/gypsum sludge that was used as a source of these valuable products was generated during AMD treatment by the ABC process. Maree et al.[21] noted that the use of calcium carbonate over lime for neutralising AMD resulted in the production of smaller sludge volumes.

Calcium carbonate from gypsum recycling also fetches a high price, as it is used in manufacturing high quality paper and pharmaceuticals. Ceramic tiles contain about 80 per cent calcium carbonate. The recovery of calcium carbonate from gypsum is also economically feasible; from 1t of gypsum, 0.58t of calcium carbonate can be recovered, with a value of R116.[22] Elemental sulphur is also a key raw material for many manufacturing industries, such as fertilisers, acids, steel, petroleum, insecticides, titanium dioxide and explosives, etc. One tonne of waste gypsum yields 0.19 tonne of sulphur.[23] Africa is a net importer of sulphur and South Africa alone imports on average 1.5 metric tonnes per year. Countries like DRC and Zambia import large quantities of sulphur at high cost. Hence the recovery of sulphur from AMD is of strategic national importance, due to the significance of the product to the South African economy and Africa at large.

Figure 14.2: Block flow diagram for the production of $BaCO_3$ and elemental sulphur[25]

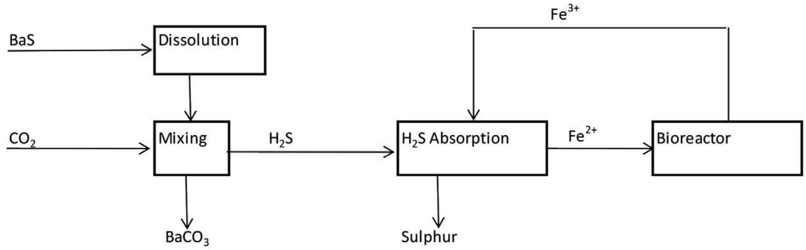
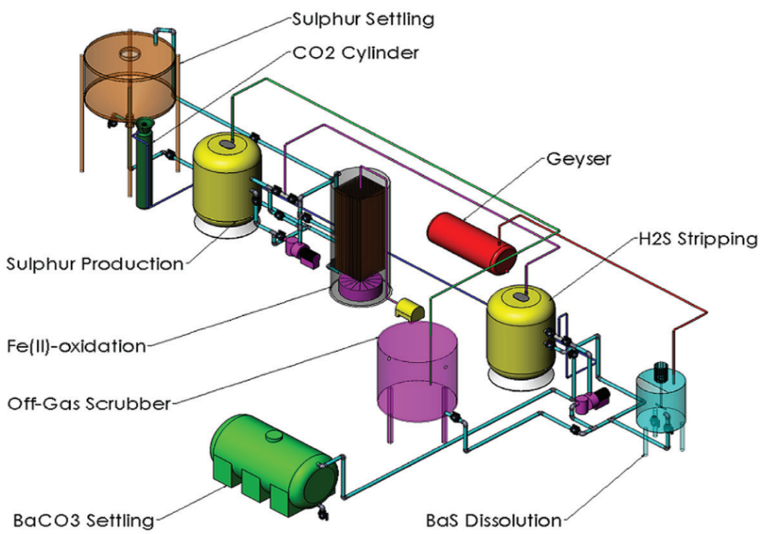


Figure 14.3: TUT sulphur recovery pilot plant



SULPHUR RECOVERY REACTIONS

Dissolution of BaS and reaction with CO_2 to form $BaCO_3$ and H_2S:

$$BaS + H_2O + CO_2 \rightarrow BaCO_3 + H_2S \quad (1)$$

H_2S stripped and converted to elemental sulphur via the ferric iron route:[26]

$$H_2S + 2Fe^{3+} \rightarrow S + 2Fe^{2+} + 2H^+ \quad (2)$$

Figure 14.4: Sulphur slurry from TUT pilot plant

RECOVERY OF SULPHURIC ACID

AMD is acidic in nature, due to high concentrations of sulphuric acid. The high acidity of AMD makes it highly corrosive and pollutant. However, sulphuric acid is commonly utilised in fertilisers and chemical processing. Hence, there is a need to recover sulphuric acid from AMD to make it corrosive free, while at the same time recovering valuable products. Various technologies (such as ion exchange[27], solvent extraction,[28] electrolytic precipitation/deposition[29] and electro-dialysis[30] have been utilised to recover acid from wastes, with electro-dialysis being the preferred method because it is efficient. Different electro-membrane processes (for example, bipolar ED, electro-dialysis or distinct ED configurations) have been effectively used to recover sulfuric acid from various industrial wastewaters, such as nuclear decontamination effluent or rinsing water used in electro-refining operations;[31,32] processes used in these technologies could be adopted for recovering sulphuric acid from AMD.

Researchers such as Marti-Calatayud et al.[33] reported on the successful recovery of sulphuric acid from AMD by means of a three-compartment electro-dialysis cell with the simultaneous removal of Fe(III) species. The authors noted that the increase in applied current density led to an increase in the concentration ratio of sulphuric acid, which reached a value of 4.00 for 15 mA.cm-2. However, the increase in the concentration ratio was not proportional to the increments in current density. The limitation of the technology is the formation of ion precipitates on the cation exchange membrane, which increases the cell voltage, thus increasing the energy requirements for the process. Marti-Calatayud[34] concluded that there is a need to explore this technology further, in order to prevent this phenomenon.

PRODUCTION OF ELECTRICITY

Many researchers have reported on the technical feasibility of the microbial fuel cell (MFC) based technology for electricity generation. The technology involves converting organic waste, including low-strength wastewater and lignocellulosic biomass, into electricity through the metabolic activity of micro-organisms.[35] Making use of the MFC principle, researchers such as Cheng et al.[36] developed the AMD fuel cell as a sustainable and cleaner technology for AMD treatment with the subsequent generation of electricity. The researchers demonstrated that an AMD fuel cell can efficiently remove dissolved iron from AMD, while also generating electricity at power levels similar to conventional microbial fuel cells. The AMD fuel cell developed had a maximum power density of 290 mW/m2 at a Coulombic efficiency greater than 97 per cent. The possibility of generating electricity from AMD is good news for countries like South Africa that suffers from loadshedding as a result of the increased national demand for electricity. It is important to note that more research work needs to be done in this area and that the government needs to provide more funds for pilot studies that lead to commercialisation of technologies to the benefit of South Africa at large.

PRODUCTION OF IRON PIGMENTS

The iron oxide pigments have wide application in construction, ceramics, coatings, ink, rubber, plastics, drugs, paint and cosmetics, with the building materials industry being the biggest user. Hence the market for iron oxide pigments is wide. Accordingly, the possibility of recovering iron oxide pigments from AMD could be good news for these industries. Marcello et al.[37] reported on the recovery of inorganic pigments from the recycling of acid mine drainage treatment sludge. The authors developed a technology wherein AMD was treated using a two-step selective precipitation process to produce marketable iron oxides as raw materials for the production of ceramic pigments. In addition, Hedin[38] reported that iron oxide sludge recovered from an abandoned coal mine in Pennsylvania was used to manufacture burnt sienna pigment in a commercially successful venture. Inorganic pigments also have wide application in paint products, resins and polymers.

Wei and Viadero Jr[39] demonstrated the technical feasibility of producing magnetite nano-particles using ferric iron recovered from AMD as a feedstock. Ferric iron was recovered from AMD via the oxidation-selective precipitation process, by co-precipitation of ferric and ferrous iron at pH 9.5 under inert conditions. Magnetite nano-particles have been applied in a variety of fluids, ranging from ferrofluid,[40] biomedicine[41] and controlled drug delivery,[42] to nano-sorbents in environmental engineering,[43] due to their nano-size effect and paramagnetic properties. In addition, Cheng et al.[44] demonstrated that it is possible to use AMD types of soluble iron solutions in fuel cell-based technologies to create spherical nano-particles of iron oxide (ferrihydrite) that are transformed to goethite (α-FeOOH) upon drying. There is great potential for the production of iron pigments in South Africa, which has revealed high Fe (II) AMD concentrations – as high as 800 mg/l.

BUILDING AND CONSTRUCTION MATERIALS

The inorganic components in acid mine drainage treatment sludge can be used for the production of building materials, such as cement and bricks.[45] This is because many of the sludge constituents (such as calcite, gypsum, silica, aluminium, manganese and iron) are raw materials commonly used in cement manufacturing[46] According to Lubarski et al.,[47] the high aluminium content of sludge produced from the treatment of acid mine drainage at some coal and gold mines could be used for the production of aluminous cement. Similarly, research by Tay and Show[48] has shown that sludge can replace up to 30 per cent of Portland cement in blended cement. In the case of South Africa, houses have already been constructed with bricks made from AMD sludge in the Witbank area. Large quantities of sludge that are currently being generated from AMD treatment by neutralisation and precipitation technologies in East and West Rand areas could be used for the manufacture of building materials.

USE AS ADSORBENT IN INDUSTRIAL WASTEWATER TREATMENT

Well established technologies for phosphorous removal from wastewater entails the use of alum, ferric chloride or lime as coagulants;[49] however, the cost of these coagulants is too high for low concentrations and the high volumes often encountered in wastewater.[50] Wei et al.[51] hypothesised that AMD sludge containing a mixture of iron and aluminium hydroxide sludge would be a suitable medium for the adsorption of dissolved orthophosphate from solutions. Consequently, several researchers have reported on the successful application of ferrihydrite sludge as an adsorbent in wastewater treatment. Acid mine drainage sludge can be utilised as a low cost adsorbent to efficiently remove phosphorous from agricultural and municipal wastewater. The adsorbed phosphorous can later be stripped from the spent sorbent and recycled into fertiliser. Sibrell et al.[52] reported on the use of Ferroxysorb media prepared from AMD sludge for the removal of phosphorous from agricultural wastewaters. Excess phosphorous in wastewater promotes eutrophication in receiving waterways. In addition, Cui et al.[53] demonstrated the capability of AMD sludge to treat acid mine drainage laden with lead, zinc and other heavy metals. The continuous system recorded removal efficiencies as high as 97.2–99.8 per cent for all heavy metals. Similarly, researchers like Flores et al.[54] have shown that iron oxides from acid mine drainage sludge can be used as effective adsorbents for the removal of carcinogenic azo Procion red H-E7B dye from aqueous solutions. The researchers also demonstrated the ability of iron oxide from AMD sludge to act as a catalyst during H_2O_2 decomposition. This material could be used as a cost-effective adsorbent for the removal of cationic, anionic and organic contaminants from water, especially in South Africa, where water resources are under threat from industrial and mining pollution.

CONCLUSION

There is great potential to recover valuable products from the huge quantities of AMD being produced in South Africa. If fully recovered, the value of these products will not only offset AMD treatment cost, to the benefit of the mining companies, but will help improve the South African economy. As reported, most of the beneficiation processes are still at the developmental stage. In order to accelerate the beneficiation evolution, key stakeholders need to play an active role. The government and the private sector need to provide enough funding in order for extensive applied research to be undertaken. There is a need to provide adequate training to research scientists in order to develop rich business mind-sets. There is a great need to invest in relevant infrastructure such as pilot plants, demonstration plants and scale up facilities.

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CHAPTER 15

Managing the Acid Mine Drainage Menace

The Way Forward

Vuyo Mjimba

INTRODUCTION

> 'The difficult we do immediately. The impossible takes a little longer.' – Motto of the US Army Corps of Engineers during World War II

Based on the preceding chapters, this book ascertains that there are three schools of thought regarding the acid mine drainage (AMD) challenge in South Africa and elsewhere. The first school of thought (hopefully supported by the minority) is that which has resigned itself to fate. This position is based on the enormity of the challenge and the length of time over which the challenge has been allowed to manifest before intervention was initiated. The second school of thought is held by those who have hopes that the problem can be managed, albeit with a considerable degree of difficulty. The third school comprises those that are energised to try (on a large scale) the various AMD remediation technologies and innovations brought to the fore by various research and development bodies. This chapter presents potential channels for dealing with AMD challenges.

The chapter unfolds in a manner that is based on the three schools of thought, that is: (i) some of the current and future AMD impacts are inevitable because of the extent of the AMD challenge; (ii) the nature and extent of the AMD challenge is such that it requires concerted effort by a divided stakeholder system, and; (iii) there are innovations that can be used to mediate the production, spread and impact of AMD. Before unpacking the way forward, a brief recap of the core messages contained in the previous chapters may be necessary.

WHAT IS THE STORY?

The preceding chapters have revealed numerous important issues in terms of the AMD management discourse. Out of these issues, this chapter posits that four issues are critical for a way forward in managing the past, current and future challenges of the AMD phenomenon. The first issue is that the genesis of the AMD challenge, which is manifesting as a series of environmental, economic and social challenges, results from a combination of limited knowledge of the genesis of large-scale mining activities in South Africa and the failure to address the challenge after the signs had been determined. The former is reflected in the development of environmental legislation that has governed the mining industry, as outlined in Chapter 7. The latter is reflected in what Lwabukuna (in Chapter 8) refers to as socio-institutional and legal issues that are impacting on the state's ability to act in preventing, minimising and addressing AMD challenges emanating from 'ownerless' historical liabilities, and ensuring that known and currently active mining houses live up to the 'polluter pays' principle.

The second issue is that the continued treatment of the environmental impacts of mining as an externality is skewing the perceived returns from the industry. Kaggwa reflects on this in Chapter 6. He correctly notes that whereas the Minerals and Petroleum Resources Development Act (MPRDA) of 2002[1] mandates the internalisation of the social and environmental cost of mining, it does not, however, explicitly refer to the AMD challenge. The author states that this legal loophole is allowing miners to circumvent the AMD responsibility challenge. Matenga and Gumbo (in Chapter 5) add to Kaggwa's argument and posit that social impact assessment prior to and post mining must be mandatory to ensure that mining firms internalise the cost of managing AMD, just like other adverse environmental impacts. The third issue is that there are means to manage the AMD challenge. Tekere and Kamika (Chapter 13) and Ndlovu (Chapter 12) outline a plethora of AMD remediation technologies. Their work reveals that the remediation processes can either be active or passive, and that these combine biological, chemical and physical approaches. The fourth and final critical issue is that the management of AMD carries pecuniary implications. This partly explains the complexity of dealing with this challenge. Banda and Zolani (Chapter 11) interrogate this subject and suggest innovative ways to manage the cost of AMD remediation.

These four issues reveal a complex knit of social, economic and technological aspects that are intricately woven around the issues of economic development and addressing the legacy of apartheid in South Africa. It is thus apparent that mapping the way forward in managing the AMD menace has to simultaneously address past, current and future social, economic and environmental factors. It is against this background that this book suggests a way forward, based on the aforementioned schools of thought.

IT IS NOT A *FAIT ACCOMPLI*

In South Africa, the AMD challenge can be traced back more than 100 years to the 1800s. Given that there have been no structured legal instruments and initiatives to deal with the challenge, the enormity of the AMD challenge in South Africa is not surprising. As Mjimba, Mujuru and Mutanga outline in Chapter 2, the AMD challenge has spread beyond its source. However, this does not mean that the problems cannot be dealt with. While some of the impacts are inevitable, given the spread of AMD, in principle, there are ways to ensure that acid water discharges from disused mine shafts and dumps are reduced or eliminated. This could be ensured by employing source control measures, which pertain to the prevention of the formation and leakage of acid water from mine shafts and mine dumps, by making the environment less ideal for AMD formation. A number of approaches are available to this end and two such approaches are outlined here.

The first plausible approach is filling and sealing all known and abandoned mine shafts. Filling can be achieved by two means: flooding, or mining waste materials in the disused mine shafts. Filling of mine shafts has the effect of consuming and excluding air. If a mine shaft is flooded, the oxygen that is dissolved in the flood water is consumed by micro-organisms and by chemical reactions. This limits the presence of oxygen, water and sulphide-bearing rock in proportions that lead to the formation of AMD.[2] Sealing the shaft serves to prevent the replenishment of oxygen by either mass transfer or diffusion. While the approach is plausible, in principle, its practical application may be a challenge. For, instance South Africa and many other mining economies are water scarce countries. Diverting this scarce resource to flood disused mine shafts may carry negative political connotations, although the long-term benefits may be desirable.

Returning mine waste to the disused mine shaft could be argued to be an extension of the age- old practice of storing waste in these shafts. Disused mine pits have long been viewed as ideal sites for storing a variety of waste materials. As with flooding, returning the waste rock to the shafts and pits serves the dual purpose of: filling the cavities where water may accumulate and accelerate AMD formation; and addressing the aesthetic concerns regarding mine dumps and tailings dams.[3] However, the approach has a challenge with seepage that may contaminate underground water. Even so, the rate of seepage is not rapid, which reduces the magnitude of the AMD challenge. A key issue is that the covering material must be impervious (as much as possible) to water and air to limit permeation and leeks.

The second approach relates to the formation of AMD outside the mine shafts. Mine dumps (spoil piles, tailings dams and spent heap-leach pile), containing sulphides bearing waste rocks are a significant source of AMD. Within this approach Kuyukac suggests four ways for preventing or minimising AMD formation.[4] The first way involves diverting both surface and underground water away from sulphide-containing waste dumps. Natural precipitation on the dumps breaks into infiltration, surface run-off or interception, depending on the texture of the dump material and the topography of the dump site. Infiltration water percolates down the dump heap and emerges at the bottom as acidic water. The practice is that this water is diverted to storage dams, where it collects with other water for treatment before re-use in mining operations or discharge into the environment. The second way pertains to storing potentially acid-producing mine waste under shallow water cover. This is similar to flooding mine shafts, in that the water acts as a barrier that limits oxygen availability of sulphide-bearing waste materials. While this is a plausible way of limiting AMD formation from mine waste, its application is limited by water availability. A third and related management approach involves covering the sulphide-bearing waste material with soil and other physical types of cover to exclude water and oxygen from this waste. The fourth and final way involves the separation of waste. The scholar suggests the separation of waste rock containing a high concentration of sulphide mineral from the rest of the waste rock. This sulphide-containing waste can then be treated to reduce its AMD formation potential.[5]

These approaches are particularly applicable to new and operational mines. However, research could be done to adapt some of the techniques for application in long-disused mines. While these and other approaches are aimed at preventing the formation of AMD, the reality is that acidic water is currently forming and being discharged into the country's national waterways. This dictates the need to treat the waterways and reservoirs that are receiving, channelling and holding acid water from AMD generation sites.

MANAGING THE BIG PROBLEM

Chapters 2 and 4 show the scale and distribution of acid water discharge from disused mines into South Africa's waterways and reservoirs and the effect on the flora and fauna in the surrounding habitats. The enormity of the challenge could be a source of despair for a number of stakeholders. However, this does not necessarily mean the challenge cannot be overcome. The experience of treating river contamination after the 2015 Colorado Mine (United States of America) spill provides important lessons for South Africa.

The Colorado spill was and continues to be managed through a combination of treating the water with caustic soda (sodium hydroxide) and lime (calcium oxide), which are very basic in pH, on the one hand, and dilution with fresh uncontaminated water, on the other hand. Caustic soda and lime serve to reduce the acidity of the water and thus maintain water in a safe condition for the flora and fauna that thrive in freshwater. Dilution acts similarly. However, the shortage of fresh water supply may affect the use of dilution as a viable treatment approach. This is particularly important for South Africa, which is a water scarce country. Climate change induced droughts are exacerbating this water scarcity problem.

A challenge to treating the waterways and reservoirs is the cost. This calls for a critical cost benefit analysis and re-evaluation of how these costs are computed and valued within the larger context of sustainable development.

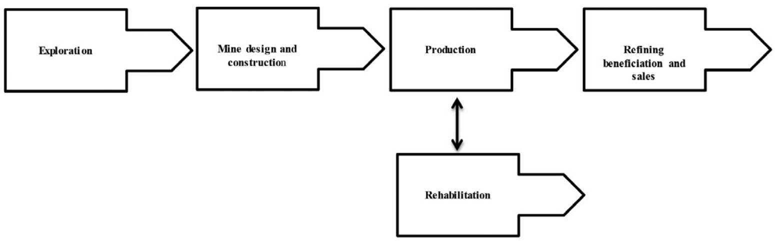
THE NEW APPROACH

An important issue to emerge from this book is Kaggwa's assertion that the treatment of during-mining and post-mining environmental effects as an externality is fundamentally flawed. This assertion echoes the conceptual sentiments of the sustainable development, triple bottom line and green economy transition theoretical underpinnings.

In these discourses, social and environmental concerns contribute to the final assessment of the economic benefits of a project such as mining. The triple bottom line concept introduces the concept of full cost accounting. For example, if a mining project creates jobs, but leads to environmental degradation that affects the health of employees and surrounding communities, then that project's financial statement must include the full societal cost benefits or otherwise. Two questions arise from this approach: (i) When do the adverse effects of such a project commence?; (ii) Who carries the associated remedial costs? To address these questions, a generic mining value chain (Figure 15.1) is used to posit that all those directly and indirectly linked to the mining industry are responsible for the AMD challenge and thus have to contribute to its management.

The first question pertains to accurate identification of the genesis of a mining project. An examination of a generic mining value chain suggests that mining begins with exploration. The process of exploration seeks to identify and confirm the presence of a technically and commercially exploitable mineral deposit. Proof of such deposits results in the construction of a mine and operations commencing. It can thus be argued that exploring and proving a viable mineral deposit, on sites that contain rocks with a high sulphide content, tacitly marks the genesis of AMD formation. If this rule holds, it therefore implies that exploration firms must bear the cost of AMD management in part.

Figure 15.1: A generic mining value chain[6]



The exploration process is followed by the mine construction phase. This phase typically involves the construction of infrastructure that serves to exploit the proven mineral deposit. A critical component of mine construction is creating access to the mineral deposit. The access is either an adit or shaft for underground mining or terraced pits for open-cast mining. Creating this access involves stripping off the vegetation and overlaying earth and rocks. This process inevitably chips and breaks rocks, some of which contain minerals that react with air and water to form AMD. This implies that mine construction firms play a role in AMD formation. As such and similar to exploration firms, it may be prudent to ensure these firms also bear part of the AMD management cost.

Following the construction phase, production (commonly known as mining) begins. Production phase activities comprise drilling, blasting, loading and hauling of the ore-bearing rocks and earth. This ore-bearing rock may be processed on-site or off-site to recover the desired mineral. The production process deepens shafts, and creates tunnels, ore stockpiles and mine waste dumps. During the production process, water accumulating in the shafts and tunnels is routinely pumped out to ensure working space accessibility. Mine dumps and stockpiles are often protected and managed for safety and environmental purposes. The effects of the production phase in AMD formation only become apparent when production ceases and water begins to accumulate in the shafts or when mining tailings dams fail. The result is that mining houses are the 'visible' contributors to the AMD challenge. While it is indisputable that they are the major and direct contributors to the AMD challenge, it is equally indisputable that they are not the sole contributors to the challenge. As argued earlier, explorers and mine constructors are also partly responsible. Also culpable are the firms that use mining outputs and these should also bear the cost of remediation. Accepting this shared responsibility is a major challenge, as is determining the level of culpability of each party and how much each party should contribute to the finance cost of the management of the AMD menace. Addressing this question is beyond the scope of this chapter and book. An indisputable truth is that the menace needs to be addressed, as it impacts both the economic and social viabilities of all firms that are integrated into the various mining value chains.

An important aspect of this 'shared responsibility' is the development and implementation of an innovative and appropriate policy and regulatory system. Government is critical in this regard. A critical caveat to note at this point is that private enterprise will frown upon any policies and regulation that carry pecuniary implications. Traditionally and inevitably, any suggestions of such legislation will almost always be accompanied by the threat of disinvestment and suggestions that the country has become 'uncompetitive'. To guard against this, South Africa can work within the larger context of the Southern Africa Development Community, in a regional context, and the African Union Agenda 2063, in a continental context. Such a larger context would ensure that the country does not legislate itself into an uncompetitive position. It would also ensure that the country does not bear the cost of poor AMD management by its neighbours.

Irrespective of the context, an ideal set of policies and regulations should contain the following elements:

- Define the department/agency that is responsible for AMD management.

- Define pre-mining, during-mining and post-mining site management, with specific reference to addressing the AMD challenge.
- Define new accounting principles for reporting returns from mining houses, so as to ensure they internalise environmental management costs.
- Define how each player that is integrated into the mining value chain contributes to the cost of AMD management.
- Define the incentives and sanctions for managing or evading responsibilities in managing the AMD challenge.

Developing a comprehensive policy and regulatory system is a complex process. Adding the 'burden' of distributing the cost of managing the AMD challenge makes this a near impossible undertaking. However, the impetus to begin this 'impossible' task is the threat that AMD poses to South Africa's infrastructure, agriculture and other economic and social sectors.

CONCLUSION

In reading this book, two important issues emerge. The first is confirmation that mining is an important industry in South Africa (and Africa) and that it is likely to continue to play a significant role in economic growth and development. Irrespective of its adverse environmental impacts, it is highly unlikely that the industry's importance will diminish. Instead, it is highly likely that it will be elevated, particularly when the world emerges from the current recession and most definitely when a number of developing countries simultaneously realise positive economic growth and development. The second is that the adverse impacts of mining are generating greater concern from a variety of stakeholders. This combination of factors dictates a need for a mining industry that is flexible enough to accommodate policy and regulatory changes regarding environmental management. An important shift in this regard will be the internalisation of mining-related environmental costs throughout the mining value chain. The motto of the US Army Corps of Engineers during World War II should serve as a reminder that this is not impossible, but that the process will simply be longer and challenging.

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