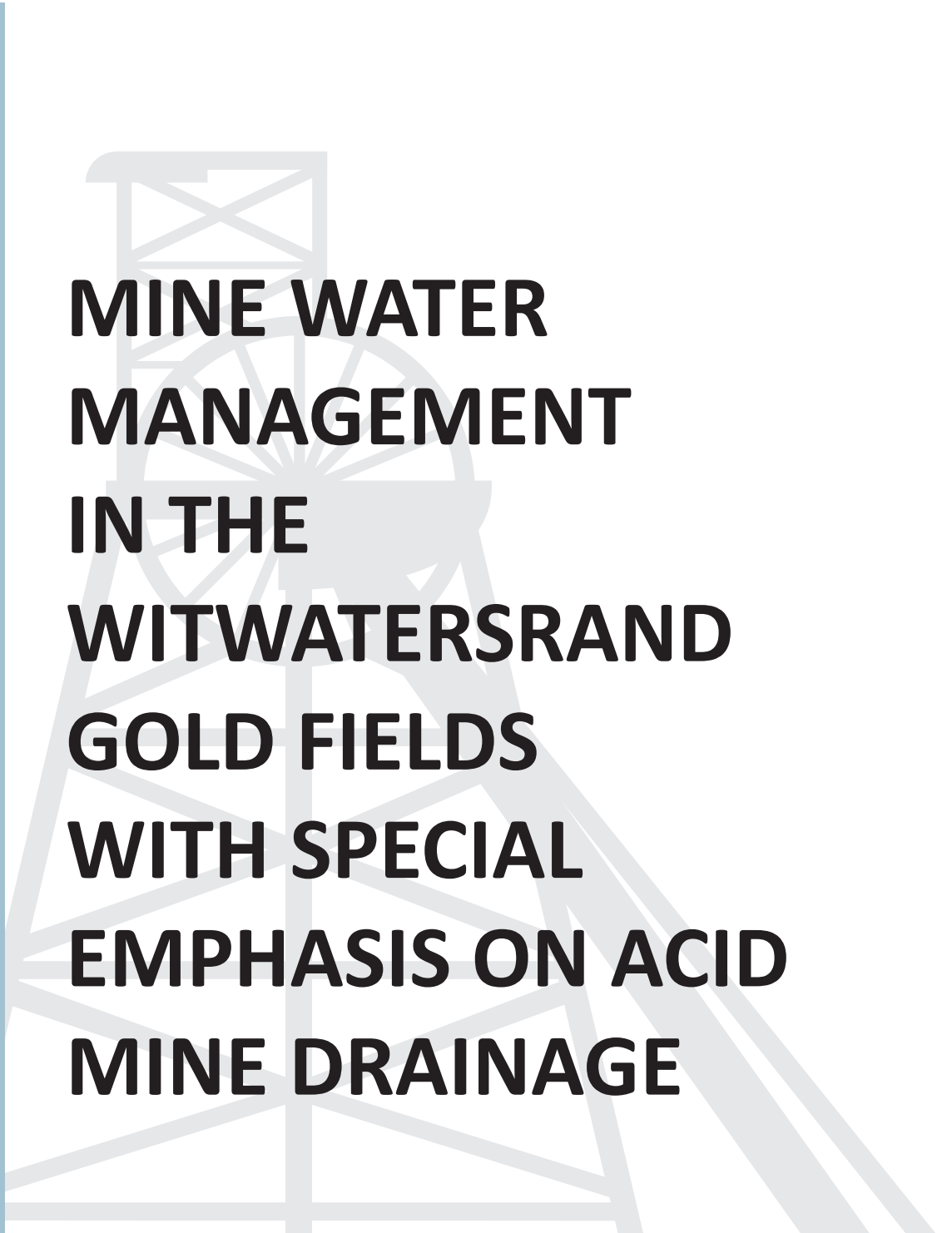
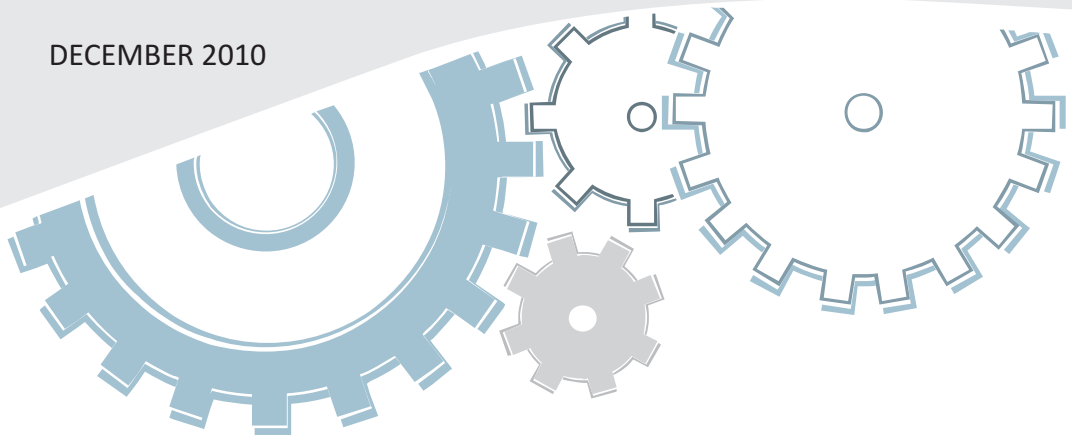




MINE WATER MANAGEMENT IN THE WITWATERSRAND GOLD FIELDS WITH SPECIAL EMPHASIS ON ACID MINE DRAINAGE

**REPORT TO THE INTER-MINISTERIAL COMMITTEE ON
ACID MINE DRAINAGE**

DECEMBER 2010



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Prepared by the Expert Team of the Inter-Ministerial Committee under the Coordination
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EXECUTIVE SUMMARY

A Team of Experts has been instructed by a Task Team, chaired by the Directors General of Mineral Resources and Water Affairs to advise the Inter-Ministerial Committee (IMC) on acid mine drainage (AMD), comprising the Ministers of Mineral Resources, Water Affairs and Science and Technology and the Minister in the Presidency: National Planning Commission. The Team of Experts is reporting on its assessment and reappraisal of the situation with respect to acid mine drainage, focusing on the Witwatersrand Gold Fields.

Examination of international and local literature on all aspects of AMD (e.g. its formation, control, management, treatment and impacts) indicates that the subject has been extensively researched and studied globally and in South Africa. This has resulted in a sound but generic understanding of the process and the various components of the AMD problem in South Africa. This examination has also, however, highlighted the complexity of the host and receiving environments that militates against a single or 'one size fits all' solution to address the problems associated with AMD. However, with regard to the Witwatersrand Gold Fields, sufficient information does exist to be able to make informed decisions regarding the origins of the mine water, potential impacts, management strategies, treatment technologies, etc.

AMD has been reported from a number of areas within South Africa, including the Witwatersrand Gold Fields, Mpumalanga and KwaZulu-Natal Coal Fields and the O'Kiep Copper District. The Western, Central and Eastern Basins are identified as priority areas requiring immediate action because of the lack of adequate measures to manage and control the problems related to AMD, the urgency of implementing intervention measures before problems become more critical and their proximity to densely populated areas. The situation in other mining regions of the country requires additional information, monitoring and assessments of risk, particularly in vulnerable areas such as the Mpumalanga Coal Fields, where the impact of mining on the freshwater sources in the upper reaches of the Vaal and Olifants River Systems is of serious concern.

The following risks have been identified with respect to the flooding of the mines in the priority areas and the subsequent decant of AMD to the environment:

- Risks owing to flooding of the mines
 - Contamination of shallow groundwater resources required for agricultural use and human consumption
 - Geotechnical impacts, such as the flooding of underground infrastructure in areas where water rises close to urban areas
 - Increased seismic activity which could have a moderate localised effect on property and infrastructure
- Risks owing to the decant of AMD to the environment

- Serious negative ecological impacts
- Regional impacts on major river systems
- Localised flooding in low-lying areas.

A generic approach to the management of these risks has been proposed for implementation in the three priority areas:

- Decant prevention and management: Experience in the Western Basin has shown the severe impacts that can be expected if the mine void is allowed to flood completely and decant. For this reason it is recommended that the water levels in the basins be held at or below the relevant Environmental Critical Levels¹ (ECLs) by pumping of water. In the Western Basin this will require pumping to lower the water level that is already at surface.
- Ingress control — reduction of the rate of flooding and the eventual decant volume: Pumping and treating water into the future will be a costly exercise. It is therefore necessary to reduce the volume of water to be pumped and treated. The water flooding the mine void comes from several sources, including direct recharge by rainfall, groundwater seeping into the workings, surface streams that lose water to shallow mine workings, open surface workings, seepage from mine residue deposits and losses from water, sewage and stormwater reticulation systems. Ingress control can be achieved by preventing the recharge of the shallow groundwater above the mine void by the canalisation of surface streams, the sealing of surface cracks and mine openings and a number other measures. In some areas it may prove feasible to abstract clean groundwater from aquifers that feed water into the mine voids, thereby reducing the volume of water that becomes polluted. This will also provide an additional clean water resource for use in the area. The possible losses from water, sewage and stormwater systems must also be addressed.
- Water quality management: Even if the above measures are implemented, AMD will still be produced and require treatment to a quality that is fit for a predetermined use, or for discharge to surface streams. Various treatment options and technologies, including active, passive and *in situ* treatment technologies, have been identified and reviewed. Given the variability in water quality between the different basins and the possibility that the water quality in the mine voids will improve over time, it is likely that a suite of different technologies will be required.

Flooding of the underground mine workings, representing more than 120 years of mining in the Witwatersrand Gold Field, culminated in the decant of AMD from the smallest basin, the Western Basin, in late-August 2002. Flooding commenced when the last mine

¹ The environmental critical level is defined as the highest water level within the mine void where no AMD flows out of the mine workings into the surrounding groundwater or surface water systems.

to shut down in this basin ceased pumping. The volume of decant has peaked at ~60 megalitres per day (ML/d) in response to recharge during exceptionally wet summer rainfall seasons. More typical, however, is a decant rate of ~15–20 ML/d. Basic treatment of this water currently permits the release of ~12 ML/d into the Crocodile (West) and Marico drainage system. The existing pumping and treatment capacity is inadequate to effectively manage the impact of AMD, with the excess volume flowing untreated into the receiving aquatic environment.

In the largest basin, the Central Basin, the water level has been rising at an average rate of 0.59 metres per day (m/d) since July 2009, varying seasonally between 0.3 and 0.9 m/d. By end-November 2010, the mine water level reached an elevation of ~1155 metres above mean sea level (mamsl), measured in Catlin Shaft at Simmer & Jack Mine. This is ~510 m below surface (mbs) at this location. Linear extrapolation of the longer water level graph for South West Vertical Shaft at East Rand Proprietary Mines (ERPM) predicts that the rising water level will reach the surface by March 2013. This will be updated as more monitoring data is collected. By this time, however, it will have sterilised still exploitable gold reserves located at a depth of less than 400 mbs. Of even greater consequence is that it will not only have flooded the shallower underground tourist facilities at Gold Reef City, but also compromised the shallow groundwater resource associated with the dolomitic strata located to the southeast of Johannesburg.

The flooding of the Central Basin has also been associated with an increase in seismic activity. A seismic monitoring programme has confirmed an increased frequency of earth tremors in the Central Basin following the cessation of pumping by ERPM in October 2008. This has established a clear cause and effect relationship between seismic activity and mine flooding. Although the magnitude of these events is unlikely to exceed those that characterised the Witwatersrand during the phase of active and extensive mining, risk analysis suggests that the probability of slightly larger magnitude events occurring cannot be ignored. Whilst the monitoring of seismicity associated with the flooding of the Central Basin cannot prevent the events from occurring, it is important to continue with this activity in the short to medium term in order to gather information and data on the frequency of occurrence and size and location of the events. This is especially important for identifying whether the events are restricted to the immediate surroundings of the mining areas, or whether they are propagating away from the flooding mine, implying that geological structures at some distance from the mining areas are at risk of being activated. The information gathered over time would also be useful for microzonation studies. This would highlight the changes in seismic risk that the infrastructure within urban areas surrounding the Central Basin would be exposed to.

The situation in the third basin, the Eastern Basin, is currently complicated owing to uncertainty regarding continuation of pumping at Grootvlei Mine. This mine has historically maintained the mine water level in this basin at a depth of ~700 mbs in its Number 3 Shaft. This has been achieved at a long-term pumping rate of 75–108 ML/d. Whilst continuation of this pumping regimen is at risk of failure owing to financial constraints, an early casualty of the situation was the treatment of the raw mine water prior to its release into the Blesbok Spruit and a Ramsar-listed wetland. Treatment of the

mine water has not occurred for some time. The cessation of pumping will result in flooding of the pump station within 30 days, after which the mine water will rise to its decant level and decant in or close to the CBD of Nigel on the East Rand.

In light of the above, it is recommended that AMD intervention and management measures are undertaken in the Western, Central and Eastern Basins as a matter of urgency. In the Western Basin, this requires the establishment of a neutralisation plant with a capacity of 20 MI/d. This is required to supplement the existing treatment capacity operated by mines in the area and the upgrade of mine water pumping facilities accordingly. In the Central Basin, it is required that a pumping facility with a capacity of ~60 MI/d be installed in one or more existing mine shafts, and a neutralisation plant or plants of matching capacity be established in close proximity. In the Eastern Basin, the pumping capability in Number 3 Shaft of Grootvlei Mine must be secured. It is also required that the existing treatment plant at this locality be returned to service as soon as possible. The volumes of water to be managed may be reduced by the timely implementation of ingress management measures, with a resultant reduction in operating costs. The design of the pump and treat systems will need to take this into account.

Neutralisation of mine water and discharge to the environment will produce conditions similar to the status quo during periods of active mining. In the medium to long term this may not be sustainable as it could result in excessive salt loads on the receiving water bodies, which will require the release of clean water for dilution, particularly in the Vaal River System. The options of direct consumptive use of neutralised mine water or desalination and sale of the water to local users must be investigated. In the very long term, it is expected that water quality could improve significantly. This will be confirmed by ongoing monitoring and will create a situation where the mines could be allowed to flood completely or to levels closer to the surface, reducing the costs of water management.

The immediate expansion of a programme to monitor mine water level, mine water quality, surface flow and quality, groundwater level and quality and seismic activity is required for the three priority basins.

The recommendations of the Team of Experts are summarised as follows:

1. Water must be pumped from the three priority basins to maintain water levels at least below the relevant Environmental Critical Levels or, by agreement with stakeholders, the lowest level of underground activity within the basin.
2. Steps must be implemented to reduce the ingress of water into the underground workings as far as is possible. This will reduce the volumes of water which need to be pumped and treated to more acceptable levels and consequently reduce the operational costs of AMD management.
3. The water that will be pumped will not be of a suitable quality for productive use or discharge to river systems and will therefore need to be treated. In the short term it is proposed that water be neutralised in a process that will address the low pH, high acidity and high iron and other metal content. In the medium to long-

term consideration should be given to steps that will reduce the mine water contribution to the salinity of major river systems.

4. Improved monitoring of mine water, groundwater, surface water, seismicity, subsidence and other geotechnical impacts of mine flooding and related targeted research is required. It is recommended that a multi-institution monitoring committee be established to facilitate the implementation of the required monitoring and the necessary assessment programmes. Monitoring will show whether there are significant changes in the quality of mine water that may have an impact on future management strategies. Monitoring results may also identify additional remedial measures required in the future.
5. The flooded mine voids are not the only sources of AMD in the Witwatersrand. Other sources, particularly mine residues, need to be monitored and appropriately remediated to reduce AMD impacts on the environment.
6. The feasibility needs to be investigated of implementing an environmental levy to be paid by operating mines in order to cover the costs of the legacies of past mining.
7. The recommendations in this report represent the start of a process. The aim of these recommendations is to avert impending crises and stabilise the situation, as well as addressing current gaps in the understanding of AMD problems in the priority areas and their potential impacts on the environment. It is therefore recommended that the process of assessment, risk appraisal and the recommendation of remedial measures be continued with ongoing assessments.
8. The problems posed by AMD will have implications far into the future, with impacts likely to continue for many years. The process of management of these impacts will therefore need to continue, with ongoing assessments and adaptation as conditions change.

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LIST OF ABBREVIATIONS

AMD	Acid Mine Drainage
ANZMEC	Australian and New Zealand Mineral and Energy Council
ARD	Acid rock drainage
CGS	Council for Geoscience
CSIR	Council for Scientific and Industrial Research
DEA	Department of Environmental Affairs
DME	Department of Minerals and Energy (former name for DMR)
DMR	Department of Mineral Resources (formerly DME)
DST	Department of Science and Technology
DWA	Department of Water Affairs (formerly DWAF)
DWAF	Department of Water Affairs and Forestry (former name for DWA)
ECL	Environmental Critical Level
ERPM	East Rand Proprietary Mines
GARD	Global Acid Rock Drainage
HDI	Human Development Index
HDS	High Density Sludge
IMC	Inter-Ministerial Committee
i.r.o.	in respect of
KOSH	Klerksdorp, Orkney, Stilfontein and Hartebeesfontein
MEM	Mine and Environmental Management
MEND	Mine Environment Neutral Drainage
MPRDA	Mineral and Petroleum Resources Development Act
OSMRE	Office of Surface Mining Reclamation and Enforcement
RMCS	Regional Mine Closure Strategies
SWM	Strategic Water Management
USA	United States of America
USEPA	United States Environmental Protection Agency
WRC	Water Research Commission

CHAPTER 1. INTRODUCTION AND BACKGROUND

South Africa's mining history has generated vast economic benefit and still plays an important role in ensuring the country's position in the global market. Despite such benefit, large-scale closure of mining operations since the 1970s within the Witwatersrand mining regions or basins (Figure 1.1) and the subsequent termination of the extraction of underground water from mines have become important national concerns. As elsewhere in the world, the activities of the mining sector have resulted in serious environmental consequences, notably in respect of poor environmental and water management and, in the case of the gold mines of the Witwatersrand, acid mine drainage (AMD). Given the magnitude and dynamics of the South African mining industry, it must be accepted that the challenges of mine water management cannot be administered by either government or the mining sector alone.

The cessation of underground mine water extraction leads to the mine voids becoming flooded. This phenomenon was highlighted in September 2002, when acidic mine water started flowing from an abandoned shaft in the Mogale City/Randfontein area of the Western Basin as a result of the flooding of the mines in this basin to a level where water could flow out onto the surface. This surface flow or decant of mine water is of concern to the environment as the water, in accordance with well-known and researched chemical and geochemical reactions between the mine rock strata, wastes and oxygen, readily becomes acidic, characterised by elevated concentrations of salts, heavy metals and radionuclides.

A similar situation is developing in the Central Basin (Johannesburg area) and Eastern Basin (Springs–Nigel area). Efforts to address and manage this problem have therefore been intensified by the responsible and relevant government departments (the Department of Mineral Resources (DMR), Department of Water Affairs (DWA), Department of Environmental Affairs (DEA), and Department of Science and Technology (DST)). The immediate concern is the threat posed by decanting mine water in the Witwatersrand area, which poses potentially severe environmental and safety impacts on the receiving water environment and concomitant surface areas. This report addresses the current crisis regarding acid mine drainage. In the longer term regional impacts on larger river systems will also need to be taken into account.

Although AMD problems are also experienced in other gold mining areas, including the Klerksdorp/Orkney/Stilfontein/Hartebeesfontein (KOSH), Free State, Far West Rand and Evander gold mining areas, the coal mining areas of Mpumalanga and KwaZulu-Natal and the O'OKiep Copper District, it is appropriate to address those areas where the risk demands the most urgent and immediate action first.

The flooding of the mine voids and/or AMD decant gives rise to the following general concerns:

- AMD extensively contaminates surface streams and could incur devastating ecological impacts

- Rising water levels could flood urban areas and result in geotechnical impacts that may jeopardise the integrity of urban infrastructure
- Rising water levels in the mine voids may lead to an increase in seismic activity, presenting serious safety risks to deep underground mining ventures and some risk to safety and property on the surface in the vicinity of the mines
- Rising mine water levels have the potential to flow towards and pollute adjacent groundwater resources
- Flooding may result in inter-mine water migration and may threaten neighbouring operational mines, limiting access to economic reefs.

An Inter-Ministerial Committee (IMC), including the Ministers of Water Affairs, Mineral Resources, Science and Technology, and Finance, and the Minister in the Presidency has been convened to deliberate on this matter. A Technical Committee, chaired by the Directors-General of the DMR and DWA has appointed a Team of Experts, comprising experts from the departments of Water Affairs and Mineral Resources, the Council for Geoscience (CGS), the Council for Scientific and Industrial Research (CSIR), the Council for Mineral Technology (MINTeK), the Water Research Commission (WRC) and involving professors from the universities of the Witwatersrand and the Free State, and the Tshwane University of Technology.

The objectives of the IMC are to:

- Be informed by facts and science
- Ensure consistency and calmness in explaining what is happening
- Communicate in order to regain and maintain the trust of the people.

The Team of Experts was tasked to:

- Reappraise the risk attributable to AMD
- Assess what has been done by various institutions
- Assess available solutions and technology
- Interrogate and assess the viability and costs of critical short-term interventions
- Propose integrated lasting and sustainable medium and long-term solutions/ measures, taking into account the requirement for ongoing maintenance
- Explore possible partnerships with the private sector.

This document reflects the deliberations and recommendations of the Team of Experts to the Directors-General and the IMC.

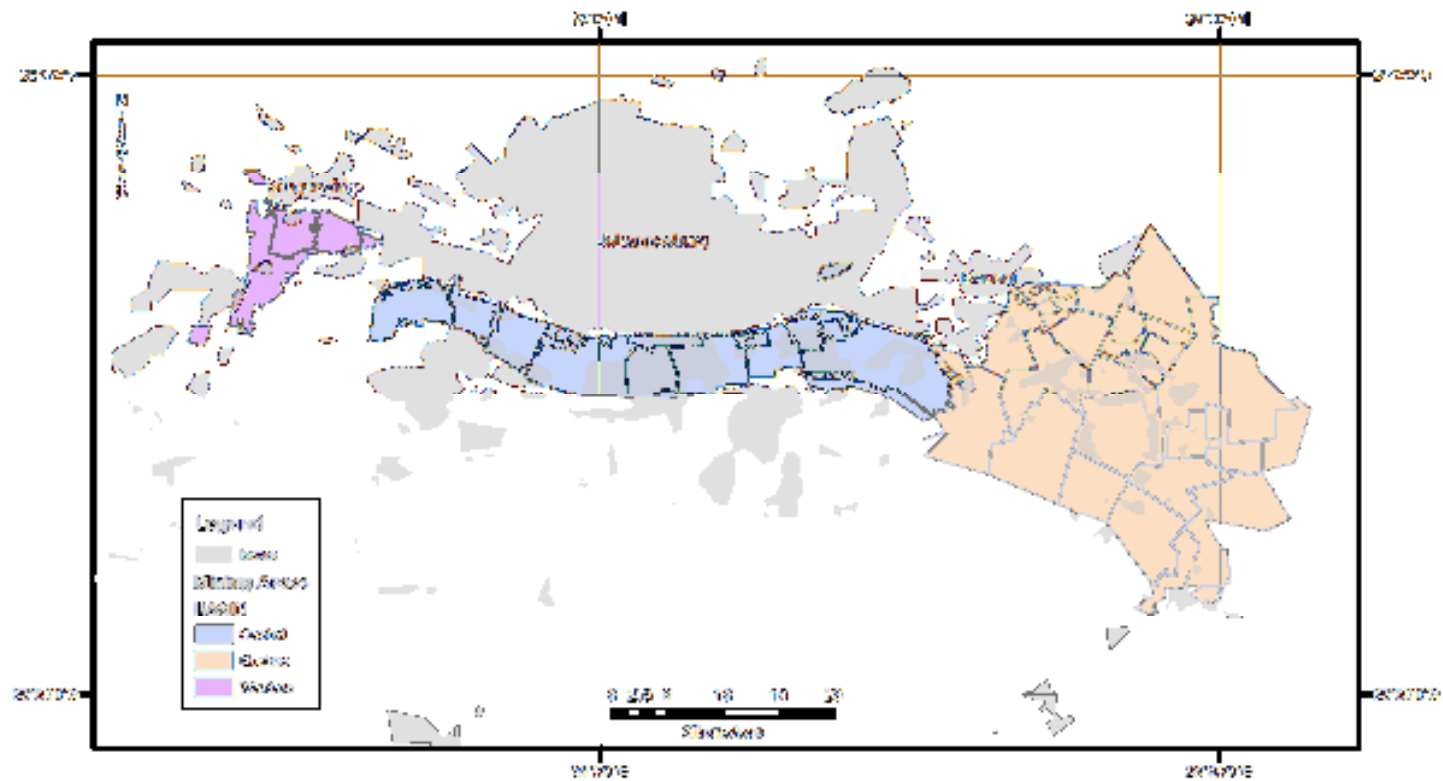


Figure 1.1. Locations of the Western, Central and Eastern mining basins of the Witwatersrand.

CHAPTER 2. INTERNATIONAL EXPERIENCE IN THE MANAGEMENT OF AMD PROBLEMS

Acid mine drainage is a significant and costly environmental impact of the mining industry worldwide. The legacy of mining continues to affect surface and groundwater resources long after mining operations have ceased. AMD is a common problem at abandoned mine sites around the world today. The oxidation of sulphur-rich mine wastes by interactions with water and oxygen and the consequent release of AMD (also called acid rock drainage, or ARD) is one of the main environmental challenges facing the mining industry. Many metallic ores contain significant amounts of sulphide minerals, particularly pyrite (FeS_2). Mining often exposes large amounts of pyrite and other sulphide minerals to the effects of water and oxygen once waste rock and tailings are produced on surface. The excavation process also exposes sulphides in the walls of opencast and underground operations, and disturbs the host rock and hydrological regime around mined out areas, allowing the ingress of water and oxygen.

It has been estimated that the cost of managing AMD at operating mines in Australia amounts to US \$60 million per year (Harries, 1997). However, the management of potentially acid generating wastes is an important environmental issue as major costs may arise late in mine life or after mine closure if proper waste management strategies are not followed. The Australian Government estimates that when AMD is discovered after mine closure the cost of remediation can be as much as US \$100 000² per hectare (Harries, 1997). The estimated cost of remediation in Canadian mine sites is three to four times (US \$2 billion to US \$5 billion) greater than for Australian sites (Harries, 1997).

2.1 ACID MINE DRAINAGE IN AUSTRALIA

In 1995, the Australian and New Zealand Mineral and Energy Council (ANZMEC) published a baseline environmental guideline for operating mines in Australia. As part of the guideline acid generation should be predicted and incorporated in the mine closure plan (ANZMEC, 1995). In order to better understand the impact of AMD in Australia and to provide the basis for assessing long-term management options, the Office of the Supervising Scientist and the Australian Centre for Minesite Rehabilitation Research initiated the preparation of a status report on AMD (Harries, 1997).

2.2 ACID MINE DRAINAGE IN CANADA

The Canadian Mine Environment Neutral Drainage (MEND) programme was established by mines and provincial, territorial and federal government agencies in 1989 in response to the recognition of AMD being the main environmental problem facing the Canadian mining industry. Mines in Canada were required to establish trust funds to cover the cost of the effect of AMD from mine wastes. A survey of metal-mine and industrial-mineral tailings in 1994 showed that of the 7 billion tons of tailings and 6 billion tons of waste rock, 1.9 billion tons of tailings and 750 million tons of waste rock were potentially acid generating (MEND, 1995).

² All currency conversions have been performed at current rates.

2.3 AMD IN THE USA

The main AMD problem identified in the United States of America (USA) was the impact of acid drainage from coal mines on the streams in the eastern states. An estimated 7 000 km of streams were affected (Ferguson and Erickson, 1988). In total between 8 000 and 16 000 km of streams in the USA are affected by AMD (USEPA, 1995). Owing to the large potential liability of AMD from abandoned mines, the regulators insist on payment of performance bonds.

In the USA abandoned mines are rehabilitated under the National Abandoned Mine Land Programme under the Office of Surface Mining Reclamation and Enforcement (OSMRE) of the US Department of the Interior. Funds are raised via a levy on active coal mines and deposited into the Abandoned Mine Lands (AML) fund — a trust administered by the U.S. Treasury (Office of Surface Mining, 2006) to pay for reclamation of mines abandoned before the passage of the Surface Mining Control and Reclamation Act of 1977 (Wikipedia, 2007).

In line with most USA environmental legislation and regulation, the principle of cooperative federalism, whereby the American states take initiatives and the Federal Government oversees these efforts, is applied (Wikipedia, 2007). The State and tribal authorities taking responsibility for these efforts agreed in 1993 to form the National Association of Abandoned Mine Lands Programmes in order to coordinate these efforts, share knowledge and foster positive cooperation between themselves (National Association of Abandoned Mine Lands Programmes, undated).

Additional programmes have been instituted by the US Geological Survey, looking at hard-rock mining sites at a catchment scale in Colorado and Montana (United States Geological Survey, 2007) and the Bureau of Land Management, which oversees abandoned mines on public land (Bureau of Land Management, 2008).

2.4 MANAGING URANIUM MINING LEGACIES IN GERMANY

Following the reunification of Germany in 1990, it became clear that huge legacies existed owing to the mining of uranium in the former East German states of Saxony and Thuringia, including AMD impacts at some mines. These were addressed by the formation of a Federal-owned company — Wismut GmbH. The mining legacy included 1 400 km of open mine workings, 311 million m³ of waste rock, and 160 million m³ of radioactive sludges (tailings) located in densely populated areas (Wismut, 2008). To this end a fund of €6.6 billion (later revised to €6.2 billion) was established under the 'Wismut Act, passed by the Federal Parliament in 1991 (Hagen and Jakubick, 2006).

While this has been extremely costly, the Wismut rehabilitation exercise has stimulated the economy in a relatively economically depressed area of Germany, creating 2 000 jobs and injecting approximately €100 million per annum into the local economy via tenders issued. A specific focus has been on the identification and stimulation of local small and medium contractors (Wismut, 2008).

Other spin-offs have included the development of expertise and technologies in local research institutions and consulting groups, which can now be transferred to other areas

and have been successfully applied in Central and Eastern Europe, Russia and Central Asia (Hagen and Jakubick, 2006). An important focus of the programme has been the productive utilisation of reclaimed areas and, while some land-uses obviously must be restricted, a number of successful projects have been undertaken.

2.5 COMPARISON OF INTERNATIONAL EXAMPLES WITH THE SOUTH AFRICAN SITUATION

The key factors which differentiate the developing problem in South Africa from the international examples cited and identified is the degree of interconnection of large voids, the sheer scale of the Witwatersrand operations and the fact that many of the problem areas are located in or close to major urban centres. This necessitates large-scale programmes to address the problem of acid mine drainage. In other countries, mine flooding was planned to minimise impacts, while in South Africa this has not been done and, in many cases, this would not have been possible owing to closure of older mines within a basin long before flooding was contemplated. The matter is exacerbated by the untimely closure of most of the mines within each of the basins.

International experience reveals a number of factors that leads to the successful implementation of programmes dealing with mining legacies, including AMD:

- Acceptance that there is a problem that needs to be addressed in a coordinated programme between government and the mining industry
- High-level coordination between a range of stakeholders, with government playing the leading role
- Decisive action by the State to secure and provide funding
- Ongoing research to provide optimal and sustainable short-, medium- and long-term solutions.

CHAPTER 3. ASSESSMENT AND COLLATION OF WORK DONE BY VARIOUS INSTITUTIONS

3.1 WORK/STUDIES UNDERTAKEN BY VARIOUS INSTITUTIONS

Several studies have been conducted in the main gold-mining basins to determine the nature of the water ingress and the resulting AMD problems. Conclusions indicate that serious environmental challenges exist, which, if not adequately addressed, could lead to crises such as have already occurred with the decant of acid mine drainage in the Western Basin in 2002 and the premature closure of Stilfontein Gold Mine in the KOSH area in 2005. This work includes specialist studies performed on behalf of the various government departments, science councils (CGS, CSIR and MINTEK), and other organisations, such as the Water Research Commission (WRC), universities, the National Nuclear Regulator (NNR), town councils and others.

This chapter summarises the body of South African knowledge available, emanating from:

- State or publicly funded organisations, including knowledge produced on behalf of government departments that are not necessarily available in the public domain
- Tertiary academic institutions that have undertaken numerous studies as:
 - Research projects, producing publications for conferences and in refereed technical and scientific journals
 - Post-graduate studies that are published in the form of theses and dissertations
 - Private work done for commercial clients
- The private sector. This information could be accessed by the government in future through interaction with mining companies
- Reports produced for private clients by consulting companies (these reports are generally not in the public domain but could also be consulted by interacting with the concerned institutions/companies). Inclusion of information from these privileged and confidential documents in this report was precluded by the timeframe.

Although approximately 38 WRC-funded projects have been completed on mine water, plus another 16 continuing at present, these projects are focussed on specific research questions, ranging from the development of treatment technologies to the characteristics of mine dumps. Only in a few instances has the flooding of the Witwatersrand mines been the topic of these research initiatives.

Very few specialist investigations appear to have been done to identify the status of the geohydrological regime, the extent of contamination, preferential pathways and

predictions regarding long-term migration. The main study conducted on the flooding of the Witwatersrand gold mines was funded by the WRC and conducted by Scott (1995), who contributed to the understanding of the inflow of water into the mine voids of the Central and Eastern Basins and proposed rates of rise and possible discharge points. More-recent WRC-funded studies have focussed on the flooding in the Mpumalanga Coal Fields (Hodgson *et al.*, 2001).

The Department of Water Affairs (DWA) has recently updated management strategies pertaining to the integrated Vaal River and Crocodile-Marico Systems. These include Reconciliation Strategies and Water Quality Management Strategies that, amongst others, specify measures to curb and manage the anticipated effects of salinisation on these river systems, noting the contribution of AMD to these salt loadings. The collective aim of these strategies is to secure continued water security in the medium to long term (Department of Water Affairs, 2010).

Information with regard to the flooding of the Witwatersrand gold mines was gathered by the Council for Geoscience (CGS) on behalf of the Department of Mineral Resources (DMR) in order to propose realistic solutions to manage water ingress and decant of polluted water or AMD. The work was performed as part of the Witwatersrand Water Ingress and the Sustainable Development through Mining and Strategic Water Management Projects. Management solutions are intended to reduce the risk to society and the country for bearing the costs of pumping into perpetuity when mines close down, and to manage and control decant on surface of highly polluted water, with its attendant risks, in particular to health. The main focus of this research work was to:

- Reduce ingress of surface water and groundwater to underground mine voids
- Establish and recommend management solutions to reduce dependency on pumping in order to manage flooding of mines and spillage of water to the surface (decant)
- Predict when and where decant will occur, should pumping operations cease
- Monitor the impact of mine flooding, including flooding-induced seismicity
- Analyse the impact on the environment and the health risks associated with polluted mine water decanting to surface
- Arrive at management options to avoid uncontrolled decant of polluted mine water onto the surface.

Through these projects the existing body of research information, as well as a GIS database, has grown substantially. The information cuts across the Witwatersrand Basin (including the three gold fields identified as priorities and the KOSH, Free State and Evander Gold Fields) and includes data related to the flooding of the mine voids, as well as potential problems with respect to AMD in the Witwatersrand. The information has been applied to quantify and propose remedial actions and strategies.

The public-funded research studies, as well as some important international work on water ingress, decant and AMD can be summarised into the following categories:

- Understanding the problem
 - Acid mine drainage impact
 - Quantification of water use and wastewater/AMD production in mining
 - Predicting and quantifying the effects of mining activity on the environment
 - Flooding of mines and mine closure
 - Seismic hazard
- Regulatory mechanisms
 - Regulatory and other management mechanisms to improve management of water in the mining sector
- Solution development
 - Minimising the impact of waste (including AMD) from mining on the water environment
 - Minimising AMD and other waste production in the mining sector
 - Treatment of mining effluents and AMD
 - Water ingress prevention
 - Decant management.

This summary focuses on South African work, and work that is funded and/or immediately available to State organisations only. The wider academic literature (scientific journals) has not been included, although it is recognised that considerable international experience and knowledge of AMD is available.

Studies by the CSIR (Durrheim *et al.*, 2006; Goldbach, 2009) and the CGS have found that rising water levels in the mine voids lead to an increase in seismic activity, similar to that experienced during active mining. The risk of seismic events related to natural seismicity and seismicity induced by mine flooding are currently being monitored by the CGS through a small dense network of monitoring sites installed in and around the Central Basin. This network has been collecting data since the first quarter of 2010.

Most studies have focussed on the surface water pollution associated with mine tailings, with less attention given to the possible decant of AMD and the effects that it will have on the environment. Several WRC projects concentrated mainly on the development of solutions to contamination derived from the generation of AMD from surface waste disposal facilities. More-recent WRC projects focussed on the treatment of AMD, as well as the disposal or use of the associated brine. Eleven WRC projects concerned with the quantification of AMD production have been completed. Several of these are generic, hence, in this case, the knowledge gap that exists refers to specific areas of the country.

The mining industry is involved in major initiatives to reclaim defunct tailings facilities containing recoverable gold resources. However, access to much of the work performed on behalf of the mining companies is restricted.

The available guidance documents relating to regulatory and institutional arrangements for managing AMD are limited to the Global Acid Rock Drainage Guide (GARD),

demonstrating that this is a subject area largely neglected by the South African State or State-funded work.

Several regulatory guidelines have been developed by government departments. These include the Best Practice Guidelines for Water Resource Protection in the SA Mining Industry, developed by DWA.

As part of the Sustainable Development through Mining Project of the DMR the following documents have been developed:

- The Regional Mine Closure Strategies (RMCS), developed by the CGS, aimed at addressing the problems, particularly in the Witwatersrand Basin, associated with interconnected underground mines
- The National Strategy for the Management of Derelict and Ownerless Mines, developed by CGS, aimed at addressing the liability of government for the thousands of derelict and ownerless mines
- Mine and Environmental Management (MEM) guidelines, developed by MINTEK, aimed at addressing the management and closure of mines in an environmentally friendly and sustainable manner.

Management solutions are two-fold, *i.e.* those associated with the management of the flooding of the mine void and those associated with the treatment of the polluted mine water. Most studies, however, focussed mainly on the latter.

Much attention has been devoted to understanding and predicting the impact of mining on the environment. Thirty-one reports dating back to 1989, of which most are of an applied nature, have been prepared utilising mainly government funding. An international best practice guideline exists in the form of the Global Acid Rock Drainage (GARD) Guide, to which South African organisations have contributed significantly. Furthermore, the DWA Best Practice Guidelines for Water Resource Protection in the SA Mining Industry and Impact Prediction are available.

Research through WRC-funded projects showed that AMD prediction, prevention and remediation depend on the understanding of the development and characteristics of oxidation zones in gold tailings and the identification of the key parameters and characteristics of oxidation zones. Thirty-seven reports or guides exist regarding the minimising of the impact of waste from mining on water resources and the environment. The majority of the theoretical and experimental work done in understanding the generation of AMD in tailings facilities was funded by the WRC. This demonstrates that there is a good understanding in the scientific and consulting communities of the requirements for technologically feasible measures that may be taken to reduce the effects of AMD and other mining-related wastes on the environment.

A substantial number of WRC-funded projects have focussed on the minimisation of the generation of AMD at mine sites. One of the most widely used methods is the provision of some kind of cover to limit the infiltration of water and to ensure the optimal slope to

enhance run-off. The development of various natural covers for mine residues and other contaminated sites has been researched (Wates and Rykaart, 1999; Vermaak *et al.*, 2004). Other reports relate to the minimisation of waste production in mining and refining of mined products. A growing interest in greener production, life cycle analysis and waste minimisation, as occurs in other industrial sectors, has not yet taken a firm hold in the mining sector.

The treatment of AMD and the potential to generate valuable by-products from it has received the most attention of all WRC subject areas. Around 40 reports on this matter have been produced. A major benefit of by-product recovery is a reduction in the overall volume of sludge, as well as a reduction in the hazard rating of the sludge produced. Several WRC projects focussed on the treatment technologies available and the development of new technologies. Both international and national best practice guidelines exist for AMD treatment methods, and South African inventions and developments abound within those guidelines.

3.2 KNOWLEDGE GAPS AND RECOMMENDATIONS

Many risks in the Central Basin have been identified, because of its proximity to central Johannesburg. However, in some cases, these risks are based on various assumptions which are yet to be confirmed. It is therefore recommended:

- That the identified risks be investigated
- That monitoring programmes be put in place to refine assumptions made and to improve future management of the situation
- That the precautionary principle be adopted in areas where significant uncertainty exists in order that prudent action can be taken to minimise latent hazards.

Uncertainty exists around the risk that rising water levels could lead to the reactivation of solution features in dolomite, resulting in subsidence and possibly even the formation of sinkholes. This is a particular concern in the dolomitic areas associated with the Far Western, Western and Eastern Basins. Although a study currently being undertaken for the Management Authority of the Cradle of Humankind World Heritage Site (Hobbs (ed.), in press) includes a cursory assessment of concerns in this regard, it is recommended that this subject be further investigated.

The body of knowledge about the volumes of water used and wastewater (volumes and quality) generated in the mining industry that is freely available is limited. However, it is likely that mining companies and/or individual mines own much more accurate and detailed knowledge of the volumes. It is imperative that all relevant information be assimilated from all available sources and utilised in the development of management solutions.

There is a need for an investigation into the legal and regulatory framework, as well as policy arrangements that will economically and administratively facilitate beneficiation of AMD and other mining effluents. A case study detailing the institutional arrangements at

the successful eMalahleni Water Reclamation Plant (Hutton *et al.*, 2009) should be done to establish best practice in the national context.

The body of work available on minimising the impact of mining wastes on the environment and on treatment of such wastes indicates that the technological solutions are already available to the country. Many of these are South African developments, and could be applied relatively quickly given an enabling regulatory/policy framework. It is recommended that these studies be utilised and compared and used when treatment technologies have to be selected.

Apportionment studies, performed by the CGS on behalf of the DMR, have found that while a number of the mines in the area are derelict and abandoned, they cannot necessarily be classified as 'ownerless'. Liability for the impacts of these mines, in terms of Section 46 of the MPRDA, can therefore not be automatically assigned to the State. The apportionment procedure for all basins needs to be verified. Further, an approach to dealing with mining legacies needs to be formulated that will not result in ongoing legal wrangling which could seriously delay the implementation of solutions.

Although localised studies have been done by various government departments, science councils and universities on the impact of AMD on the environment these studies are highly focussed. There is a need for a birds-eye-view environmental risk assessment of the entire Witwatersrand gold-mining basin, focussing on the impacts of mining on the environment and the health and safety of communities. A similar study must also be conducted for the Mpumalanga Coal Fields.

Many recommendations for ingress prevention have been proposed through the work done by the CGS on behalf of DMR — these recommendations need to be implemented as part of the management of the current situation.

Monitoring of seismicity associated with the rising water level in the Central and East Rand by the CGS must be continued, using the infrastructure already in place. Studies and reporting of the seismicity and the potential safety risks must be conducted, using the CGS data and expertise in cooperation with local and international experts, including practitioners from the mining industry.

Other proposed investigations through continuous improvement of the knowledge base include:

- Baseline studies
 - Identifying mines, surface and underground infrastructure and mine interconnection
 - Quantification of water use and wastewater/AMD production in mining
 - Predicting and quantifying the effects of mining activity on the environment
 - Identify ingress and decant areas
 - Verification of predicted ingress and decant (where possible)
 - Site characterisation (geology, hydrology and geohydrology)

- Source identification, quantification and characterisation of mine related pollutants
 - Recipient identification and characterisation
 - Assessment of environmental risks (seismic, subsidence, radiation, dust, noise, aesthetics, risky openings)
- Regulatory mechanisms
 - Regulations to address the problem
 - Development of management tools
- Solutions
 - Design ingress prevention and decant management schemes
 - Suggest improved mine waste and water management.

3.3 SUMMARY AND CONCLUSIONS

Work done to date on the AMD problems in the Witwatersrand by the institutions involved in the Team of Experts of the IMC is summarised in Table 3.1.

Based on this information, and given the urgency of the situation, sufficient information exists to be able to make informed decisions regarding the origins of the mine water, potential impacts, management strategies, treatment technologies, etc. The large body of research conducted on the Witwatersrand Gold Fields provides sufficient background information to be able to predict impacts and direct the data collection and monitoring necessary to minimise any uncertainties that exist in the current predictive models.

Additional research is required to reduce the current areas of uncertainty and to identify and investigate long-term solutions that would reduce the requirement for pumping and treating of AMD. This research will need to continue in parallel with a concerted programme of action for the solution of identified problems, and should not be allowed to delay the commencement of the necessary actions to manage and avert the current crisis.

Table 3.1. Summary of work done on the AMD problem in the Witwatersrand by the institutions involved in the IMC Team of Experts

Organisation	What has been done on the problem	Solutions
CGS	Ingress identification and management Baseline studies A lengthy process of investigations across the basins was necessary to establish the baseline data. Investigations included the following studies: • Field survey of all mining areas • Underground water sampling • Water levels and quality at shafts across the basins • Isotopic and chemical analysis for fingerprinting • Influence of slimes dams on the hydrogeology and water balance • Hydrogeology and water balance • Monitoring of water flow and quality • Investigation of remediation techniques • Detailed geophysical survey • Hydrogeological census Data and map compilation: • Monthly dewatering flow/pumping volumes for all the mines in the study area. • The depths at which these volumes are abstracted must also be recorded • Coordinates of dewatering zones • Borehole logs where available • Water levels • Spring locations • Monthly rainfall data from all the rainfall stations in the study area • Digital topographic terrain model (DTM) of the study area • Monthly surface water and groundwater quality data from all the mines in the study area • The volume of mined out material or void volume at each of the mines • The number of and surface area of tailings dams, waste rock dumps, return-water dams per dam/dump per mine	Ingress prevention Preliminary suggested solutions Decant management Preliminary suggested solutions Environmental management Preliminary suggested solutions

Organisation	What has been done on the problem	Solutions
	• Mining depths • A description of the regional, local and structural geology at each of the mines • Previous publications • The location of geological exploration boreholes (xyz) • All previous geohydrological reports • Surface geological GIS map for each of the mines in shape file format • GIS maps that show: ○ The mineshafts, tailings dams, return-water dams, waste rock dumps and plants ○ The surface geology ○ The structural geology with regional faults, dykes and contact zones ○ The locations of existing boreholes from NGDB data ○ Surface water flow volumes (rivers and streams) • Geological cross-sections • Surface water storage volumes (dams, lakes, pans) • A project technical report that describes the data, analyses and interprets the information with conclusions. Site investigations per basin Extraneous water derived from rainfall enters the mines via unprotected outcrops, holings and infiltration from storm water drains and culverts. Other possible sources include: • Rivers and streams crossing the outcrops • Municipal storm water discharge • Fissure water • Aquifers • Fractures or features connecting surface water to underground workings. GIS-Ingress areas with volumes are shown on a map and GIS database Hydrological modelling	

Organisation	What has been done on the problem	Solutions
	Underground water sampling Remote sensing was used for direct and indirect visual identification of holings and ingress areas. Decant management The investigation of potential areas where decant of water from the mine void might occur was also divided across the basins. Potential decant areas and volumes are shown on a map and GIS database. Environmental protection Remote sensing and geophysics Multi-spectral remote sensing and airborne geophysics have revealed the general distribution of various hazardous chemical elements. Ground geophysical surveys have been used to map the subsurface flow of water in ingress zones. Seismology The risk related to seismic events related to natural and mine flooding induced seismicity needs to be assessed as part of the overall study of the Witwatersrand gold-mining area. The seismology unit of the Council for Geoscience (CGS) has been given the task to set up seismic monitoring networks to assist in assessing seismic risk.	
WRC	Quantification of water use and wastewater/AMD production in mining Regulatory and other management mechanisms to improve management of water in the mining sector Minimising the impact of waste (including AMD) from mining on the water environment Minimising AMD and other waste production in the mining sector	Management of AMD through treatment and minimisation Understanding of mine flooding

Organisation	What has been done on the problem	Solutions
	Predicting and quantifying the effects of mining activity on the environment Treatment of mining effluents and AMD Flooding of mines and mine closure	
CSIR	Treatment of mining effluents and AMD Acid mine drainage and viable treatment options. Pilot plant operation: biological sulphate reduction and sulphide oxidation with the recovery of sulphur. Bioremediation of sulphate-rich mine effluents, using grass cuttings and rumen micro-organisms. Cellulose fermentation products as energy source for biological sulphate reduction. Removal of sulphates, metals and acidity from a nickel and copper mine effluent in a laboratory scale bioreactor. Improved sulphate removal rates at increased sulphide concentration in the sulphidogenic bioreactor. Treatment of acid and sulphate-rich effluents in an integrated biological/chemical process. Biological sulphate removal from acid mine effluent using ethanol as a carbon and energy source.	Development of technologies for treatment of AMD

Organisation	What has been done on the problem	Solutions
	Groundwater assessment of AMD impacts Hydrogeological assessment of acid mine drainage impacts in the West Rand Basin, Gauteng Province	Hydrogeological assessment for an improved understanding of impacts
MINTEK	Treatment of mining effluents and AMD	Development of technologies for treatment of AMD
DWA	Integrated water management strategies to utilise the allocatable water quality to the benefit of the water users, and identify intervention measures to ensure adequate water supply and protect water quality.	Remove significant salt streams from a range of sources including underground mine water return-flows as part of a larger medium- to long-term strategy

CHAPTER 4. THE CURRENT SITUATION*

4.1 FLOODING OF THE WITWATERSRAND GOLD MINES

4.1.1 Flooding of mines

The nature of the gold deposits in the Witwatersrand has led to the development of large complexes of interconnected mines, which have been referred to as 'basins' (Scott, 1995). Since the earliest days of mining, the inflow of water into the mines has been a problem and water was pumped from the mines to allow access to the gold reserves. When individual mines ceased operations they stopped pumping, allowing their operations to flood. Owing to the interconnections, this water will have flooded until it reached an opening into a neighbouring mine, after which it will have flowed into that mine, increasing the volume of water to be pumped from the neighbouring mine. Over time, as more mines closed, the burden of pumping water was carried by fewer and fewer mines, until the last operating mine stopped pumping (Scott, 1995; Department of Minerals and Energy, 2008a, 2008b).

In the case of two of the three oldest basins — the Western and Central Basins — no underground mines are operating and no water is pumped from the underground workings. In the Western Basin this water has already risen to surface and is decanting — flowing from old shafts and other structures — into the surface environment, while in the Central Basin no water is pumped from the underground workings and the water level is rising at an average rate of 0.59 m per day, with the water level measured at around 500 m below surface at Catlin Shaft on Simmer & Jack Mine in early December 2010. This level is monitored continuously by the CGS, using automated instrumentation providing real-time measurements. In the Eastern Basin the water level is controlled by pumping by a single mine — Grootvlei Mine — that pumps water from their No. 3 Shaft to maintain the water level around 700 m below the surface. Recent financial problems at Grootvlei Mine have created a situation that could result in the termination of this pumping.

4.1.2 Sources of water entering the underground workings

A number of sources have been identified for the water entering the underground workings (Scott, 1995; Krige, 1999; Horstmann *et al.*, 2004a 2004b). These include:

- Direct recharge by rainfall falling onto open mine workings, stopes and old surface workings.
- Groundwater, recharged by rainfall, which seeps into the workings owing to the disturbance of natural groundwater conditions by mining (Scott, 1995; Department of Minerals and Energy, 2008b).
- Surface streams that lose water directly to mine openings and to the shallow groundwater systems above zones of shallow undermining and historical surface operations. This process is compounded in urbanised areas as the paved

surfaces tend to produce surface run-off, rather than allowing water to seep naturally into the ground.

- Where open surface workings exist, these often connect directly to the underground workings and provide a pathway for water to flow from the surface to the mine void. In the Western Basin the problem is exacerbated where mining companies allow acid drainage from their surface tailings reclamation operations to flow into abandoned open pits.
- Mine residues, in particular tailings, are seen as areas of enhanced seepage where the volume of water entering the mine void is relatively high. The interactions between water and tailings can lead to contamination of the water and AMD production, resulting in the flow of contaminated water into the mine voids (Scott, 1995; Rosner *et al.*, 2001).
- Losses from the water, sewage and stormwater reticulation systems are also a possible source of water in the zone, where these cross old shallow mine workings. These will need to be investigated in cooperation with the relevant local government entities.
- Isotopic studies undertaken by the Council for Geoscience have indicated that a significant component of the water is groundwater that infiltrated rapidly after recharge by rainfall (Horstmann *et al.*, 2004a, 2004b)

4.1.3 Acidification and contamination of water in the flooded mine voids

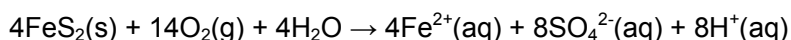
Acid mine drainage forms in mining environments when ore and waste materials, containing sulphide minerals such as pyrite, are exposed to water and oxygen. A detailed study of AMD formation, transport and impacts in the Witwatersrand has been performed by the Council for Geoscience, on behalf of the Department of Mineral Resources (Coetzee *et al.*, 2007). The disturbance of ore bodies and the transport of large volumes of pyritic material to the surface create conditions highly conducive to the generation of acid mine drainage, both owing to the exposure of ore in the underground environment and owing to the transport of blasted and/or crushed waste rock and tailings to the surface.

In order for pyrite to oxidise, both oxygen and water must be present. Water serves not only as a reactant, but also as a reaction medium and a product transport solvent (Forstner and Salomans, 1988). The rate of AMD generation, in an environment where sulphidic material is exposed to oxygen and water, will be determined by a number of factors. The reactions will proceed rapidly in warm humid environments, while other environmental factors, such as the specific sulphide mineralogy and grain size, and the presence or absence of acid neutralising minerals, such as carbonates will also influence the rate of AMD production and its eventual environmental impact. Unfortunately, these parameters can only be evaluated on a site-specific basis, via investigations that will include field, laboratory and modelling studies.

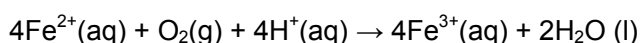
The oxidation of sulphide-bearing minerals consists of several reactions. Each sulphide mineral has a different oxidation rate. For example, marcasite and framboidal pyrite will oxidise quickly, while crystalline pyrite will oxidise more slowly.

For discussion purposes, the oxidation of pyrite (FeS₂) will be examined.

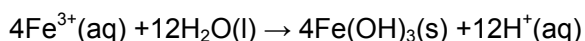
Pyrite oxidises to form an acidic solution of ferrous iron and sulphate:



Oxidation of the ferrous ion to ferric ion occurs more slowly at lower pH values:



Ferric iron precipitates as ferric hydroxide, producing further acid:



(From Coetzee *et al.*, 2007)

Fe(OH)₃ is identifiable as the deposit of amorphous, yellow, orange or red deposits on streambeds ('yellow boy') (Figure 4.1).

When either of the processes represented by the equations are slowed or stopped, AMD generation is slowed down or ceases.

Acid mine drainage can impact on the environment in a number of ways:

- Lowering of the pH of water to a point where it is unsuitable for domestic or other uses (Department of Water Affairs and Forestry, 2006). The pH of the acid mine drainage entering streams in the Western Basin is often around or slightly lower than 3 (Tutu *et al.*, 2008). This is similar to the pH of lemon juice, *i.e.* while not as corrosive as concentrated acids, it will have long-term effects on materials with which it comes into contact and will not support normal aquatic life.
- The reactions which produce acid mine drainage result in a high sulphate content in the resultant water that will remain high even after the acidity is neutralised. This renders the water unfit for domestic use, may make it unfit for agricultural and some industrial uses and will increase the salinity of the receiving aquatic environment.
- The acidity of the water liberates metals, including toxic metals and radionuclides from the rocks with which it interacts. This may result in acute and chronic toxicity to both human users and the environment, and will generally render water unfit for most uses (Coetzee *et al.*, 2006; Wade *et al.*, 2002).

It is therefore desirable that acid mine drainage not be allowed to discharge to surface streams or aquifers without adequate control and treatment.



Figure 4.1. Acid mine drainage in the West Rand

In the flooding Witwatersrand mine voids, two processes leading to the acidification of water have been identified:

- Interaction between the inflowing water and the sulphides in the ore and host rocks, leading to the generation of AMD. This will be particularly important in the unsaturated zone at the top of the void where water and air mixes with the rock material, providing the combination of water, oxygen and sulphides required to produce AMD. Owing to the topography of the Witwatersrand, if the mine voids are allowed to flood completely there will always be an unsaturated zone above the final water level within the mine voids, covering most of the geographic extent of the basins. This will result in an environment where new AMD is continually produced owing to the interactions between water, air and sulphide minerals (Rosner *et al.*, 2001).
- Ingress of AMD into the mine void after interactions between water and waste rock and tailings stored on the surface. This may take the form of contaminated surface water entering the mine workings via surface features, as has been observed in the Western Basin or seepage to the underground water which then recharges the mine void (Hobbs and Cobbing, 2007).

4.2 THE SITUATION IN THE MAJOR WITWATERSRAND GOLD FIELDS

4.2.1 Western Basin

Although there is mine water pumping and treatment of infrastructure in the Western Basin (Figure 4.5), the technology applied is unable to produce the desired final water quality for release into the environment. Further, the pumping capacity is inadequate to effectively control the rate of decant by managing the water. Water has decanted (Figure 4.2) continuously since late August 2002 (Coetzee *et al.*, 2005a; Council for Geoscience, 2004c), on occasion exceeding the capacity of the infrastructure established to manage it, resulting in untreated mine water entering the downstream environment via the Tweelopie Spruit, an upper tributary of the Crocodile River System (Council for Geoscience, 2004; Hobbs and Cobbing, 2007; Department of Minerals and Energy, 2008a). Such circumstances are typically associated with the wet summer months. The seriousness of the situation and concerns regarding the impacts on the receiving environment (Hobbs and Cobbing, 2007), notably the Cradle of Humankind World Heritage Site, resulted in an intervention by the DWA who granted a subsidy of R6.9 million over a three-month period in early 2010. This measure was aimed at reducing acidity and removing some heavy metals in the water through in-stream lime dosing. Although peaking at some 60 MI/d, the decant volume has more recently averaged 20 MI/d of which around 12 MI is partially treated. The remainder is diluted with the daily output of partially treated mine water before discharging into the Tweelopie Spruit.



Figure 4.2. Decant of AMD from 18 Winze — a shaft in the Western Basin

The Western Basin is a close geological analogue to the Central Basin, although it is considerably smaller. The likely course of events related to the flooding and eventual decant of the Central Basin are therefore likely to be similar and to have similar consequences to those seen in the Western Basin.

4.2.2 Central Basin

Pumping from this basin (Figure 4.6) was stopped in October 2008 owing to fatalities, apparently attributable to inadequate ventilation at the pump station in East Rand Proprietary Mines (ERPM) (pers comm. P Kelly, DMR). The rate of rise measured by ERPM Mine varies between 0.35 and 0.900 m/d (Figure 4.3), depending on rainfall. Previously, an average volume of approximately 60 Ml/d was neutralised and discharged into the Klip River (Scott, 1995; Council for Geoscience, 2004a; Council for Geoscience, 2004b; Council for Geoscience, 2005a; Department of Minerals and Energy, 2008c). Lin and Hansen (2010) have identified the Environmental Critical Level (ECL) for the Central Basin (Figure 4.3) at 150 m below surface, measured at South West Vertical Shaft at ERPM. The recent water level measurement at South West Vertical shaft is equal to levels within the Central Basin, and is taken as representative value for the whole basin. Furthermore, they have also identified possible decant points and studied the acidification of water related to the flooding of the Central Basin.

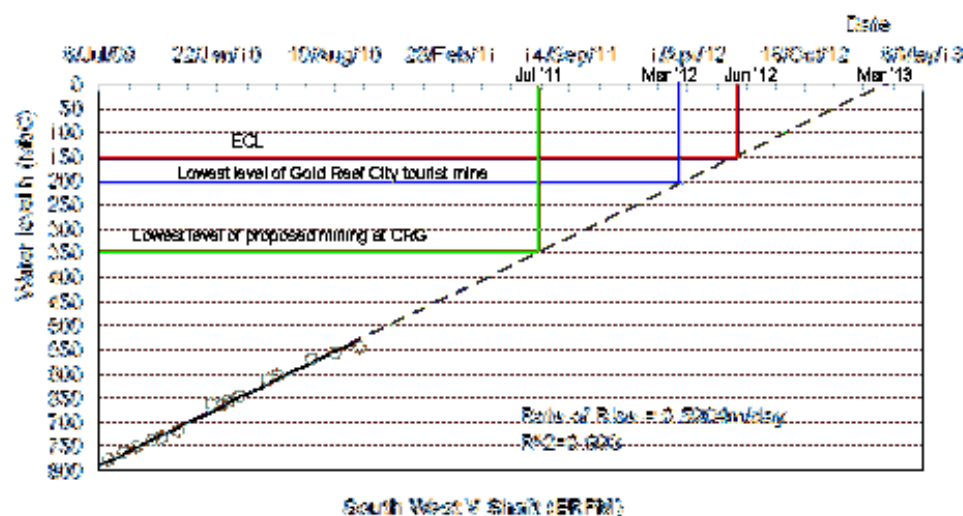


Figure 4.3. Rising water levels in the Central Basin, extrapolated to the points where they will reach various critical levels, including the decant forecast for March 2013 (CRG — Central Rand Gold, compiled by L Lin, 2010)

If this water is allowed to continue to rise, it will:

- Make mining of the remaining gold in the Central Basin uneconomic. Central Rand Gold (CRG), a new entrant to the mining industry, has recently commenced underground operations in the Central Basin to extract remaining gold (Central Rand Gold, 2008). Central Rand Gold have already ordered the pumps necessary to prevent the rising water from reaching the levels where they intend to mine.

- Flood the underground mine operated as a tourist attraction at Gold Reef City. This site is visited by up to 3 000 tourists daily and showcases an important piece of the heritage of Johannesburg and, indeed, South Africa.
- Rise to an environmentally critical level where local groundwater systems could be influenced, particularly the dolomitic aquifers to the south, ERPM in Boksburg and Durban Deep in Roodepoort.
- Rise to the surface, decanting in low-lying areas in the vicinity of the ERPM Mine in Boksburg and possibly elsewhere across the Witwatersrand.
- The hydraulic regime in the underground workings is not well understood, and it cannot be proven that the water level will stabilise at this lowest decant level (beneath central Boksburg). Further rise in water level would impact on higher-lying areas across the Central Basin — from Roodepoort, through Johannesburg to Boksburg (Figure 4.6).

The similar mining methods practised and similar geology of the Central and Western basins suggest that the likely consequence of flooding within the Central Basin could be similar to that experienced in the Western Basin. However, flooding within the Central Basin would occur within a highly urbanised area, while the impact of flooding in the Western Basin has largely been on the peri-urban areas to the north of Krugersdorp and Randfontein.

4.2.3 Eastern Basin

In the Eastern Basin (Figure 4.7), a single-pump station is currently pumping mine water at Grootvlei Mine at a rate of 75–108 Ml/d (Council for Geoscience, 2008b; Scott, 1995; Department of Minerals and Energy, 2008c) (Figure 4.4). A number of factors, including the inflow of large volumes of dolomitic water with high alkalinity and the removal of a large number of surface residue deposits in this basin, contribute to the production of a better quality of water with higher pH and lower sulphate levels than has been observed in the other basins. However, the water is not fit for uncontrolled discharge to the environment, as it contains significant sulphate and iron concentrations. Recent financial limitations have resulted in the Grootvlei Mine discharging untreated water, thereby failing to meet the discharge standards as per their water use license. The substandard effluent is being discharged into the Blesbok Spruit, which flows through a Ramsar-listed wetland. The DWA was forced to institute legal action following this contravention, and the matter remains under investigation. Given Grootvlei Mine's financial position, the pump station will be flooded within 30 days, should their pumping operations cease, whereupon the water level will continue to rise until it decants into the surrounding dolomitic aquifers and, eventually, to the surface, with the predicted decant point being within the town of Nigel (Scott, 1995; Council for Geoscience, 2005b; Esterhuysen *et al.*, 2008). This is likely to happen as early as five years after the cessation of pumping (Scott, 1995).



Figure 4.4. Water pumped from the Eastern Basin to the treatment plant at Grootvlei Mine

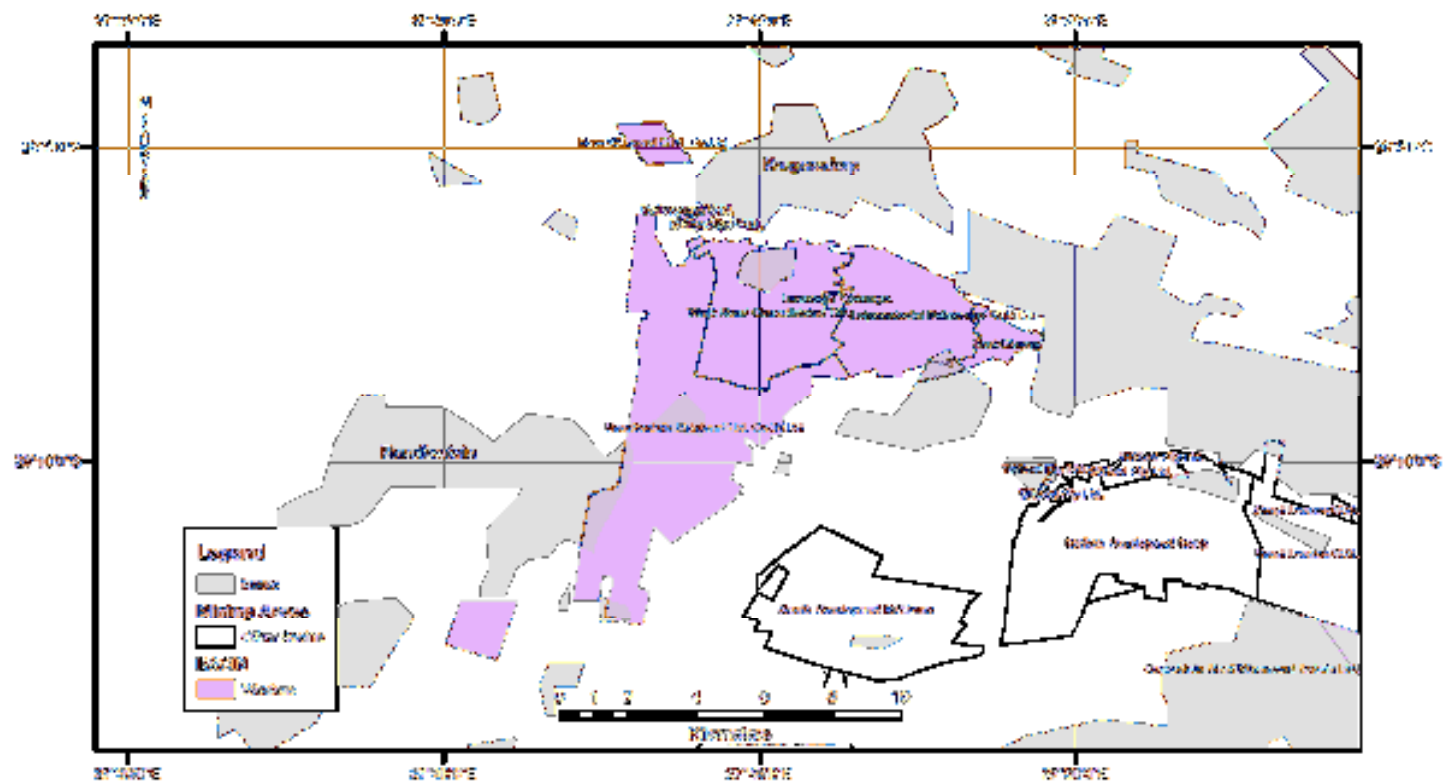


Figure 4.5. Locations of mines of the Western Basin

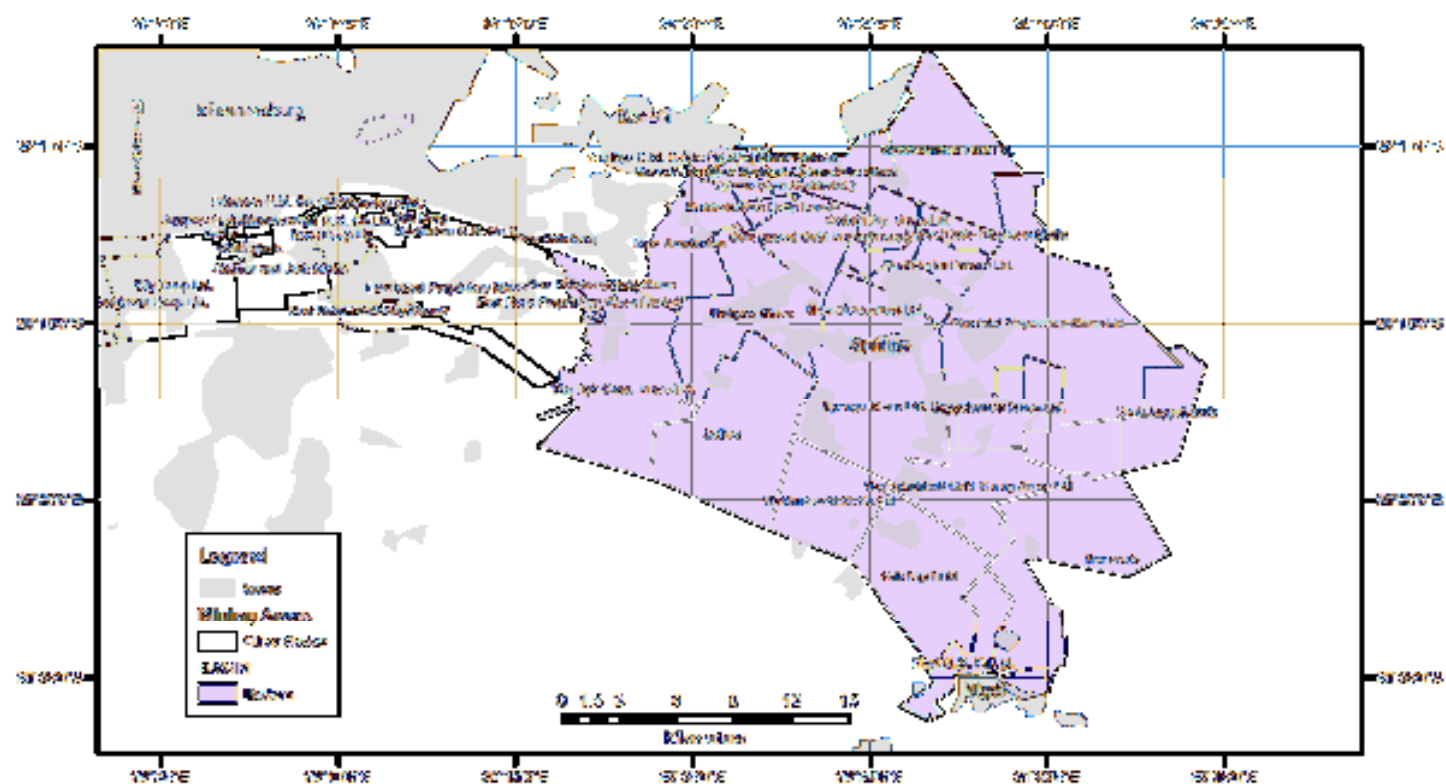


Figure 4.7. Locations of mines of the Eastern Basin

4.2.4 Far Western Basin

Most of the mines in this basin are still operational and AMD problems owing to flooding are not regarded as urgent at this stage (Department of Minerals and Energy, 2008d). There is, however, uncertainty with regard to the quality of water filling the mine voids after mining has ceased, indicating that attention must be paid to potential impacts on the overlying dolomitic aquifers (Department of Minerals and Energy, 2008d; Van Tonder *et al.*, 2008; Van Tonder *et al.*, 2009). This poor quality water is believed, at least in part, to originate from tailings facilities that were historically located over cavernous dolomite to encourage the drainage of the tailings, without regard for the underlying groundwater quality. A contributory factor is the historical practice of filling sinkholes in the dolomite with mine tailings (Dill and James, 2003).

4.2.5 Klerksdorp, Orkney, Stilfontein and Hartbeesfontein (KOSH) Basin

Continued mining operations in the KOSH Gold Field depend on the pumping infrastructure at Margaret Shaft (Stilfontein Gold Mine) (Department of Minerals and Energy, 2008e) for the dewatering of the mine void in the down-dip underground workings of the other mines in the area. Stilfontein Gold Mine was declared insolvent in 2005, resulting in the temporary abandonment of all the mine workings, including the pumping station at Margaret Shaft. In order to prevent the flooding of all of these workings, the other active mining companies in the area took over the pumping operations at Margaret Shaft and have been operating the pump station under transitional arrangements with the DMR and the DWA. A water utility company has been formed to operate the pumping station and it has been proposed that revenue can be generated from the water pumped.

4.2.6 Free State Gold Field

Most mines in the Free State are still operating and pumping is active. Studies conducted by the mines suggest that there is no immediate serious threat of decant, even if mining were to cease because of the geological features of the area, including the topography. However, a number of challenges result from the closure of some shafts and the need to increase pumping capacity at the remaining shafts. It is also necessary to isolate the remaining mining areas by installing plugs between them and the closed areas. In the latter case, seismicity and the rate of the water level rise will have to be monitored.

The current main concern pertains to the large number of evaporation and return-water dams in which the partially treated mine water has a high concentration of heavy metals and salts, impacting surface water bodies in the area.

The possibility of treating mine water and selling it to the local bulk water supplier has been raised, but has not been undertaken yet as water demand is not high enough in the area.

Some tailings facilities have been shown to be responsible for contaminating borehole water in the area. Most of the reclaimed tailings facilities have not been rehabilitated yet, and they are sources of both groundwater and surface water contamination.

4.2.7 Evander Basin

The Evander Gold Field is currently operating through a single shaft. However, the pumping facilities at two other shafts are still in use, extracting some 4 Ml/d. About 90 % of this water is stored in evaporation dams, while the remainder is reused in the mining processes. There have been no reports of AMD problems and sinkholes related to gold mining in the area. Nevertheless, there is evidence that the evaporation dams and tailings facilities contaminate the local shallow aquifers hosted in alluvial and/or Karoo sediments. Water management in the area is further complicated by the presence of underground coal mines located directly above the gold mines.

CHAPTER 5. PRIORITISATION OF GEOGRAPHIC AREAS AFFECTED BY AMD WITHIN SOUTH AFRICA

An analysis of currently known AMD sources in South Africa has identified the following mining areas (Figure 5.1):

- Western Basin
- Central Basin
- Eastern Basin
- Free State Gold Field
- KOSH Gold Field
- Far Western Basin
- Evander Gold Field
- South Rand Gold Field
- Mpumalanga Coal Fields
- KwaZulu-Natal Coal Fields
- O’Kiep Copper District

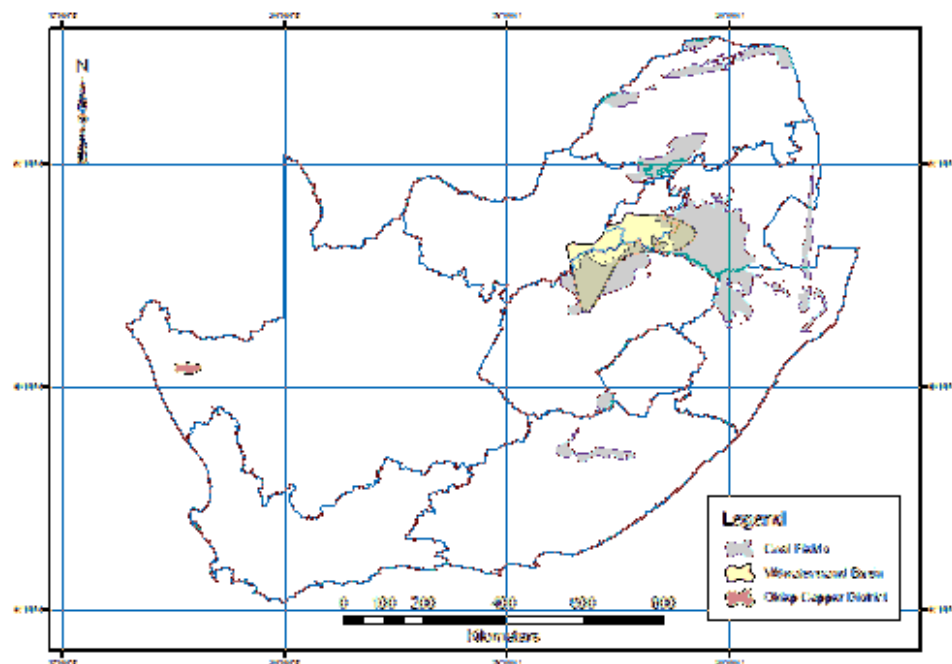


Figure 5.1. Identified areas of AMD generation and potential AMD generation in South Africa

5.1 HIGHEST PRIORITY AREAS

Of the above listed problematic areas with respect to AMD, critical problems are known to exist in the Western and Central Basins where, respectively, limited and no pumping is taking place. Decant has already occurred in the Western Basin, while the Central Basin is currently flooding and will decant within two to three years unless decisive action is taken immediately to prevent it. In the Eastern Basin, one mine that is not producing revenue is currently pumping water. These areas are prioritised owing to the lack of adequate measures to manage and control the problems related to AMD, the urgency of implementing intervention measures before problems become more critical, and the proximity of these problem areas to densely populated areas. The situation in these areas can be regarded as in need of critical intervention in the short term.

5.2 VULNERABLE AREAS WHERE ADDITIONAL INFORMATION IS REQUIRED

Severe water related problems, including numerous AMD decants (Figure 5.2), have been reported in the Mpumalanga Coal Fields. These must be regarded as serious and in need of follow-up action and assessment, particularly in view of the expansion of coal mines in the area and the regional-scale impacts already reported.



Figure 5.2. Decant of AMD from the abandoned Transvaal and Delagoa Bay Colliery close to eMalahleni in Mpumalanga

The other large gold-mining areas listed, namely the Free State, KOSH, Far West Rand and Evander Gold Fields, are currently being mined actively and water is pumped from these basins. It is recommended that a risk assessment of these areas be carried out to determine their vulnerability to the premature closure of specific mines and shafts.

5.2.1 Lower priority areas requiring assessment and monitoring

Considering the commodities mined, AMD impacts can also be expected in the Waterberg, Molteno and Limpopo Coal Fields and the South Rand Gold Field. As no serious problems are known to have developed yet in these areas, they cannot be regarded as high priorities, but the individual circumstances need to be assessed and monitored in order to provide timely information on possible future problems.

A number of AMD impacts have been identified in the O'Kiep Copper District (Figure 5.3) in the Northern Cape by the CGS during the investigation of derelict and ownerless mines and other research activities (Coetzee *et al.*, 2008). These appear to have a localised impact, although potential long-term impacts have also been identified.



Figure 5.3. Decant of copper-rich AMD in the town of O'Kiep, Northern Cape

CHAPTER 6. REAPPRAISAL OF THE RISKS ATTRIBUTABLE TO ACID MINE DRAINAGE

6.1 INTRODUCTION

This reappraisal of the risks attributable to AMD in South Africa has become necessary in order to assist government in the management of a perceived national crisis with respect to acid mine drainage, particularly in the gold and uranium mining areas of the Witwatersrand (Figure 1.1 on page 3). In recent months, media reports have highlighted the problems related to the flooding of the mining basins of the Witwatersrand, often sensationalising the risks faced in these mining areas. It is therefore necessary that the risks identified be assessed, based on concrete information and reliable scientific input, in order to establish a management plan that will minimise risk to the public and the environment.

6.2 DEWATERING AND REWATERING OF THE MINING BASINS OF THE WITWATERSRAND

In order to comprehend the issues related to the flooding of the Witwatersrand mines, it is necessary to understand how they developed over time, the geometry of the mine voids and their relationship to the surface and surface infrastructure.

Gold was discovered on the farm Langlaagte — now in the Western suburbs of Johannesburg — in 1886 (Antrobus, 1986). This initial discovery was of a surface deposit of weathered conglomerate with an east–west strike. Opencast mining developed rapidly to the east and the west of the discovery site, eventually extending across most of the Central and Western Basins. In a relatively short time, the near-surface weathered zone had been mined out completely and it became necessary to mine the harder rock below. This required underground workings to be developed, first via incline shafts on the reef horizons and later via deep vertical shafts sunk to the south of the outcrop zones, accessing the reefs via a network of underground tunnels. As these deeper workings were developed it became necessary to pump out the water which seeped into the underground workings in order to prevent them from flooding. The gold ore was extracted from narrow stopes dipping to the south, with underground workings extending from as shallow as less than 10 m below surface down to great depths, in some cases more than 3 000 m below surface. The gold reefs extend more or less continuously for many kilometres and, as a result, large networks of interconnected shafts, tunnels and stopes have developed across the Witwatersrand, with each basin representing a zone of near-continuous gold reefs, bounded by geological discontinuities. In the peak of mining on the Witwatersrand, multiple mines extracted ore from underground workings, each having to pump water from their own workings.

Over time the easily accessible and higher grade ore was depleted, leading to the closure of such mines. This placed a greater burden on the remaining mines to pump water flowing in from neighbouring mines, as well as water from their own workings. Where this happened, the State instituted a system of subsidies for mines to assist with the pumping of extraneous water from their workings. Eventually the last mine in a basin would stop mining, stop pumping and the basin would flood. This has occurred in two of

the three priority areas — the Western and Central Basins — while a single mine, Grootvlei, still pumps water from the Eastern Basin, maintaining the water level 700 m below surface.

The inflowing water comes from a number of sources, including surface water directly entering old mine workings, surface water that recharges the shallow groundwater directly above the mine workings, groundwater recharged by rainfall directly above the shallow workings, and water seeping from the numerous large mine residue deposits that overlie the mine workings. In addition to these natural water sources, some leakage from the infrastructure carrying potable water, sewage and stormwater across the zone of shallow undermining occurs and will require pumping.



Figure 6.1. AMD formed owing to interaction between water and mine residues on the surface, exposed in a surface tailings reclamation operation in the Western Basin. Note that this site drains into open pit operations that are directly connected to the mine void

Unfortunately this water is of poor quality. Some is already contaminated owing to interaction with mining residues and other materials on the surface before it enters the mine void (Figure 6.1). Acid mine drainage is formed when sulphide minerals — particularly pyrite — interact with oxygen and water, forming a dilute solution of sulphuric acid and iron that leaches other metals from the material in which it forms. Acid mine drainage in the Witwatersrand typically has a pH value around 3 — the pH of lemon juice or vinegar, not battery acid or swimming pool acid as has been reported in the media — and is enriched in a number of toxic metals, often including uranium. This is typically 3 to 5 pH units below what would normally occur in an unimpacted environment. The

associated high concentrations of sulphate and iron also pose serious water quality problems if they enter the surface environment.

Flooding of the mine voids will create an oxygen-poor environment where acid forming reactions will slow down significantly. Unfortunately, the topography of the mining areas, in the three prioritised basins, will not allow complete flooding, as decant will tend to control the water level at the lowest topographic level within each basin. Above this level a significant unsaturated zone exists in the shallower portion of the underground workings. The mixing of air, water and exposed sulphides in this zone will continue to form new acid mine drainage.

After the cessation of mining the inflowing water slowly fills the mine voids and the water rises as the interconnected voids become flooded. The Central Basin is currently flooding after the last operating mine — ERPM — ceased pumping in 2008, with the water level measured at 545 m below surface on the 22nd of September 2010, with an average daily rate of rise over the past year of 0.59 m. If unchecked, this will rise to the surface and decant, flowing out of one or more low-lying shafts or other water conduits, such as boreholes or water-bearing geological structures. This happened in the Western Basin following the cessation of pumping in the late 1990s. Acid water surfaced in 2002, contaminating a local stream and having a serious impact on the ecology of the Krugersdorp Game Reserve immediately downstream, which has continued since this time, although some efforts have been made by local mining companies and the DWA to contain this water and minimise its impacts on the environment.

6.3 APPRAISAL OF RISKS

A full appraisal of risks has been performed using the software package RiskMatrix (Engert and Landsdowne, 1999). The detailed results are presented in Appendix A.

6.3.1 Risks owing to the flooding of the mine voids

The risks owing to the flooding of the mine voids are listed below. The sequence in which they are listed does not imply any prioritisation of the risks.

6.3.1.1 Increased seismic activity

Mine flooding related seismicity was identified as a problem more than 500 years ago (Klose, 2007). The closest comparable phenomenon would be seismic activity related to the filling of large reservoirs, fluid injection into oil field wells and in hydrothermal fields. The flooding of mines is assumed to trigger seismicity in a similar manner as water fills mining voids from the deepest parts of the mines to the surface. The high water pressures owing to the flooding can affect the stability of artificial and natural fractures causing them to slip, generating seismic events. High pore pressures, coupled with lubrication of faults reduce clamping forces on the fractures/faults, which can cause even previously non-seismic fractures to slip (Durrheim *et al.*, 2006; Goldbach, 2010). In such cases, the frequency of seismic events is likely to increase during and shortly after the period of flooding, after which it will likely stabilise and decrease over a period of several years after flooding has been completed or a stable water level is maintained. Seismic

events triggered by mine flooding have previously been observed in Canada, India, Japan and Poland.

The closure of mines in the Central Basin resulted in the shutting down of the pumping stations that previously maintained the underground water level. As a direct consequence, the water level has been rising within the abandoned mines. The South African National Seismograph Network (SANSN), operated by the CGS, has observed a dramatic increase in seismicity coinciding with the closure of the pumping stations (Figure 6.2). The average number of events per month increased from 5.9 before pumping stopped to 11.7 afterwards. With the installation of 12 seismic stations in the Central and East Rand under the Strategic Water Management Project, the average frequency of observed events has increased to 24 per month. However, the increase observed in April 2010 may only be an apparent increase in seismicity, since the denser network of stations is capable of recording smaller events than the SANSN. Continued monitoring and interpretation will track the observed change in the rate of seismicity and provide further insight into the risk posed by these events.

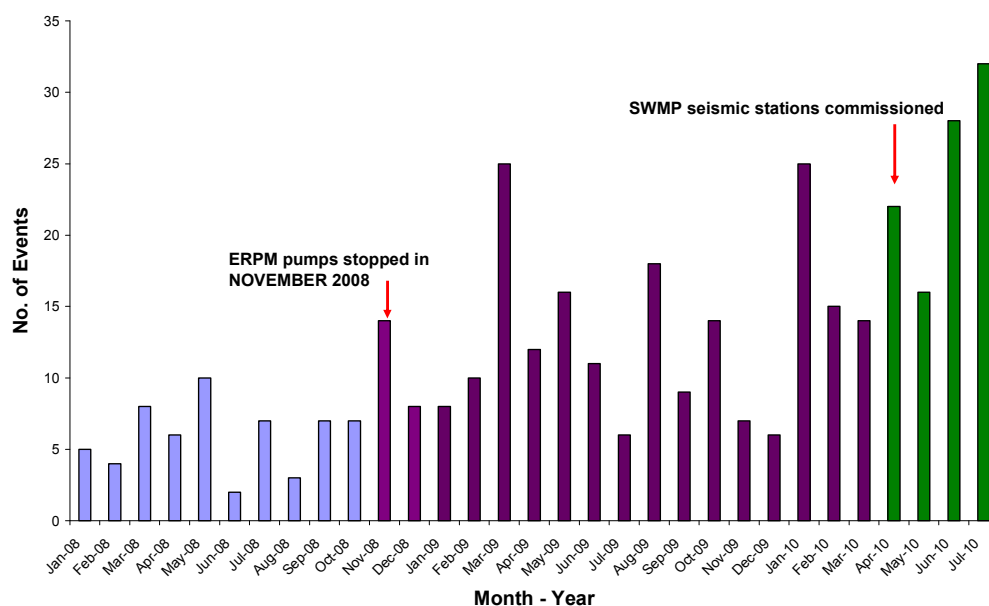


Figure 6.2. Number of seismic events measured by the CGS in the Central and East Rand area before and after pumping at ERPM stopped

Figure 6.3 shows the located seismic events in relation to the city of Johannesburg and the old mining districts. It is clearly seen from the map that most of the recorded seismic events are confined to the area of flooding of the old mines. The fact that the metropolitan city of Johannesburg is situated directly adjacent to this basin represents a situation of concern. However, international and local case studies reveal that the magnitude of seismic events that can occur owing to mine flooding is expected to fall within the range of magnitudes observed during mining operations; which have reached magnitudes of up to M_L (local magnitude) 5.3 in the Witwatersrand Basin. Such events have in the past caused structural damage and disruption throughout the Witwatersrand

region, including the Johannesburg urban area. The occurrence of an event of similar magnitude owing to mine flooding, which could lead to serious consequences if it struck a densely populated urban area or a key business interest, can at present not be excluded. Therefore, the nature of seismic events triggered by mine flooding, as well as the damage potential of surface ground motions associated with such events, needs to be monitored and investigated.

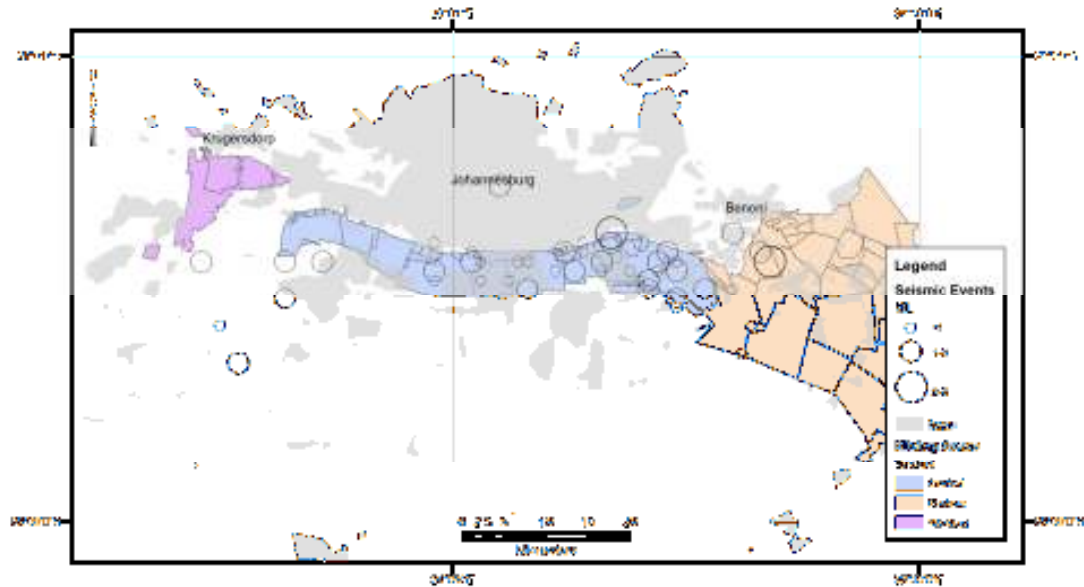


Figure 6.3. Seismic events recorded and located by the Council for Geoscience in the Central and East Rand between March and July 2010

6.3.1.2 Contamination of shallow groundwater resources

Rising AMD within the mine voids will not only come into contact with surface water resources, but will also tend to flow into down-gradient areas via groundwater conduits. This will be most pronounced in the dolomitic aquifers adjacent to and overlying the mine workings (Figure 6.4) in the Eastern and Western Basins. In the Western Basin this is an area of specific concern as the dolomitic aquifers located down-gradient of the mining area provide clean water to the Cradle of Humankind World Heritage Site (Hobbs and Cobbing, 2007, Hobbs (ed.), in prep.). In the Central Basin, dolomitic aquifers to the south of Boksburg could be affected by rising water levels (Lin and Hansen, 2010).

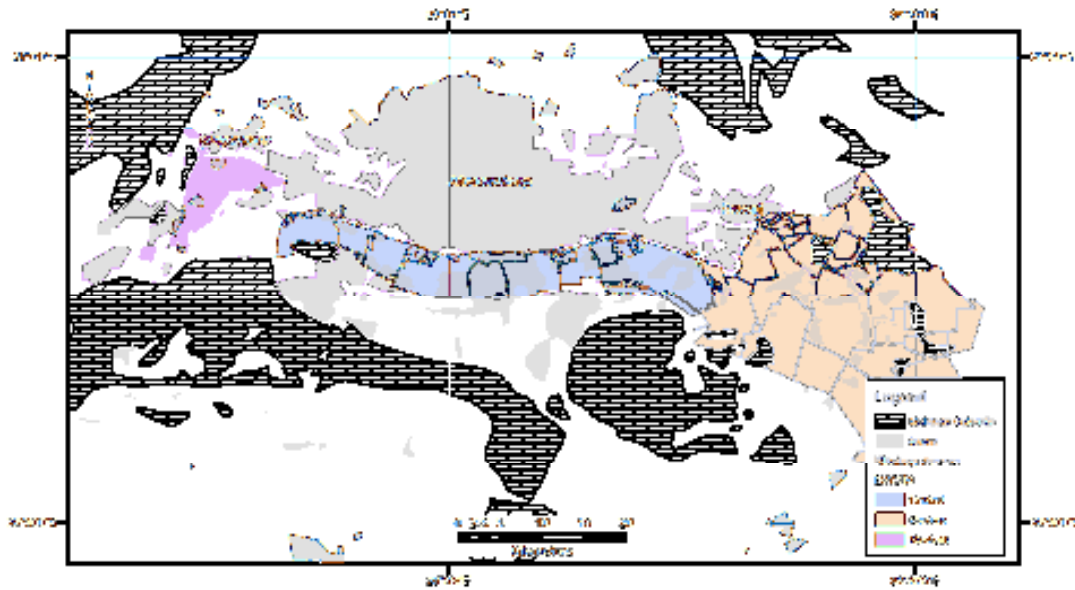


Figure 6.4. Relationship between the Witwatersrand mining basins and the outcrop of the Malmesbury Dolomite

6.3.1.3 Geotechnical impacts if the water reaches the near-surface environment

The geotechnical impacts of rising water levels on ground stability have been raised by Coetzee *et al.*, (2008b):

- Subsidence at the outcrops could occur owing to the mobilisation of poorly compacted fills within steeply dipping stopes
- Acid mine water could result in the chemical corrosion of building foundations, but this aspect has not been well studied and site-specific studies are necessary
- Foundations, basements and municipal services could be flooded as a result of rising groundwater levels driven by the flooding mine void, if water levels are allowed to rise high enough to impact on these structures. These effects may be localised to low-lying areas.

The area where severe negative impacts are of greatest concern is the Central Basin, because of its proximity to Central Johannesburg and, particularly, in the presence of abandoned near-surface workings in the city centre. However, most of the Johannesburg CBD is located up to 100 m higher than the lowest-lying parts of the basin where water is likely to decant. The Western Basin has little urban development in close proximity to the old mine void, and therefore is less at risk from this type of impact. The same is true for large parts of the Eastern Basin, although impacts are possible in Nigel if pumping stops and the water level rises to its decant level.

While many of these impacts are relatively unlikely in the Central Basin, because of the elevation differences between the decant level and the CBD of Johannesburg, they may

occur in lower-lying areas, such as parts of Boksburg and areas to the south of the CBD. Regular monitoring of water levels across the mine voids, as well as monitoring of possible impacts, will provide early warning of these impacts, allowing preventative action to be taken if required.

6.3.2 Risks owing to decant of water to the surface

6.3.2.1 Ecological impacts

The decant of water in the Western Basin provides an example of the ecological impacts that could be expected downstream of a decant of AMD into a surface stream. In 2002 water decanted from the Western Basin mine void into the Tweelopie Spruit, a surface stream draining into the Krugersdorp Game Reserve (Figure 6.5). The downstream impacts of this water were assessed by Coetzee *et al.* (2005a), who reported a number of parameters far exceeding the DWA guidelines for stock watering and aquatic ecosystems (Department of Water Affairs and Forestry, 1996b), while aquatic biomonitoring results collected in 2000 and 2004 showed the deterioration of the system from one classified as Class C (in a good ecological condition) to a Class F (unsustainable and unable to support normal aquatic life). The operators of the Game Reserve have subsequently reported a number of animal deaths which they believe are attributable to the poor water quality, as well as a dramatic decrease in the reproductive rates of animals in the Game Reserve. These effects are likely to be experienced downstream of any decant of AMD to the surface water environment, and will persist downstream until sufficient additional water is added to the stream to have a significant dilution effect.



Figure 6.5. Salt crusts precipitating on vegetation downstream of the decant from the Western Basin

6.3.2.2 Regional impacts on major river systems

One of the pervasive messages regarding AMD from the Witwatersrand Gold Fields is that it has a major impact on South Africa's major river systems and that the water pumped from the Witwatersrand mine voids, *i.e.* the water that is currently decanting from the Western Basin, the water that will decant from the Central Basin if action is not taken to prevent it, and the water that is pumped from the Eastern Basin by Grootvlei Mine is an important contributor to the salinity of the Crocodile and Vaal River Systems. This has far reaching implications, as the DWA currently manages water quality in the Vaal System via the discharge of clean water from upstream sources, including the Lesotho Highlands Water Project. The addition of saline water to the system requires large volumes of clean water to be discharged to maintain water quality at acceptable levels. The Vaal River Reconciliation Strategy of the DWA (Department of Water Affairs and Forestry, 2009) identifies the point sources of mine water as sources that can be removed from the system by desalination. The pollution from the mine discharges form the most concentrated salt stream entering the Vaal System and therefore represent one of the areas where desalination of a waste stream could be achieved efficiently. Other discharges to the Vaal System, including diffuse pollution from mining sites, pollution from coal mines, and discharges from sewage works and industries will also need to be addressed to ensure water security in the Vaal System.

Impact of the Western Basin decant on downstream surface water

The bulk of the mine water from the Western Basin does not currently enter the Vaal System, discharging to the Tweelopie Spruit, an upper tributary in the Bloubank Spruit System of the Crocodile (West) River catchment. A small volume of seepage has been observed to enter the Wonderfontein Spruit, which drains to the Vaal System via the Mooi River (Coetzee *et al.*, 2005b). The decant of AMD and the discharge of partially treated mine water have had severe negative impacts on the aquatic ecology and the large mammal population in the Krugersdorp Game Reserve immediately downstream of the decant and discharge points. Impacts have also been experienced in streams further downstream, notably the Riet Spruit. However, the Bloubank Spruit as main stem in this drainage system itself has not exhibited any significant impact from AMD in the past 8 years since the start of decant in late-August 2002. This is shown in Figure 6.6, which does not reflect a notable change in total dissolved salts (TDS) load at the downstream monitoring station A2H049 in the post-decant record. For example, the post-decant median and 95th percentile values are not significantly different from the whole record values.

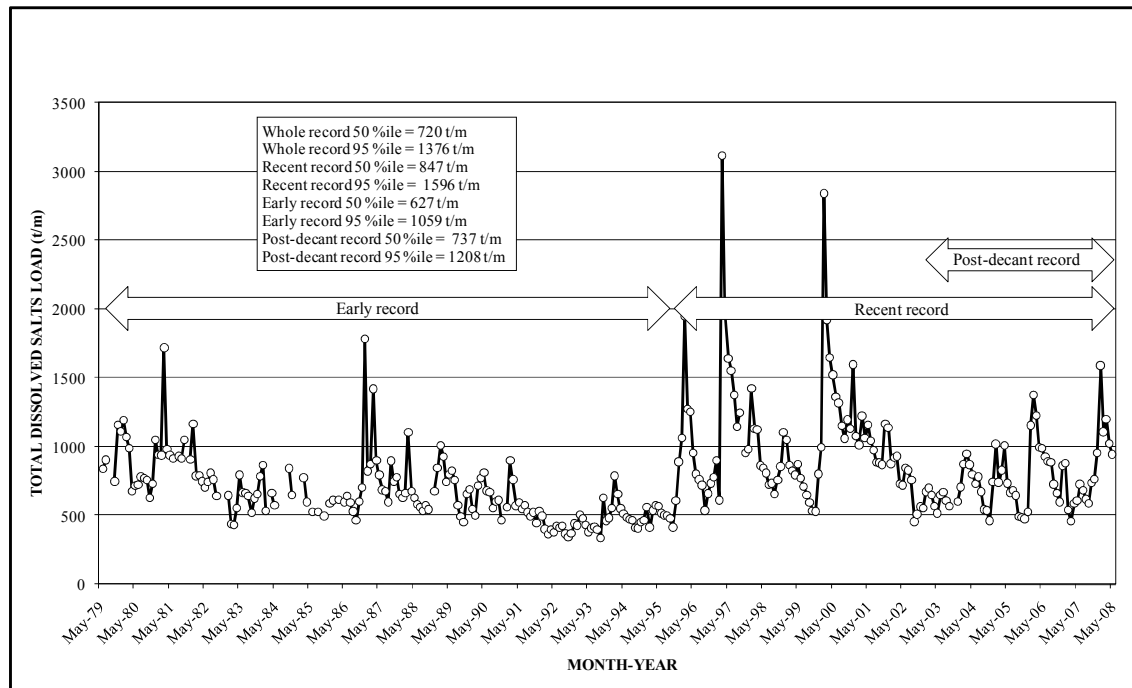


Figure 6.6. Long-term monthly TDS load pattern at station A2H049, Bloubank Spruit System (from Hobbs (ed.), in press).

Figure 6.7 shows the sulphate concentrations leaving the Bloubank Spruit System and Hartebeespoort Dam in the post-decant period. It would appear that the AMD decant phenomenon has had little discernible impact on the water quality (as represented by the sulphate concentration — Figure 6.7) at either of the monitoring stations. This observation is explored further in Figure 6.8 on the basis of the TDS and sulphate loads leaving the Bloubank Spruit System in the post-decant period. Although a linear regression analysis of the data sets indicates a rising trend in both instances, the poor

correlation coefficients (R^2 of 0.08 for TDS and 0.12 for SO_4) suggest that not too much value can be attached to the trends. A visual fit through the summer (wet season) peak loads as represented by the pecked lines in Figure 6.8 suggests a more definitive, but still admittedly tenuous, trend.

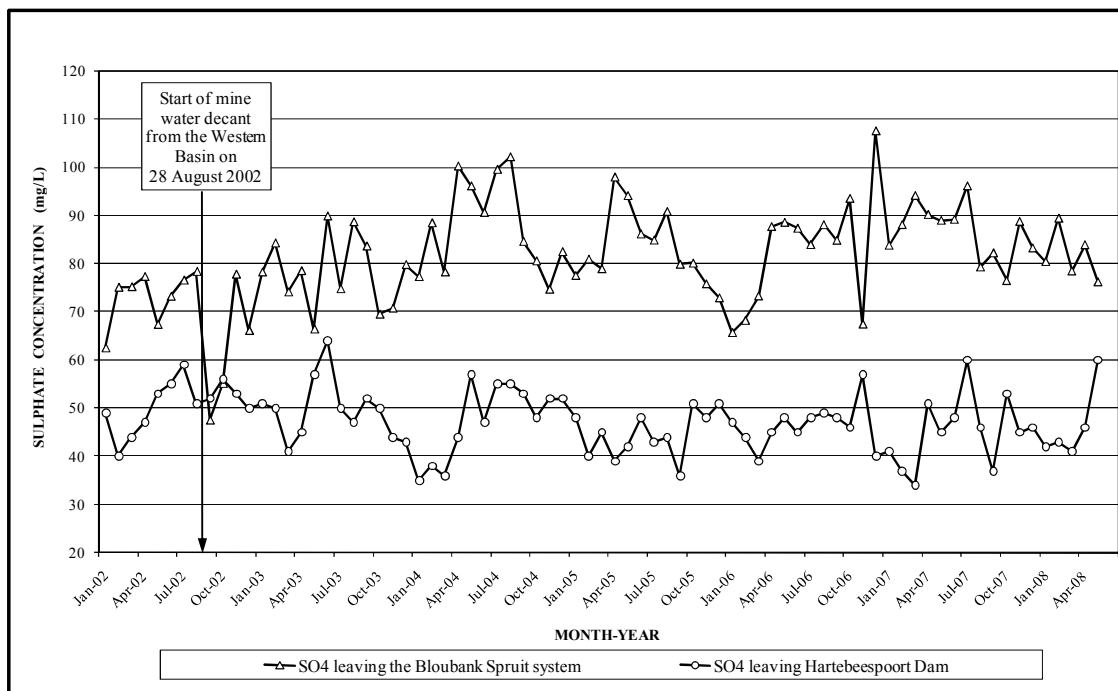


Figure 6.7. Comparison of the SO_4 concentration in surface water leaving the Bloubank Spruit System at station A2H049 with that leaving Hartebeespoort Dam since the start of mine water decant from the Western Basin

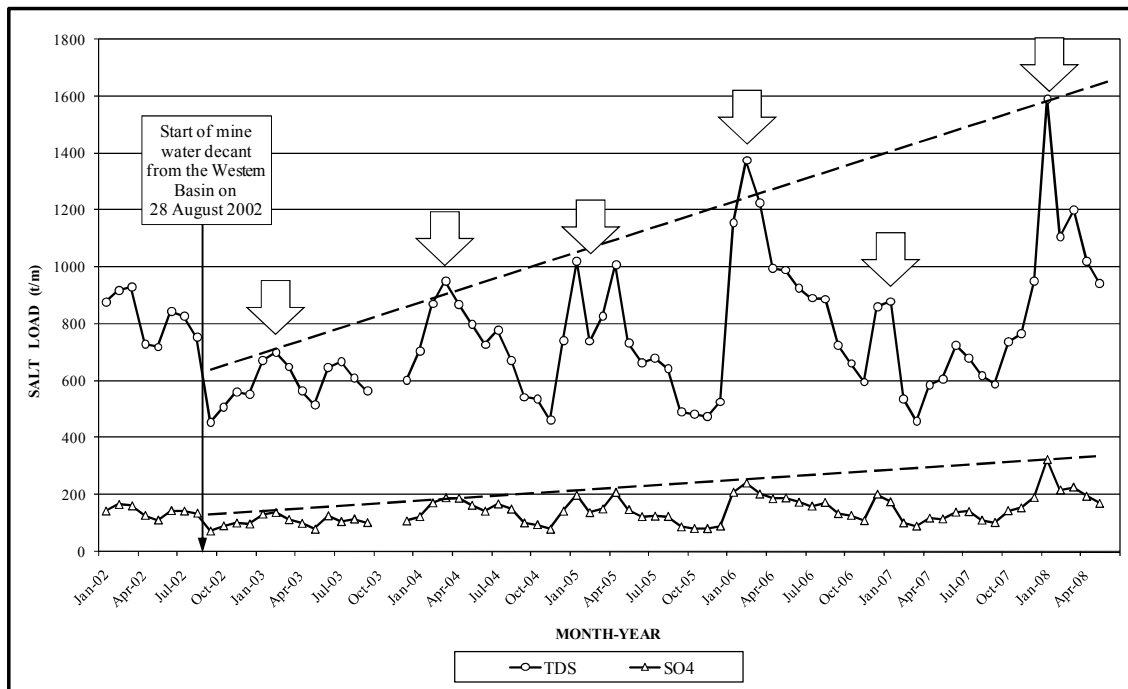


Figure 6.8. Comparison of monthly TDS and SO₄ loads leaving the Bloubank Spruit System at station A2H049 since the start of mine water decant from the Western Basin. Arrows denote higher summer (wet season) loads (from Hobbs (ed.), in press)

The above observations are likely attributable to a combination of dilution, precipitation of sulphate as sulphide in the aquatic environment (particularly wetland environments), and, specifically in the Bloubank Spruit System, surface water losses to groundwater. The latter phenomenon is an intrinsic characteristic of dolomitic environments, and raises concern for the impact of poor quality surface water on the receiving groundwater resources. Whilst groundwater samples collected from boreholes in close proximity to the losing stream reaches do show higher salinity, calcium and sulphate values, this is not widespread. Similarly, the presence of heavy/trace metals in the dolomitic groundwater, if at all detectable, remains low to very low. Finally, the pH of the dolomitic groundwater even in proximity to the losing stream reaches remains greater than 6.4, which reflects the continued neutralising capacity of the carbonate dolomitic strata. Because of the ongoing input of contaminated water, the dolomitic aquifer will require monitoring. Should poor water quality be detected, remedial action will be required to improve the quality of water in the system.

Impact of the Central Basin on downstream surface water

In the Central Basin, it is possible to gauge the effects of the mine water discharges on the downstream environment by examining water quality before and after the cessation of pumping by ERPM in October 2008. If the impact on downstream water quality is significant, a decrease in the sulphate concentration of the downstream river water should be noticed at around this time.

Data from two sampling sites — the Elsburg Spruit upstream of its confluence with the Natal Spruit (Figure 6.9) and a site in the Klip River upstream of Henley on Klip (Figure

6.10) — have been extracted from the DWA database. In both cases the downstream effect of the mine water discharge can be clearly seen. Unfortunately, very little flow data for the relevant periods are available so that total salt loadings cannot be calculated.

It is evident that at the Klip River sampling site the sulphate concentration decreased by approximately one half after the cessation of pumping by ERPM, suggesting that other sources of sulphate in the water are approximately as significant as the water which was pumped and discharged from the Central Basin.

The impact of the salt load from the underground mine water in the Central Basin is therefore an important source of salts entering the Klip River System and subsequently the Vaal Barrage, but is by no means the only source. The fact that it is not possible to calculate a salt load for the mine water source or the salt load in the Klip River underscores the need for monitoring of flow in the affected river systems.

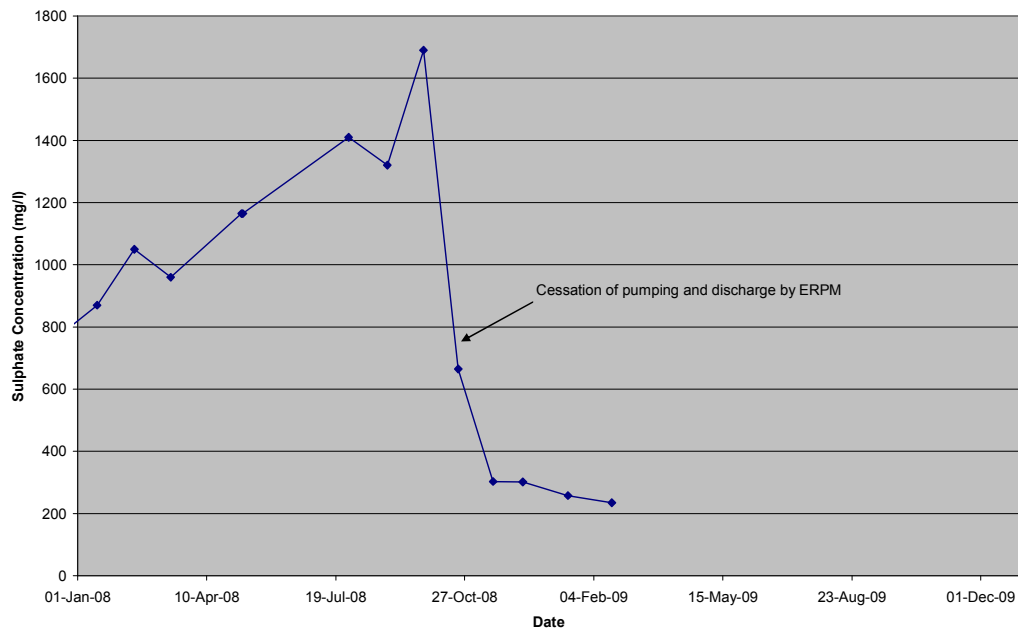


Figure 6.9. Time series of sulphate concentration in the Elsburg Spruit downstream of ERPM mine, showing the effects of the cessation of pumping and discharge by ERPM

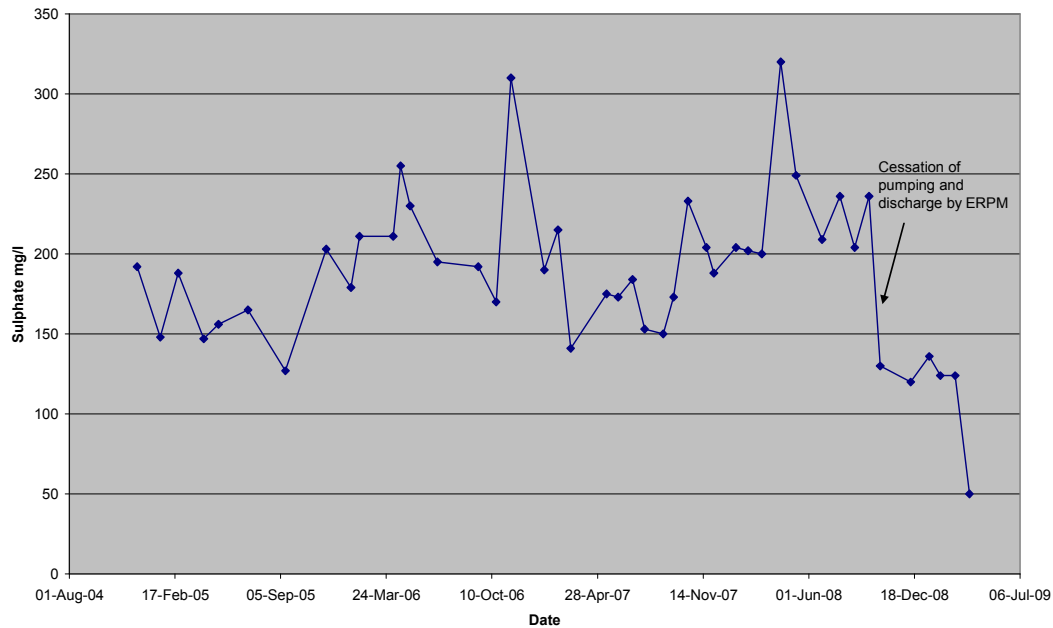


Figure 6.10. Time series of sulphate concentration in the Klip River, showing the effects of the cessation of pumping and discharge by ERPM

Impact of the Eastern Basin on downstream surface water

Water quality data from a DWA sampling point on the Blesbok Spruit downstream of Nigel (C2H184) are presented on Figure 6.11. The high sulphate concentrations suggest that water contaminated by mining is entering the system, but, as in the case of the Central Basin, the lack of flow data prevents the identification of the exact contribution of the discharge of pumped water to this stream. The overall decrease in sulphate concentration during the period from 2001 to 2009 could occur as a result of the measured decrease in the sulphate concentration of water pumped from Grootvlei Mine (pers. comm. I Lea — Grootvlei Mine), or from increased dilution because of greater return-flows from the Ekurhuleni Metro.

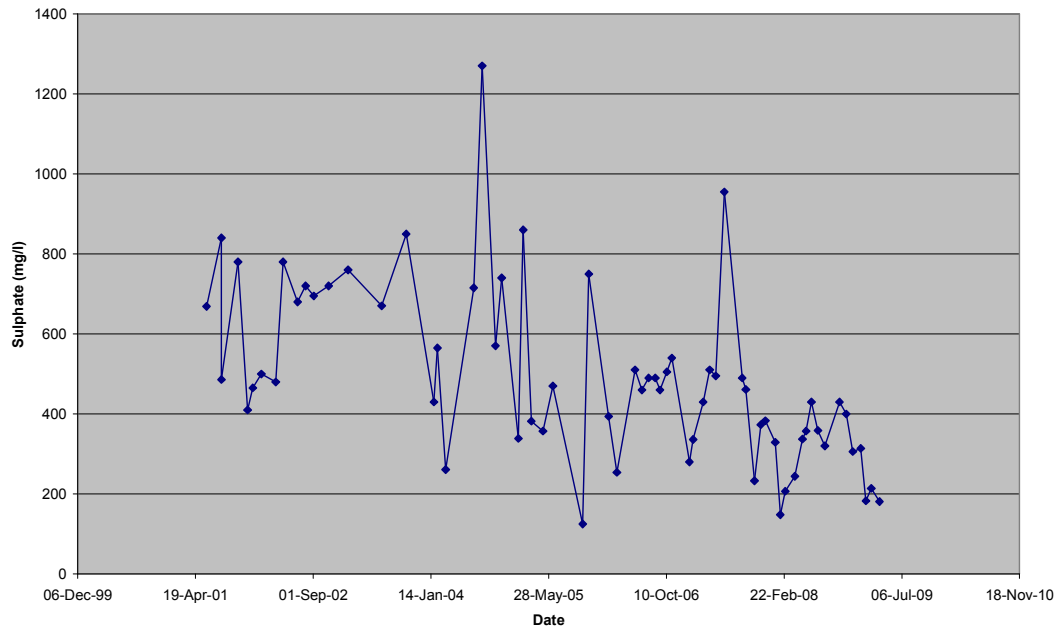


Figure 6.11. Time series of sulphate concentration in the Blesbok Spruit, downstream of Nigel

Impacts on surface water, with respect to the development of solutions

Perusal of DWA water quality data suggests that although the impacts of mine discharges have only a localised impact on surface water in the Western Basin, groundwater pollution is likely to increase in the future. In the Central and Eastern Basins measurable impacts occur in the downstream rivers. In the Eastern Basin it is not possible to distinguish the effect of the discharge of water pumped from the mine void by Grootvlei Mine, while in the Central Basin, the water pumped by ERPM accounts for approximately half of the sulphate concentration measured downstream. Unfortunately, the lack of available flow data precludes the calculation of salt loads, which would be more indicative of the total input of pollution to the Vaal River System.

Solutions to the problem should be approached from the point of view that in the short term, conditions should be no worse than those which were experienced during periods of active mining. Treatment during mining was limited to neutralisation and metal removal. This should be seen as a minimum requirement for any water that is discharged. As some impacts on groundwater have been identified as resulting from the Western Basin decant, the situation must be closely monitored and remedial action taken if it is shown to be necessary. In the longer term it will be desirable to reduce the salt load emanating from these discharges into the already stressed Vaal River System.

Where impacts are limited to localised areas, alternatives that address these localised impacts should be sought.

6.4 RISK MANAGEMENT MEASURES

The final component of risk assessment is the introduction of risk management measures that will allow identified risks to be eliminated or their severity reduced.

6.4.1 Decant prevention and management

In all three basins uncontrolled decant to the surface and shallow groundwater will need to be prevented. Decant to surface has already started in the Western Basin, with decant from three shafts (Black Reef Incline, 18 Winze and 17 Winze) and seepage from low-lying areas along the Tweelopie Spruit and Wonderfontein Spruit. The decant from the Central Basin is predicted to occur from low-lying shafts at ERPM and/or via the low-lying areas along the Elsburg Spruit. In the Eastern Basin decant is likely to occur from a low-lying shaft and low-lying areas in Nigel. This will require maintaining the water level at or below the Environmental Critical Level (ECL) for the basin. Pumping of water from the mine void is likely to be necessary.

Within the Central Basin the possibility of constructing an artificial decant tunnel to carry water from the underground workings at ERPM has been identified in studies undertaken by the CGS. This should be revisited to establish whether it will still be feasible and whether it will provide a more cost-effective long-term solution than pumping. However, this solution would not protect the underground workings preserved for tourism at Gold Reef City and would not allow the control of the water level at the ECL, 150 m below the surface, measured at the South West Vertical Shaft of ERPM.

The topography of the Eastern and Western Basins is not conducive to the location of an artificial decant point at the ECL, and will require water to be pumped from the mine void to maintain the water level below the ECL.

6.4.2 Ingress control — reduction of the rate of flooding and the eventual decant volume

6.4.2.1 Ingress reduction measures

In accordance with the hierarchy of water management actions of the DWA, as contained in the Best Practice Guidelines (Department of Water Affairs and Forestry, 2008), actions that prevent water pollution and reduce the inflow of water into the mine voids must be given a high priority. These actions will reduce the need to pump and to treat water in the long term, slow the flooding of the mine voids and reducing decant volumes or the volumes that need to be pumped. It is recommended that a proactive and precautionary basin-wide approach be taken to limit water ingress into the underground mine voids. The measures required are relatively site specific:

- Water ingress into the Western Basin is believed to be largely via open pits and from a shallow perched aquifer. Control of the water ingress from the shallow perched aquifer is probably impracticable, while the filling of the open pits with mine tailings is currently being undertaken by the mining industry in the area. Filled pits will need to be shaped and capped to limit the infiltration of water into the underlying mine void. Lowering of the water level in the mine void to below the ECL will open up new pathways for water ingress from areas that lie below the current water level. The Wonderfontein Spruit and Tweelopie Spruit will require water ingress management measures, such as drainage of pumped water

via canals, to be investigated and implemented, if necessary, to limit ingress and to 'keep clean water clean'.

- Netili *et al.* (2010) and Krige (1999) have identified a number of areas of water ingress into the Central Basin, particularly those areas where surface streams cross areas of shallow undermining. Canalisation of these streams, as well as grouting within these areas could also reduce the ingress of water into the zone of shallow undermining. Krige (1999) estimates that as much as 32.5 Ml/d of ingress could be stopped. This accounts for 54% of the total volume of water entering the mine void; although this figure still needs to be verified by flow measurements and monitoring. The construction of a canal to the south of Florida Lake is currently underway, and additional sites for canal construction have been identified. The loss/leakage of water from the municipal water supply networks (attributable to decaying infrastructure), as well as tree root growth into municipal systems, sewerage and storm-water reticulation systems are suspected to contribute to ingress into the Central Basin. These possible sources will need to be investigated in collaboration with the Johannesburg and Ekurhuleni metropolitan councils.
- In the Eastern Basin this can commence immediately with the opening up of culverts under roads in the Blesbok Spruit to prevent ponding of water and the consequent ingress to the underground mine void. Other ingress prevention actions have been identified by Netili *et al.* (2010) and will require focussed study and urgent implementation, noting that stream flows are greatly increased above their historical levels owing to other discharges, in particular treated sewage discharges (Scott, 1995).

6.4.2.2 Groundwater abstraction

In some areas in the Eastern Basin the mine void is in contact with a dolomitic aquifer located immediately above the Black Reef workings. At this interface clean dolomitic groundwater has been observed flowing into the mine void. In its passage through the mine void to the pumping station, this water becomes contaminated and acidified. Interception of this water before it becomes polluted via a well field or in-mine infrastructure would make a source of clean water available for use and also reduce the volume of water from the basin that needs to be pumped and treated. This pumping will need to be approached with caution to prevent subsidence effects that could be triggered by dewatering of the dolomites.

6.4.3 Water quality management

6.4.3.1 Pollution prevention — 'keeping clean water clean'

A primary objective of water management must be pollution prevention. In the context of AMD generation, this will largely be achieved in two areas:

- Ingress prevention as described above that will isolate surface water from the underground pollution sources

- Proper management of mine residue deposits that have been identified as sources of both water and pollution in the mine voids.

6.4.3.2 Water treatment

Even if all the measures described to limit water ingress and prevent pollution are taken, some water will be polluted and some AMD will be generated. This will need to be treated to a quality suitable for discharge or use. The options available are discussed in Appendix B.

6.4.3.3 Natural attenuation

It may be found that natural systems will effectively attenuate pollution in the environment in a limited number of cases. This is unlikely in the case of the large volumes of extremely poor quality water encountered in the priority areas. Wetlands which have been shown to attenuate pollution do so by concentrating large amounts of waste material in the environment, creating problems of sediment contamination (Coetzee *et al.*, 2002).

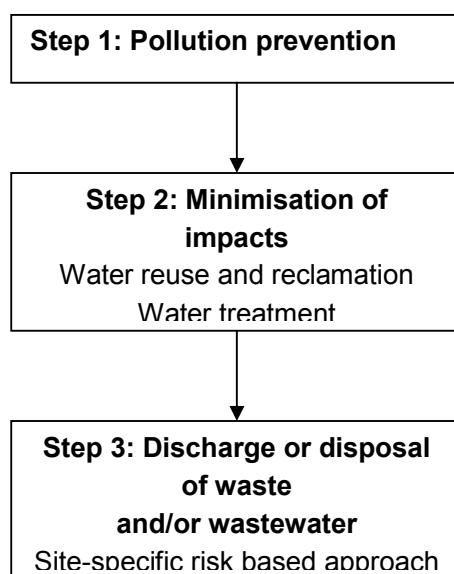
6.4.4 Monitoring

The implementation of these management programmes needs to be informed by sufficient data of high certainty to establish what needs to be achieved and, once implementation begins, whether or not the measures implemented are having and continue to have the desired effect. This will entail the monitoring of water levels in the mine void, water quality and water flow volumes in the affected streams. Monitoring will need to be coordinated between the different entities involved in the development and implementation of solutions.

CHAPTER 7. OPTIONS FOR THE MANAGEMENT OF ACID MINE DRAINAGE IN THE WESTERN, CENTRAL AND EASTERN BASINS

7.1 KEY PRINCIPLES

Principles and a hierarchy of actions for mine water management are defined in the DWA Best Practice Guidelines for Mine Water Management (Department of Water Affairs and Forestry, 2008).



It is proposed that this approach be adopted for the management of AMD from the Witwatersrand gold mines.

7.2 OBJECTIVES OF AMD MANAGEMENT

The objectives of AMD management for the Witwatersrand stem from the DWA Best Practice Guidelines, in particular the highest priority issues in terms of the hierarchy defined above, *i.e.* the prevention of pollution and the minimisation of impacts. The implementation of the principle of water reuse and reclamation is essential and must be applied, either via direct reuse of water or via discharge and indirect reuse by downstream water users. In either case, water would need to be treated to a quality suitable for the intended use or point of discharge.

7.3 A GENERIC APPROACH TO AMD MANAGEMENT IN THE WITWATERSRAND

In order to develop a management strategy, the problems faced can be split into two components based on an assessment of available information:

1. Management of Flooding: Water flows into the mine voids on a continuous basis. Unless water is pumped from the mines, it will eventually fill the voids to a point

where water decants to the surface. The current status of each of the priority Basins is presented in Table 7.1.

Table 7.1. Flooding status of the Western, Central and Eastern Basins

Basin	Status
Western	Flooded and decanting to surface
Central	Pumping has ceased. The water level in the basin is currently rising.
Eastern	Pumping is undertaken at Grootvlei Mine, maintaining the water level at around 700 m below surface.

2. Management of water quality: The water that accumulates in the mine void is of poor quality, with relatively low pH, high acidity and elevated concentrations of sulphate, iron and other metals.

A number of options exists for the management of each of these aspects. These are summarised in Figure 7.1 and presented, together with an assessment of their advantages and disadvantages and applicability in each of the priority areas, in Table 7.2. This table also includes options for the reduction of ingress and the monitoring of conditions affected by the water management system. Note that all of the objectives listed need to be fulfilled in order to implement a holistic AMD management strategy.

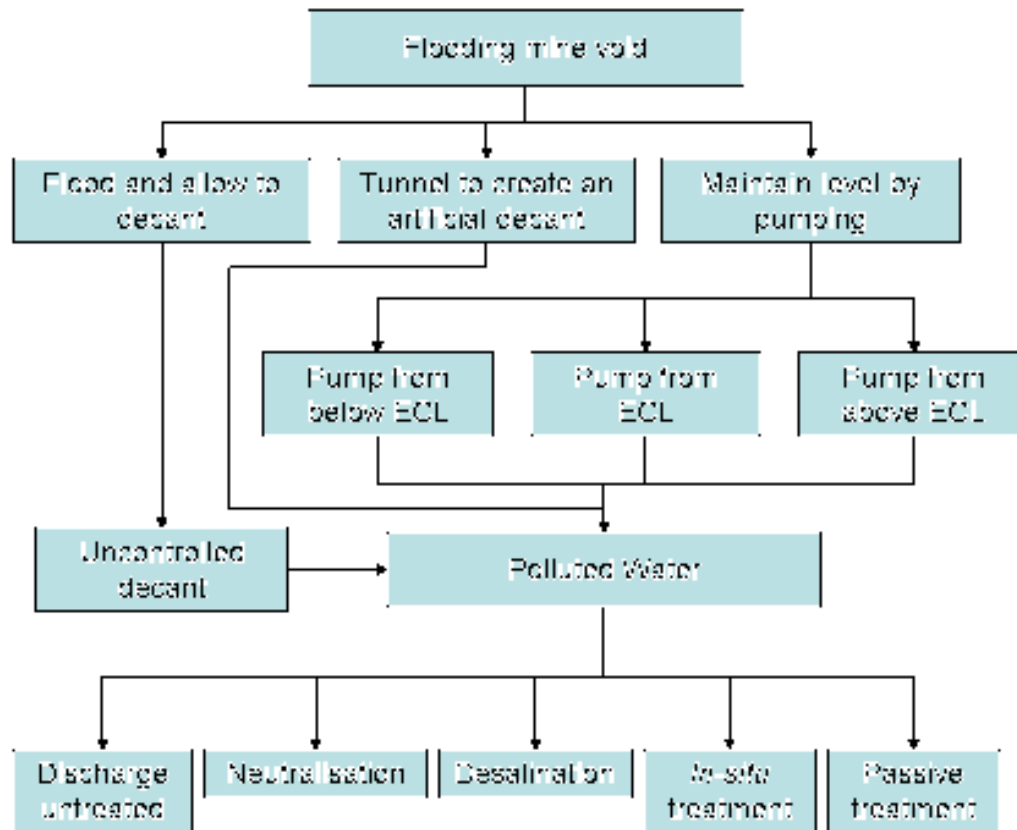


Figure 7.1. Water management options for the Western, Central and Eastern Basins

Table 7.2. Options for water management in the Witwatersrand mining basins and their applicability to the different basins (W – Western Basin, C – Central Basin, E – Eastern Basin).

Objective	Option	Advantages	Disadvantages	Relative cost		Applicability		
				CAPEX	OPEX	W	C	E
Management of flooding and/or decant	Pump water from ECL	Environmental Protection	Pumping may prove costly	Moderate	High	Y	Y	Y
	Pump water from level shallower than ECL	Lower cost than pumping from ECL	Is likely to place the environment at risk	Moderate	Moderate	Y	Y	Y
	Allow to decant	- No pumping costs - May be possible in areas where younger surficial cover rocks act as a seal above the mine void	- Seepage and secondary decant points could develop - Water rising into dolomitic layers could lead to groundwater contamination and sinkhole formation - Does not allow seasonal balancing of volume i.r.o. water treatment	Low	Low	N	N	N

Objective	Option	Advantages	Disadvantages	Relative cost		Applicability		
				CAPEX	OPEX	W	C	E
	Tunnel ³ to create an artificial decant	- No pumping costs - Will ensure that decant occurs in a controlled fashion	- High capital costs - Does not fully protect the environment unless the tunnel can be constructed at the ECL - Does not allow seasonal balancing of volumes i.r.o. water treatment - Long-term maintenance costs of tunnel - Risk of tunnel failure	Very high	Low	N	Y	N
	Tunnel to a remote pumping station to reduce pumping costs	Allows the location of the abstraction point for water according to the optimal location for a treatment plant	- Limited access to the underground workings will complicate construction - Does not remove the requirement to pump water	High	Moderate	Needs further investigation		

³ The idea of tunneling to create a preferred pathway for mine water to flow out of the void was proposed by the Council for Geoscience several years ago and detailed design studies have been undertaken. This will allow the mine void to drain by gravity feeding water through a tunnel to a low-lying point.

Objective	Option	Advantages	Disadvantages	Relative cost		Applicability		
				CAPEX	OPEX	W	C	E
Ingress management	Seal areas of surface ingress (riverbeds, old mine workings, etc.)	- Long-term reduction in water management costs - Lower water volumes may result in more options for management - Some projects may be implemented by mines (W Basin)	Some projects involve high capital costs	High	Low	Y	Y	Y
	Abstract clean water from overlying aquifers before it enters the mine void	'Keeps clean water clean' - Reduces ingress - Provides a source of clean water to local users	Will need to be properly managed in dolomitic areas to prevent subsidence	Moderate	Moderate	N	N	Y
Water treatment	Neutralisation and iron removal	- Lowest cost option - Removes most heavy metals - Can be implemented in a relatively short time - Pre-treatment stage necessary for most more-advanced treatment methods - Returns conditions to those that existed during active mining	- Does not fully address salinity problems - Water produced has limited uses - Requires facilities for sludge disposal	Moderate	Moderate	Y	Y	Y

Objective	Option	Advantages	Disadvantages	Relative cost		Applicability		
				CAPEX	OPEX	W	C	E
	Desalination (may be one of a range of several treatment methods based on chemical precipitation, membrane treatment, ion exchange or biological sulphate removal)	- Proven, with a limited number of commercial biological sulphate removal, membrane treatment and chemical precipitation plants - Produces clean water that can be used for any purpose, including drinking - Can remove salts from river systems completely - May produce saleable by-products that could offset some or all costs.	- High capital and operating costs - Not all technologies have been tested at full scale - Membrane processes at very high cost - Need for management of wastes	Very high	Very high	Y	Y	Y
	Discharge water without treatment	No costs	- Will seriously affect downstream environments. - Will increase salinity of downstream river systems	Low	Low	N	N	N

Objective	Option	Advantages	Disadvantages	Relative cost		Applicability		
				CAPEX	OPEX	W	C	E
	<i>In-situ</i> treatment	• No fixed plant required • Creates options as relatively clean water can be abstracted from the mine void • Active and ongoing operational personnel required, but permanent presence on site not required • Requires chemicals, operations staff, intermittent field maintenance, electrical power and low frequency monitoring	• Requires a system with good mixing characteristics and sufficient points of access to the void water, which is not the case in the Witwatersrand mines • Relatively inefficient mixing requires large inputs of reagents.	Low	High	N	N	N

Objective	Option	Advantages	Disadvantages	Relative cost		Applicability		
				CAPEX	OPEX	W	C	E
	Passive treatment	• Perceived to be a low cost option: moderate capital investment with periodic reinvestment to replace depleted wetlands media • Self-sustaining processes, periodic maintenance, intermittent monitoring. May require replacement or supplement of materials at low frequency • Natural energy sources of gravity flow, solar energy and bio-chemical energy • Requires little intervention	• Creates contaminated areas in treatment systems • Generally regarded to be unsuitable for the large volumes and poor qualities expected from the Witwatersrand • Requires extensive monitoring to evaluate success • Requires an additional energy (carbon) source for bacterial processes • Treated water quality poorer and more variable than other options	Moderate	Moderate	N	N	N

Objective	Option	Advantages	Disadvantages	Relative cost		Applicability		
				CAPEX	OPEX	W	C	E
Monitoring	No monitoring	Low cost	- No way to evaluate improving/deteriorating conditions - No early warning of problems	Low	Low	N	N	N
	Maintains current monitoring regime	No additional costs	- Current regime has proven inadequate to assess the extent and degree of problems - No early warning capacity	Low	Low	N	N	N
	Improved monitoring systems	- Will allow the assessment of problems and solutions - Will provide early warning capabilities	- Higher costs - Will place additional strain on resources unless monitoring activities are well resourced.	Moderate	Moderate	Y	Y	Y

7.4 OTHER AMD SOURCES IN THESE AREAS

The water emanating from flooded mine voids in the Witwatersrand is not the sole source of AMD that requires management. The tailings and waste rock generated by mining are significant sources of AMD owing to their interactions with rainwater and surface streams. Research into their impact has identified them as an important source of AMD (Steffen, Robertson and Kirsten, 1989), but the total proportion of the pollution load which they contribute to the streams is not fully quantified. Unfortunately, the lack of current flow monitoring in most of the surface streams draining the Witwatersrand prevents the determination of a more accurate water and salt balance at the degree of detail required to fully quantify these inputs into the system.

7.5 OPTION SELECTION AND RECOMMENDATIONS

A summary of the options available is presented in Figure 7.1. Two critical components are required: the control of flooding to maintain an acceptable water level within the mine voids, and action to manage the poor quality of water that will need to be discharged or reused. In parallel with these actions, steps need to be taken to reduce the volume of water entering the mine void and to monitor the impacts of the management actions taken.

7.5.1 Control of mine flooding/decanting

7.5.1.1 Status and options

The status of the three priority areas with respect to the water levels varies greatly, presenting different priorities:

- In the Western Basin, water is already decanting to the surface via a number of shafts and other conduits. The decant volume has been observed to vary widely on a seasonal basis
- In the Central Basin, the water level is still approximately 500 m below surface, but as no pumping is taking place, the water level is rising continuously. Calculation of the rate of rise of the water also shows a strong seasonal variation in the volume of water entering the mine void
- The water level in the Eastern Basin is currently controlled at 700 m below surface by pumping at Grootvlei Mine.

An analysis of the options in each basin is presented in Table 7.3.

Table 7.3 Analysis of flooding control options for the three priority areas (unfeasible options highlighted in grey)

Option	Western Basin	Central Basin	Eastern Basin
Flood and allow to decant	This has already happened with serious negative consequences	Undesirable as this could cause unpredictable decants and negative effects on urban areas, as well as flooding the underground mine of Gold Reef City and sterilising underground gold reserves	Will negatively impact on dolomitic groundwater resources and could lead to sinkhole/subsidence formation. Uncontrolled decant could negatively affect infrastructure in Nigel
Tunnel to create an artificial decant point	Not feasible owing to topography and lack of access to the underground workings	Difficult (but possible) as there is currently no access to the underground workings at ERPM. Will not allow the water level to be maintained at the ECL, or allow for seasonal balancing of volumes for treatment	Not feasible owing to topography
Transfer water from one basin to another	The transfer of water pumped from the Western Basin to the Central Basin has been proposed as a means to centralise the management of water, but is likely to lead to an accelerated flooding of the Central Basin, mixing of waters of different qualities, greater uncertainty with respect to flow, and flooding of the Central Basin and enhanced AMD generation and is therefore not recommended.	No practicable and cost-effective option exists for the transfer of Central Basin water to another basin	No practicable and cost-effective option exists for the transfer of Eastern Basin water to another basin
Pump from deeper than ECL	Unnecessary as there are no underground operations	Desirable but more costly option to maintain the tourist operation at Gold Reef City and preserve resources for	Current status quo to maintain underground workings at Grootvlei Mine

Option	Western Basin	Central Basin	Eastern Basin
		new entrants to the mining industry	
Pump from ECL	Desirable option	Desirable option	Desirable option after final closure of underground mines
Pump from above ECL	Unacceptable environmental risk	Unacceptable environmental risk	Unacceptable environmental risk

It will be necessary to lower the water level in the Western Basin to a point where it can be demonstrated by monitoring that mine water is not impacting on the local and regional drainage network, or on local and regional aquifers. This could require lowering the water level to as low as 1 530 m above mean sea level, but the optimum level may be higher, requiring lower pumping costs, if monitoring results are favourable. The pumping system will require a capacity of up to 40 MI/d to control current ingress and lower the water level in a reasonable time.

In the Central Basin, pumping infrastructure needs to be established before the rising water inundates the underground workings at a level above the underground tourist attractions of Gold Reef City, or the proposed underground workings of Central Rand Gold, depending on an equitable arrangement where private mine operators assist with the costs of pumping water to protect their underground workings. This agreement will need to take the additional pumping depth, as well as the inflow of extraneous water into account. In this regard it should be noted that Central Rand Gold has already ordered pumps necessary to maintain the water level. The approach to address the problem should therefore aim to identify the best option for both government and the mining industry. Failing such an arrangement being accepted, the water should be allowed to flood up to the Environmental Critical Level (150 m below surface, measured at the South West Vertical Shaft of ERPM). A pumping capacity of 70 MI/d is recommended to allow for the estimated average daily inflow of 60 MI of water, as well as providing a safety margin in case of extremely high rainfall. The Environmental Critical Levels, taking possible groundwater contamination into account for the three basins, are presented in Table 7.4.

Table 7.4. Environmental Critical Levels (ECLs) for the Western, Central and Eastern Basins

Basin	ECL (m above mean sea level)
Western Basin	1 530
Central Basin	1 503
Eastern Basin	1 150

7.5.1.2 Pumping as a means of balancing seasonal variations in water ingress

The experience of the decant in the Western Basin and the water level monitoring data collected in the Central Basin have shown that the inflow of water into the basins varies widely from season to season. In the Western Basin this can vary from 10–15 MI/d in the dry season to as much as 60 MI/d in the wet season. A similar pattern has been observed with the calculated rate of rise of water in the Central Basin, which varies between 0.3 and 0.9 m/d. Maintaining some freeboard above the water level in the mine void will allow space for periods of high inflow. This can be created by pumping a volume greater than the total inflow during periods of low ingress. The pumping of a constant volume of water will allow the optimal design of the necessary treatment facilities.

7.5.1.3 Recommendations

It is recommended that pumping infrastructure be established in the Western and Central Basins as a matter of urgency in order to manage the flooding of these basins and eliminate the risks associated with the uncontrolled decant of AMD.

Current pumping infrastructure needs to be maintained in the Eastern Basin to allow access to the underground workings. If necessary, State assistance to Grootvlei Mine should be continued to allow pumping to continue and the infrastructure to be maintained.

7.5.2 Water quality management

7.5.2.1 Status and options

Four options have been identified:

- Untreated discharge of water
- Neutralisation and metal removal
- Desalination
- *In-situ* treatment
- Passive treatment.

Current water qualities in all three priority areas are not fit for untreated discharge to the environment or direct use. Some degree of treatment will be required. An analysis of the above options is presented in Table 7.6.

The expected water qualities from the three basins are presented in Table 7.5.

Table 7.5. Typical water qualities for the Western, Central and Eastern Basins

Parameter	Western Basin	Central Basin	Eastern Basin	Guideline for Category 4 Industrial Processes ⁴
pH	3.5	2.8	6.65	5–10
Electrical conductivity (mS/m)	510	467 ^(a)	246	250
Total dissolved solids (mg/l)	6 580	4 936 ^(b)	2 041	1 600
Sulphate (mg/l)	4 010	3 700	1 037	500
Iron (mg/l)	697	112	38	10
Information source	Median value of >200 samples collected by Harmony Gold/Rand Uranium	Modelled inflow water chemistry (after Scott, 1995)	Median of data collected since 2008, provided to CGS by Grootvlei Mine	(Department of Water Affairs and Forestry, 1996a)
^(a) Derived from TDS/EC ratio of 10.6				
^(b) Derived by summation of reported salts				

⁴ This is the least strict of the DWA Guidelines for industrial water use, prescribing the water quality for processes such as ash quenching, use as a transport agent, dust suppression, fire fighting, irrigation and rough washing.

Table 7.6. Analysis of water quality management options for the three priority areas (unfeasible options highlighted in grey)

Option	Western Basin	Central Basin	Eastern Basin
Untreated discharge	Environmentally unacceptable option	Environmentally unacceptable option	Environmentally unacceptable option
<i>In-situ</i> treatment	Technically unfeasible owing to the geometry and complexity of the mine void	Technically unfeasible owing to the geometry and complexity of the mine void	Technically unfeasible owing to the geometry and complexity of the mine void
Neutralisation and metal removal	Short-term option that will return conditions to those during active mining. Practicable option provided that monitoring data are favourable	Short-term option that will return conditions to those during active mining. Practicable option provided that monitoring data are favourable	Current status quo, as long as the treatment plant at Grootvlei continues to operate. This will maintain current conditions. Practicable option provided that monitoring data are favourable
Passive treatment	Could provide an acceptable quality of water for direct discharge to streams; however, the large flow and poor quality of the water pose challenges regarding space needed and a suitable energy source for biological processes	Could provide an acceptable quality of water for direct discharge to streams; however, the large flow and poor quality of the water pose challenges regarding space needed and a suitable energy source for biological processes	Could provide an acceptable quality of water for direct discharge to streams; however, the large flow and poor quality of the water pose challenges regarding space needed and a suitable energy source for biological processes
Desalination	Desirable medium- to long-term option that will reduce downstream salt loads and consequent environmental risks	Desirable medium- to long-term option that will reduce downstream salt loads, leading to an improvement of water quality	Desirable medium- to long-term option that will reduce downstream salt loads, leading to an improvement of water quality

7.5.2.2 Recommendations

It is recommended that neutralisation plants be established in the Western and Central Basins to treat the volumes of water required to be pumped.

Construction of the plant for the Western Basin must commence as soon as possible, with the aim of supplementing the existing treatment capacity of the plant currently operated by Rand Uranium. A plant with a capacity of 20 MI/d will be required to supplement the existing treatment capacity in the basin. Ultimately a plant will be required to treat the full volume of AMD pumped.

Construction of a plant in the Central Basin to treat 60 MI/d (Scott, 1995) must commence as soon as is necessary to treat the water that will be pumped (this volume could be reduced in the medium to long term if ingress prevention measures are put in place). If the pumping site is at ERPM mine, the refurbishment of the existing HDS treatment plant can be considered if this is a cost-effective option and if ERPM is identified as the ideal point for water abstraction.

In the Eastern Basin, the current treatment infrastructure at Grootvlei Mine must be maintained.

The proposed steps of neutralisation and metal removal will still result in the discharge of saline water. While this will maintain the status quo that prevailed during active mining, it may prove necessary to complement this with steps to reduce the salinity of the discharges in the medium to long term. This could be achieved via desalination or direct consumptive use of the water that does not result in a discharge of saline water to the Vaal River System.

Remaining issues must be more fully researched so that a detailed medium- to long-term action plan can be developed in parallel with the implementation of the short-term plan.

7.5.3 Reduction of water ingress into the mine voids

Ingress points and areas have been identified in all three priority areas and preliminary estimates of the volumes of water entering the mine voids have been made. Measures have been recommended to control water ingress, since this is recognised as a key intervention in the management of the flooding of the mines. These estimates and proposed interventions, generated by the CGS, are discussed in more detail in Table 3.1.

A key measure to minimise the costs associated with pumping and treatment of mine water is the reduction of the rate of ingress of water into the mine voids. This can be achieved via (a) the prevention of recharge of the voids directly from surface water flowing or ponding above or directly adjacent to zones of old surface operations and shallow undermining, and (b) the abstraction of groundwater from aquifers that directly feed the underground mine workings with clean groundwater. Krige (1999) estimated that water ingress in the Central Basin could be significantly reduced by constructing canals to prevent the loss of water from surface streams that cross the mined-out reef

outcrops. These actions will have the dual effect of reducing the volumes of water flooding the mine voids and 'keeping clean water clean' so that it can be utilised for other purposes. This is expected to reduce the operating costs of mine water management in the medium to long term. The benefits of implementing these measures will also result in savings in the recapitalisation of pumping and treating infrastructure in the long term.

7.5.4 Monitoring

The success of the proposed programme can only be verified by detailed monitoring of the water in the mine voids and the affected environments.

The investigations undertaken in the identification of treatment options have identified serious shortcomings in the current monitoring of water quality and, in particular, flow in the areas downstream of mining activities. These shortcomings need to be identified and remedied so that the required medium- to long-term strategies can be optimised for AMD management, particularly where this impacts on the Vaal River System.

It is recommended that a multi-institution monitoring committee be established to facilitate the implementation of the required monitoring programmes.

CHAPTER 8. ASSESSMENT OF TECHNOLOGIES FOR THE TREATMENT OF AMD IN THE WITWATERSRAND AREA

8.1 BACKGROUND

Acid mine drainage has significant economic and environmental impacts owing to both the corrosive effects of acid water on infrastructure and equipment, and the severe environmental impacts related to the low pH and high metal and salt loadings. In most cases, AMD will not be suitable for direct use or discharge into the environment. These impacts continue long after mine closure and can have adverse impacts on the ecology of streams, affecting the beneficial use of waterways downstream of mining operations. In the mining basins of the Witwatersrand two major classes of AMD sources exist:

- The large volumes of AMD that flood the mine voids and will decant unless suitable steps are taken to reduce the recharge volumes and water is extracted from the mine voids to maintain an environmentally acceptable water level. These typically constitute a single large source emanating from one or more shafts and low-lying conduits in the lowest-lying area(s) of a mining basin.
- The multiple smaller volumes of seepage and run-off from contaminated areas, largely mine residue deposits. The diffuse nature of this drainage poses specific challenges for treatment.

8.2 AVAILABLE TECHNOLOGIES FOR THE TREATMENT OF AMD

Extensive information regarding technology choice is available in the Global Acid Rock Drainage Guide (GARD Guide) (INAP, 2009).

Several technologies have been identified for the treatment of AMD. These include active, passive and *in situ* methods (Table 8.1).

Global experience has shown that there will not be one single treatment method that can be used in every situation and that appropriate treatment methods need to be selected from the range available for each mine water type encountered. As wide variation in water quality is recorded from the different basins studied, with, for example, the Eastern Basin producing a near-neutral water with a sulphate content of around 1 000–1 500 mg/l, and the Western Basin producing a highly acidic water with a sulphate content of as much as 5 000 mg/l, appropriate technologies will need to be identified for each of the different waters and will need to take the likely changes in water quality over time into account.

Table 8.1 Comparison of different categories of AMD treatment

Characteristic	Active treatment	Passive treatment	<i>In situ</i> treatment
Application to phase of mining	Exploration and operational phases because it requires active control and management. Closure and post-closure applications mainly associated with large flows	Most attractive to the closure and post-closure phases, because it requires only intermittent supervision, maintenance, and monitoring of self-sustaining processes	Appropriate to the exploration and operational phases because it requires ongoing operation and maintenance
Operational involvement	Active and ongoing plant operations and maintenance systems and personnel	Constant operations not required, but regular maintenance essential	Active and ongoing operational personnel required, but permanent presence on site not required
Operational inputs and materials	Requires chemicals, operations staff, maintenance staff, electrical power, continuous and/or regular monitoring	Self-sustaining processes, periodic maintenance, intermittent monitoring. May require replacement or supplement of materials at low frequency	Requires chemicals, operations staff, intermittent field maintenance, electrical power and low frequency monitoring
Supply of power	Electrical and mechanical energy sources	Natural energy sources of gravity flow, solar energy and bio-chemical energy	Electrical and mechanical energy sources
Management and supervision requirements	Ongoing management engagement, constant facility supervision	Low level management engagement and low frequency intermittent supervision	High frequency supervision, but no permanent site presence required
Range of applications (flow rates and constituents)	Application to all flow rates, especially high flow rates and any constituent of interest	Mainly applied to low flow rates and acidity, metals, and sulphate removal	Large spectrum of volume and flow applications, mainly to deal with acidity and metals removal
Treated water quality	Treatment process can be purpose built to deal with spectrum of treated water requirements	Treated water quality poorer and more variable than other options	Treated water quality lower and more variable than active treatment process
Waste sludge and brine production	Waste sludge and brine are produced, depending on level of treatment, requiring disposal	No brine production, but longer-term liability to deal with accumulated pollutants in wetland sludge	Sludge and waste production accumulated <i>in situ</i> that may pose a long-term environmental liability.
Capital investment cost	High capital investment and periodic capital replacement required	Moderate capital investment, with periodic reinvestment to replace depleted wetlands media	Low capital investment typically to deal with a short-term problem
Operating and maintenance cost	High operating and maintenance cost, with some potential for cost recovery by sale of product water, metals and by-products.	Low operating cost.	Moderate operating costs, but chemical usage may be high owing to process inefficiency.

8.2.1 Active treatment technologies

Active treatment technologies include aeration, neutralisation, which often includes metal precipitation, metals removal, chemical precipitation, membrane processes, ion exchange, and biological sulphate removal (EPA, 2008). Active treatment is characterised by ongoing high intensity flow of chemicals into and out of a treatment plant that is continuously maintained by trained personnel.

Active treatment generally requires the construction of a treatment plant with a variety of reactor systems, such as agitated reactors, precipitators, clarifiers and thickeners. Active treatment of AMD may include the installation of a water treatment plant, where the acid is first neutralised by dosing the AMD with lime, or, more recently, limestone or limestone and lime together, and passing it through settling tanks to remove sediments and particulate material. The effluent produced by such neutralisation systems often contains more sulphate than is acceptable for either discharge to the environment or many other uses. To date, this has been the experience in the Witwatersrand Gold Fields, with poor-quality water having been discharged from neutralisation plants to streams, resulting in local impacts on biodiversity and an increase in the salinity of major river systems downstream of the discharge points. In these cases, a strong case is being made for the desalination of this water that may afterwards be used for domestic or other purposes. Examples of sites where this is taking place are the eMalahleni and Optimum Water Reclamation Plants in Mpumalanga where AMD from coal mines is treated to potable quality and used to supplement the local municipal water supply.

Active treatment systems can be a very expensive option, where a medium sized mining operation may spend millions of Rand annually on the cost of lime alone. However, this expensive option may not be applicable in many cases, particularly where there are 'orphan discharges' and/or remote locations. To address this problem alternative 'passive' treatment systems have been developed over the last 15–20 years that utilise natural ameliorative processes.

8.2.1.1 Pre-treatment-Partial treatment for neutralisation and metal removal

Untreated mine water needs to be neutralised and treated to remove metals. The water quality from the Central and Eastern basins is expected to be better than that from the Western Basin and therefore needs less pre-treatment; however, none of the water measured in the different basins is suitable for discharge to river systems. A neutralisation facility is urgently required to manage uncontrolled decant from the Western Basin. The following criteria have to be met:

- Partial treatment (neutralisation and metal removal) has to be applied as soon as possible to address the immediate problem
- Chemical costs need to be kept to a minimum
- Construction costs need to be kept to a minimum

- Construction time needs to be kept to a minimum.

Lime or limestone/lime can be used for partial treatment of the decant water from the Western Basin. This will offer the most cost-effective short-term management option.

8.2.1.2 Desalination

Desalination — the removal of salts from water — is a serious consideration because of the need to reduce the salt loads entering river systems. In the case of desalination the following criteria need to be met:

- Minimum running cost
- Minimum capital cost
- Minimum sludge/brine disposal cost
- Maximum value of treated water and by-products.

Tshwane University of Technology has evaluated several technologies that could be considered for treatment of the mine water in all the mining basins:

1. CSIR ABC (Alkali-Barium-Calcium) Process (CSIR). This is a precipitation process, using barium to precipitate dissolved sulphate from mine water. The sludge produced can be processed into raw materials and valuable by-products, such as sulphur and lime. This process is a strong candidate for cost-effective treatment of mine water, provided that current pilot-studies on the thermal stage are completed successfully.
2. SAVMIN (Mintek): Developed by Mintek over nine years to treat polluted mine water (AMD). It is based on the selective precipitation of insoluble complexes at different stages during the process and the recycling of some of the reagents used in the process. The end products of the SAVMIN process are potable water and a number of potentially saleable by-products.
3. HiPRO (High Pressure Reverse Osmosis) Process (Key Plan). Two 20 Ml/d plants are in operation at Anglo Coal mines in Mpumalanga. The treated water is sold as drinking water to eMalahleni Municipality at R3.00/m³. The cost of this process amounts to R11.00/m³. The shortfall is carried by Anglo Coal. Gypsum produced as a by-product can be processed to CaCO₃, and sulphur by using the CSIR GypSLiM process. This will solve the problem associated with waste brine and waste sludge.
4. SPARRO (Slurry Precipitation and Recycle Reverse Osmosis). A variation of the membrane desalination process, involves the use of tubular reverse osmosis membranes. The slurry precipitation and recycle reverse osmosis (SPARRO) process was developed and holds potential. The concept of the SPARRO process is based on the protection of the membrane surfaces by providing a

slurry suspension onto which the precipitation products can form. High water recoveries were achieved by a demonstration scale plant (Pulles *et al.*, 1992).

5. EARTH (Environmental and Remedial Technology Holdings) Ion Exchange. The cost of chemicals amounts to R11.00/m³ and the value of the by-product (ammonium nitrate) amounts to R10.00/m³, although these figures will vary depending on the quality and composition of the feed water. The feasibility of this technology is dependent on there being a market for the products and stable prices. Seasonal fluctuations and droughts may influence the financial viability.
6. ThioPac (Delkor/Paques). A 3 Ml/d plant was built by Anglo Coal. Owing to an increase in the price of ethanol and butanol, the energy sources, the attractiveness of this technology has diminished.
7. The Rhodes BioSURE process, a locally invented biological treatment that has been used at Grootvlei by ERWAT (the East Rand Water Care Company). Developed by the Environmental Biotechnology Group (EBRU) of Rhodes University over the past ten years. The Rhodes BioSURE process removes acidic sulphate using free waste stock, such as sewage sludge, instead of expensive carbon and electron donor sources (ethanol and hydrogen). This makes it significantly cheaper than other similar alternatives. A 10 Ml/d plant was built by ERWAT to treat Grootvlei Mine water. This technology is restricted by the availability of sewage sludge or other organic wastes used as carbon and energy sources; however, it has the advantage of providing an option for the co-disposal of sewage sludge, reducing the costs of landfilling solid waste.
8. TUT MBA (Magnesium-Barium-Alkali) Process (TUT). This is an improvement on the CSIR ABC Process. This is a more feasible option than the ABC Process, as Ba(OH)₂ is used for two functions simultaneously: (i) sulphate removal by means of BaSO₄-precipitation, and (ii) magnesium removal by Mg(OH)₂-precipitation. Certain test work has to be completed prior to full-scale implementation.

Table 8.2 shows the running costs and potential income for the various technologies, based on an assessment performed by the Tshwane University of Technology. Note that the only technology currently being applied at full scale operation is the KeyPlan HiPRO technology, used at the eMalahleni Water Reclamation Plant.

Table 8.2 Examples of technologies available in South Africa, including indicative running costs, based on the treatment of AMD of a similar quality to that produced in the Western Basin, and potential cost recovery

Technology	Projected running costs (R/m ³)	Income (R/m ³)	Difference (R/m ³)	Comments
CSIR ABC (Alkali-Barium-Calcium)	4.04	3.56	-0.49	
KeyPlan HiPRO	9.12	3.35	-5.78	Operating at eMalahleni.
AR Technologies Sodium Carbonate Reverse Osmosis (ARRO)	12.79	4.29	-8.51	
Mintek SAVMIN	11.30	3.84	-7.46	
EARTH Ion Exchange	12.95	10.70	-2.25	Variable costs and cost recoveries depending on water quality
Paques Thiopaq	8.73	5.70	-3.03	
CSIRosure	8.73	6.12	-2.61	
BioSURE	3.80	0.00	-3.80	These figures are based on the operation of a 1/d plant at Grootvlei Mine. Note that the quality of the input water is considerably better than that of the water in the Western Basin. The applicability of this technology may be limited by availability of sewage sludge, although it offers an alternative to landfilling of sludge.
TUT/CSIR MBA (Magnesium-Barium-Alkali)	2.22	5.58	3.36	Still in laboratory development phase
Lime treatment for industrial water	5.50	0.70	-4.80	
Current treatment undertaken by Rand Uranium in the Western Basin	8.20	0.00	-8.20	These costs are for an emergency treatment plant established by Harmony Gold after the start of decant in 2002

8.2.2 Passive treatment technologies

One widely accepted definition of passive treatment is as follows:

Passive treatment is the deliberate improvement of water quality using only naturally available energy sources (e.g. gravity, microbial metabolic energy, photosynthesis) in systems which require only infrequent (albeit regular) maintenance in order to operate effectively over the entire system design life. (PIRAMID Consortium, 2003)

Many passive systems, especially those treating acidic waters, utilise one or more materials that would normally be classified as 'waste products'. These include materials from industrial processing and farming practises that, in most cases, can be locally sourced, thereby reducing transport costs.

Although by definition passive treatment systems require little or no input of energy and only infrequent interventions, it is the opinion of this study that the majority of passive treatment systems (permeable reactive barriers, constructed wetlands) require maintenance, where the frequency depends on the system and the environmental conditions.

The passive treatment method uses a treatment system (such as constructed wetlands, diversion wells containing crushed limestone, or open ditches filled with limestone) that employs naturally occurring chemical and biological reactions to minimise AMD with little maintenance (EPA, 2008). Passive remediation systems, unlike active systems, ideally require little or no input of energy or reactive materials after initial installation, only infrequent monitoring. They potentially provide the long-term solution to AMD, although their success has been limited in cases where excessive volumes, high iron loadings or excessively low pH values are encountered (pers. comm. P Younger). Passive treatment on its own is therefore unlikely to offer a sustainable solution to the large volumes of AMD encountered in the Witwatersrand.

8.2.3 *In situ* treatment technologies

In situ treatment of mine drainage can be undertaken in many different ways and configurations. Typically this involves the introduction of alkaline material into the mine water body, which can be highly effective in open cast mines, as has been demonstrated in a number of closed brown coal-mining operations in Germany, and the spreading of alkaline material across impacted mine land and mine water. Neither of these options is necessarily of relevance to the large underground mine voids of the Witwatersrand, where the scale of operations, both laterally and vertically, the lack of access points to the flooded mine voids and the difficulty of ensuring distribution of the alkaline material throughout the affected water body will probably prevent effective application of these techniques. The possibility of neutralising water within a pumping shaft before pumping and the settling of the precipitates formed within the mine void has been suggested and needs to be investigated further.

Permeable reactive barriers (PRBs) offer an approach for the passive interception and *in situ* treatment of AMD-impacted groundwater. The reactive materials, which incorporate various forms of organic carbon, promote microbially mediated sulphate reduction, the generation of hydrogen sulphide, and the subsequent precipitation of sparingly soluble iron and other metals, such as Cd, Ni, Co, Cu, Zn or As sulphide minerals. These methods may well be used in the management of localised seepage plumes from mine residues that contaminate shallow groundwater.

8.3 CONCLUSIONS

Currently two plants are treating AMD to potable quality in South Africa at full scale. These are, however, not financially self-sustaining. This is similar to the experience internationally that has shown that AMD treatment is unlikely to be financially self-sustaining. The costs of this treatment are estimated at around R11 per cubic metre, with a capacity of treating 20 MI/d (20 000 m³/d) at each plant, including amortisation of the capital costs of the plant (several hundred million Rand) over the projected 20 year design life of the plant. This is not economically self-sustaining and relies on a subsidy from the mining companies. Therefore, it is foreseen that there will be a shortfall between the cost of clean water produced in a plant and the revenue recoverable from the sale of water. Some of the water treatment methods identified can recover further costs via the sale of other by-products, such as gypsum, sulphur, sulphuric acid, explosives and fertilisers. The remaining shortfall may be made up using the Waste Discharge Charge System and water use charges; however, care needs to be taken to ensure that the costs of pollution by historical mining activities are not unfairly passed on to other water users.

Because the recorded water qualities of the different basins vary so much, it is not possible to recommend one single treatment method suitable for all types of mine water. Mine water can be acidic or neutral, have high or low metals content, have high or low sulphate and these characteristics determine which treatment methods are appropriate. Furthermore, it is possible that water quality in the mine voids will improve over time, given proper water management. A suite selected from the available technologies may therefore be needed. The quality of the water to be treated will also strongly influence the treatment costs.

Historically water discharged by the mines was only treated to neutralise low pH and remove metals. For the management of the current crisis, this level of treatment should be considered acceptable, as it will lead to a situation that is no worse than the pre-existing conditions. However, in the medium to long term the salts associated with mine water discharges will need to be removed from river systems.

CHAPTER 9. EXPLORING POSSIBLE INVOLVEMENT OF THE PRIVATE SECTOR

9.1 GOVERNANCE OPTIONS FOR AMD MANAGEMENT

Governance options for AMD management may be conceptualised in terms of the table below. The table also shows indicative advantages and disadvantages with regard to the respective options.

9.2 INTERNATIONAL EXPERIENCE

The South African mining industry is one of the most developed in the world (Organisation for Economic Cooperation and Development, 2002) and therefore has an important role to play in global AMD management. Such a role would be facilitated by an up-to-date comparative analysis of international experience, taking into consideration aspects such as the development ranking (United Nations Development Programme, 2009), economic significance of the mining sector, as well as the extent of potential AMD for the countries involved.

9.2.1 United States

In the United States of America (which has an HDI⁵ rank of 13), the Comprehensive Environmental Response Compensation and Liability Act (CERCLA 1980) is used by the Environmental Protection Agency (EPA) to locate, investigate and clean up abandoned hazardous waste sites. The policy involves that Potentially Responsible Parties (PRPs) carry the cost, except where these cannot be located or cannot afford to carry the cost, when the EPA undertakes the clean-up using a trust fund (the so-called Superfund). The balance of the trust fund has varied over time, largely depending on the government's ability to collect taxes to support the Superfund programme. The changing composition of the fund over time (United States Government Accountability Office, 2008) might allow insight into potential funding mechanisms for addressing South African AMD.

Where abandoned mines on government land are determined to need rehabilitation and reclamation, these are addressed, using a risk-based system, with funding provided by the coal-mining industry in terms of 1977 legislation (Bureau of Land Management, undated).

9.2.2 Canada

Canada has an HDI rank of 4. The environmental legacies in respect of orphaned mines are the responsibility of the State. However, in some cases, partnerships with the private

⁵ The Human Development Index (HDI) is a composite index reflecting real per capita income, life expectancy and education. According to the United Nations Development Programme (UNDP) ⁽⁶⁾, in 2009 Norway was ranked 1, South Africa was ranked 129 and Niger was ranked 182. HDI ranking of countries would give a sense of competition for State funding in countries.

sector (e.g. the Lynn Lake project in Manitoba) were addressed through an agreement between government and relevant parties.

9.2.3 Zambia

In a 2002 study it was found that Zambia, which has an HDI ranking of 164 (United Nations Development Programme, 2009) is the most dependent of African countries on its mining industry, predominantly copper-cobalt mining (Organisation for Economic Cooperation and Development, 2002). At the time of privatisation of Zambian Consolidated Copper Mines (ZCCM) in the late 1990s, the mature environmental liability was passed on to the government as the opinion was that new owners should not be held responsible for damage they did not cause. This is confirmed in agreements between the new owners and government, which allow for delayed compliance with environmental plans, and referral of non-compliance disputes to a nominated expert. With respect to past environmental legacy, an NGO in a joint effort with government, ZCCM and the World Bank as financing institution, has drawn up a US \$50 million Copperbelt Environmental Programme.

9.3 CONCLUSIONS AND RECOMMENDATIONS REGARDING PARTNERSHIP WITH THE PRIVATE SECTOR

National and international practices indicate that private sector initiatives are unlikely to be economically sustainable without major financial subsidies.

Two options have been identified:

- The State will fund and operate measures to manage AMD in the Western, Central and Eastern Basins via one or more of its agencies. In the short term, the mining industry is expected to contribute some of the costs. In the medium to long term the country should also explore the viability of an environmental levy on all operating mines to fund the environmental legacies of the mining industry, including the management of acid mine drainage. Funding could also be sourced using raw water tariffs and the Waste Discharge Charge System
- Allowing private sector/entrepreneurs to treat acid mine drainage and sell to the market. This will most likely require a subsidy from the State.

Table 9.1. Governance options for AMD management

Option	Advantages	Disadvantages	Selected international examples	Viability
State funds and operates the project through one of its entities	Control by the State Cost of capital lower	Funding burden on State Lack of State management capacity and skills	Germany Japan	Yes
Individual mining companies fund the rehabilitation programme and are held responsible to treat the water — applying ‘polluter pays’ principle	‘Polluter pays’ principle adhered to Incentive to prevent future pollution	Proving and enforcing liability will be costly and time consuming — difficult to apportion liabilities Difficult to manage regionally	Practised for currently operating mines in most mining countries	Unlikely to be effective as most mines are not operative in the priority areas

Option	Advantages	Disadvantages	Selected international examples	Viability
Collective responsibility of the mining industry via a voluntary fund	Reduced burden on individual companies Economies of scale could protect vulnerable sectors	Difficult to manage and coordinate Governance burden of collecting and distributing revenue Potential for some mines to be reluctant to contribute to the fund Ethics of spreading burden among all companies Possible disincentive to some companies to reduce pollution	Not aware of a country employing such a scheme — further investigations need to be done	A contribution is possible in the short term but this will not guarantee long-term sustainability

Option	Advantages	Disadvantages	Selected international examples	Viability
Collective responsibility of the mining industry via taxes and levies	Easier to coordinate and manage Lengthy legislative process Reduced burden on individual companies Economies of scale could protect vulnerable sectors	Ethics of spreading burden among all companies Possible disincentive to some companies to reduce pollution	United States of America	Yes
Entrepreneurs are engaged to treat AMD and sell to market and the water system	Financial risk carried mostly by private sector Leveraging private sector efficiencies could shorten implementation time	Return on investment measured only in private sector financial terms Low level of State control State faces risk in case of failure	At eMalahleni in South Africa, a private concern has been appointed to treat water from a number of coal mines and sell it to the local metro council. While this is technically successful, it is not financially sustainable, requiring subsidisation by the mining companies involved	Yes, but will require subsidies from the State

Option	Advantages	Disadvantages	Selected international examples	Viability
Shared responsibility (funding) via partnerships amongst e.g. State, mining industry and entrepreneurs	Financial burden and risk shared Leveraging private sector skills and efficiencies while retaining State control	Governance complexity Long-term viability of funding streams and projects Uncertainty about long-term pricing implications	Canada. Not in all instances	

CHAPTER 10. CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

Recent media reporting has highlighted issues related to acid mine drainage (AMD) in the gold-mining areas of the Witwatersrand. Government has responded to this by forming the IMC to address the issue. This committee has, in turn, appointed a team of experts to assess the situation and make recommendations regarding a prudent course of action in this regard.

10.1.1 Occurrence of acid mine drainage in South Africa

Acid mine drainage is formed by a series of chemical reactions that occur between water, sulphide minerals, such as pyrite and oxygen, which combine to form an iron-rich sulphuric acid solution. This will occur in any area where sulphide minerals are exposed to air and water in the environment, but is most prevalent in areas where mining has exposed fresh sulphide minerals to the elements. AMD is known to occur in a number of areas in South Africa, most notably the Witwatersrand Gold Fields, the country's various Coal Fields and the O'Kiep Copper District.

10.1.2 Assessment of work done by various institutions

A number of South Africa's statutory institutions have done significant research on the nature and extent of the AMD problem in the country and proposed a number of measures to mitigate the problem. This research includes measures to better manage water and prevent AMD formation, as well as technologies to treat AMD. Key institutions in this regard have been the CGS, CSIR, Mintek, the WRC and the DWA. In the opinion of the Team of Experts, sufficient information exists to be able to make informed decisions regarding the origins of the mine water, potential impacts, management strategies, treatment technologies, etc. The large body of research conducted on the Witwatersrand Gold Fields provides sufficient background information to be able to predict impacts and direct the data collection and monitoring necessary to minimise any uncertainties that exist in the current predictive models, although some research is still needed to minimise uncertainties and to develop sustainable solutions for the medium to long term.

10.1.3 The current situation in the Witwatersrand Gold Fields

The nature of the gold deposits in the Witwatersrand has led to the formation of large complexes of interconnected mines, which are often referred to as 'basins'. As a consequence, as mines within a basin stop operating and stop pumping water from their underground workings, this water flows into adjacent mines, increasing the volume of water which the adjacent mines need to pump. Eventually the last mine in a basin will cease operations and stop pumping, after which the underground workings will flood and the water level will continue to rise until it reaches the surface and decants from a low-lying shaft or other pathway(s) to the surface. Unfortunately the water that floods the

basins is of poor quality, largely owing to reactions with sulphide minerals in the surface and underground environments.

The water entering the underground workings comes from a number of sources:

- Direct recharge by rainfall falling onto open mine workings, stopes and old surface workings
- Groundwater, recharged by rainfall, which seeps into the workings owing to the disturbance of natural groundwater conditions by mining
- Surface streams that lose water directly to mine openings and to the shallow groundwater systems above zones of shallow undermining and historical surface operations
- Where open surface workings exist, these often connect directly to the underground workings and provide a pathway for water to flow from the surface to the mine void
- Mine residues, in particular tailings, are seen as areas of enhanced seepage, where the volume of water entering the mine void is relatively high and the water is typically of poor quality
- Losses from the water, sewage and stormwater reticulation systems are also a possible source of water in the zone where these cross old shallow mine workings.

On entering the mine voids, water comes into contact with sulphide minerals, reacting to produce AMD. This interaction will be particularly prevalent in the unsaturated zone between the surface of the water in the mine void and the surface where air flows freely through the mine void.

Decant has already taken place in the Western Basin, where the decant of AMD to the surface has had a devastating effect on the ecology in the areas immediately downstream of the decant and has degraded streams and groundwater which feed the Cradle of Humankind World Heritage Site.

In the Central Basin no pumping has taken place since 2008 and the water level in the underground workings is rising steadily at an average daily rate of 0.59 m per day. The water level is monitored continuously by the CGS and was measured at 516m below surface on 18 November 2010.

In the Eastern Basin, one mine, Grootvlei Mine, is still operating and controls the water level by pumping from 700 m below surface. Unfortunately, Grootvlei Mine's financial position is not secure, placing the pumping of this water and its subsequent treatment at risk.

Other areas in the Witwatersrand Gold Fields — The Free State, KOSH, Far West Rand and Evander Gold Fields — still have significant numbers of mines active, which continue to pump and treat water and prevent the development of immediate problems.

10.1.4 Prioritisation of areas for attention

The Western, Central and Eastern Basins are regarded as priority areas owing to the lack of adequate measures to manage and control the problems related to AMD, the urgency of finding solutions before problems become more critical and the proximity of these problem areas to densely populated areas. The situation in these areas can be regarded as in need of critical intervention in the short term.

10.1.5 Re-appraisal of risks in the priority areas

Risks have been appraised looking at those attributable to the flooding of the mine voids and those attributable to the poor quality of water in the flooded voids.

Risks identified related to mine flooding are:

- Contamination of shallow groundwater resources
- Geotechnical impacts, which are most likely to be experienced in low-lying areas directly affected by rising water levels
- Increased seismic activity.

Risks identified owing to decant are:

- Serious negative ecological impacts on the receiving environments
- Local and regional impacts on the Vaal and Crocodile River Systems that could affect fitness-for-use of the receiving water resources to downstream water users. AMD will aggravate an already upward trend associated with salinisation of the receiving river systems, necessitating additional dilution releases to be made and subsequently risking water supply security within the integrated Vaal River System.

Risk management measures are proposed that will minimise these impacts. These are discussed in the recommendations presented below.

10.1.6 Exploring models for cooperation with the private sector

A number of models have been identified for private sector involvement in the implementation of solutions. These represent a continuum between an entirely State funded programme operated by a State entity and the implementation and funding of the entire programme by private entities.

Local and international experience suggests that the pumping and treatment of AMD from the Witwatersrand is unlikely to be financially self-supporting. Various funding and cost-recovery models exist, including a model where all contributors to salt-loading of the Vaal River System may contribute towards the funding of such a shortfall through a system of waste discharge charges in terms of the National Water Act, 1998 (Act No. 36 of 1998). Financial viability may also be realised through the introduction of an additional tariff component to the tariffs charged on raw water use (comparable to the financing model applying to the Lesotho Highlands Water Project). Subsidies from the State treasury is another possibility.

A feature of some of the international examples studied is the use of an environmental levy imposed on the mining industry to help cover the cost of dealing with the legacies of historical mining activities where no financial provision has been made for remediation and long-term environmental management.

10.2 RECOMMENDATIONS

In order to adequately address the risks identified in the priority areas, a number of options have been identified and assessed and the following short-, medium- and long-term measures are recommended:

10.2.1 Prevention of decant — pumping to ensure that water levels are maintained at or below the Environmental Critical Levels

It will be necessary to pump water from the mine voids in all three priority areas. Environmental Critical Levels (ECL) — defined as the highest level to which the water in the mine void can be allowed to rise without having negative environmental impacts, taking both surface and groundwater into account — have been identified in all three priority areas. These levels are presented in Table 10.1.

Table 10.1. Environmental Critical Levels for the priority areas

Basin	ECL	Rationale
Western	150 m below decant level	Protection of the dolomitic groundwater resources in the Cradle of Humankind World Heritage Site
Central	150 m below surface at the South West Vertical Shaft of ERPM; however, it is recommended that a level 50 m below this be selected to protect the underground operation at Gold Reef City which receives as many as 3 000 tourists per day. Pumping from a deeper level would be necessary to protect the underground resources of interest to new entrants to the mining industry in the area.	Protection of the dolomitic aquifer to the south of Boksburg

Basin	ECL	Rationale
Eastern	400 m below surface, measured from the likely decant point at Nigel	Prevention of the rise of mine water into the overlying dolomitic aquifer

It is therefore recommended that pumping infrastructure is established in the Western and Central Basins as a matter of urgency to manage the flooding of these basins and eliminate the risks associated with the uncontrolled decant of AMD.

In the Eastern Basin, current pumping infrastructure must be maintained to allow access to the underground workings. If necessary, State assistance to Grootvlei Mine must be continued and possibly increased to allow pumping to continue and the infrastructure to be maintained.

In the case of the Western Basin, water will need to be pumped from the mine void to lower the level from the current level where water decants to the surface to the ECL.

In all cases, water will need to be pumped at a rate that balances the ingress of water into the mine workings. The estimates of the required pumping capacities are based on records of what was historically pumped from the basins during periods of active mining.

Basin	Required pumping capacity (an additional safety factor will probably need to be added)	Information sources
Western	40 MI/d	Compilation of flow estimates and measurements, taking into account the need to lower the water level in the Basin from its current level to the ECL
Central	60 MI/d	Scott (1995) presents an average volume based on pumping figures between 1952 and 1959

Basin	Required pumping capacity (an additional safety factor will probably need to be added)	Information sources
Eastern	108 Ml/d	Current maximum pumping rate required to manage large inflows triggered by storm events (pers. comm. J Botha — Grootvlei Mine, 2010)

10.2.2 Ingress control — reduction in the rate of mine flooding and the volumes required to be managed

The Best Practice Guidelines of the DWA for Mine Water Management prescribe a hierarchy of actions in mine water management. The prevention of impacts is at the top of this hierarchy. Research undertaken by the CGS has identified areas in the Western, Central and Eastern Basins where measures can be implemented to reduce the ingress of water into the mine void. This will reduce the volume that needs to be pumped from the mine void and treated, and consequently will reduce the costs of water management in the medium to long term. It is therefore recommended that the programme to implement these measures be undertaken.

In addition to the prevention of ingress, opportunities have been identified in the Eastern Basin where clean groundwater, which would otherwise have entered the mine void and become polluted, can be abstracted before it enters the underground workings, providing a source of clean water. It is recommended that this be fully investigated and implemented.

Both of these measures will have a positive impact at a regional level, increasing the supply of clean water and reducing the pollution load on the relevant catchments.

The implementation of some of the ingress prevention measures could take several years to complete, allowing for the regulatory processes such as EIAs, Water Use License Applications and concluding agreements with land owners. During this period it will be necessary to pump and treat a greater volume of water than will be required after the measures have been implemented. This will be taken into account in the design of pumping and treatment systems.

10.2.3 Water quality management

The water pumped from the mine voids will initially be of a poor quality and will require treatment before it can be discharged to river systems or utilised. Initially, treatment can be limited to neutralisation and the removal of metals from the water prior to discharge

into river systems. This will result in conditions which are the same as those prevalent during the period of active mining. However, this does not represent a sustainable solution in the long term, as the salt loads in the affected river systems are already high. In the medium to long term, the removal of the saline mine water discharge streams from the river systems must be considered, as part of a larger strategy looking at a range of pollution sources.

In the very long term it can be expected that water quality in the mine void will improve as oxygen is excluded from the flooded voids and available contaminants are flushed from the system. In this case, water levels may be allowed to recover to their natural levels, provided that this does not cause uncontrolled flooding problems or unintended geotechnical impacts.

10.2.4 Monitoring

The success of the proposed programme can only be verified via detailed monitoring of the water in the mine voids and the affected environments.

The investigations undertaken in the identification of treatment options have identified serious shortcomings in the current monitoring of water quality and, in particular, flow in the areas downstream of mining activities. These shortcomings need to be identified and remedied so that the required medium- to long-term strategies can be optimised for AMD management, particularly where this impacts on the Vaal River System.

It is important to continue with seismic monitoring in the short to medium term in order to gather information and data on the frequency of occurrence and size and location of the seismic events. This is especially important for identifying whether the events are restricted to the immediate surroundings of the mining areas or whether they are propagating away, hence implying that geological structures at some distance from the mining areas are at risk of being activated. The information gathered over time would also be useful for microzonation studies. This would highlight the changes in seismic risk that the infrastructure within urban areas surrounding the Central Basin would be exposed to.

It is recommended that a multi-institution monitoring committee be established to facilitate the implementation of the required monitoring and assessment programmes. Monitoring will show if there are significant changes in the quality of mine water that may have an impact on future management strategies. Monitoring results may also identify additional remedial measures required in the future.

10.2.5 Addressing other AMD sources

The flooded mine voids are not the only source of AMD in the Witwatersrand. The tailings and other waste materials generated by mining are also significant sources of AMD. Unfortunately, the lack of a comprehensive flow monitoring network in the priority areas precludes the quantification of these impacts. This highlights the need for

improved monitoring. Follow-up studies and remedial measures will also be required to minimise the impacts of these AMD sources.

10.2.6 Further research to identify and optimise sustainable solutions in the medium to long term

While immediate measures must be implemented in the short term, some areas of uncertainty still exist that need to be resolved if sustainable medium- to long-term solutions are to be implemented. Targeted research is required to address these areas of uncertainty to ensure sustainability in the longer term. This conforms with international experience, no country having sustainable solutions to all of its AMD-related problems, and active research being pursued in a number of other countries.

10.2.7 Investigation of the feasibility of an environmental levy on operating mines

The implementation of an environmental levy to be paid by operating mines to cover the costs of the legacies of past mining needs to be investigated and implemented, if feasible.

10.2.8 Ongoing assessment and future actions

The recommendations in this report represent the start of a process. The aim of these recommendations is to avert impending crises and stabilise the situation, as well as to address current gaps in the understanding of the AMD problems in the priority areas and their potential impacts on the environment. It is therefore envisaged that this process will continue into the future, with the ongoing assessments being reported to the IMC periodically.

The problems posed by AMD will have implications far into the future, with impacts likely to continue for many years. The process of management of these impacts will therefore need to continue, with ongoing assessments and adaptation as conditions change.

CHAPTER 11. ACTION PLAN

11.1 ACTION PLAN: SHORT TERM

11.1.1 Short-term interventions

11.1.1.1 Western Basin

Table 11.1. Actions and time frames for the Western Basin

Action	Time frame
Construct a 20 Ml/d emergency neutralisation plant to treat uncontrolled decant to supplement current treatment capacity	Commence immediately
Install pumping infrastructure to lower water level in the mine void to the ECL and maintain in the long term	2 years
Continuous monitoring of water levels, flow, quality and profiles	Commence immediately
Continuous prevention of ingress	Commence immediately
Continuous monitoring of seismic events	Commence immediately and continue until stability is achieved
Continuous monitoring of subsidences	Commence immediately
Stakeholder engagement	After meeting of Ministers

11.1.1.2 Central Basin

Table 11.2. Actions and time frames for the Central Basin

Action	Time frame
Pump and treat the water: - Assess the viability of refurbishing the existing treatment plant at ERPM - Determine the optimal placement of pumps - Negotiate cost sharing with other stakeholders within the basin, in particular Central Rand Gold	Commence immediately, to have all requirements in place before the water rises above the ECL or deeper level that will allow new mining to commence
Commence real-time monitoring (levels, quality and flows) — systems to be installed for the entire Witwatersrand Basin	Commence immediately
Prevention of ingress (construction of canals and other measures)	Commence immediately
Continuous monitoring of seismic events and production of microzonation risk maps	Commence immediately and continue until stability is achieved
Commence research to optimise medium- to long-term solutions, looking at: - Funding mechanisms - Institutional models - Legal issues - Communications strategies - Engineering and cost-benefit studies	Commence immediately

Action	Time frame
Stakeholder engagement — media statement after meeting of Ministers and public awareness	After meeting of Ministers

11.1.1.3 Eastern Basin

Table 11.3. Actions and time frames for the Eastern Basin

Action	Time frame
Monitoring of pumping	Commence immediately
Due diligence on the integrity of the pumping infrastructure	Commence immediately
Consider issuing a directive to ensure compliance with water license conditions	Immediate
Regular inspection of the integrity — mine inspectors	Ongoing
Prevention of ingress (e.g. construction of canals)	Commence immediately
Continuous monitoring of seismic events	Commence immediately and continue until stability is achieved
Continuous monitoring of subsidences	Commence immediately
Real-time monitoring (levels, quality and flows) — systems to be installed for the entire Witwatersrand Basin	Commence immediately
Stakeholder engagement — media statement after meeting of Ministers and public awareness	Time frame

11.2 ACTION PLAN: MEDIUM TO LONG TERM

11.2.1 Medium- to long-term interventions

This report has identified the short-term actions that are required to address current crises and to create a situation that is equivalent to the status quo during the period of active mining of the Witwatersrand Gold Fields. While this situation has been tolerated for the past century, it is not ideal and the continued salinisation of river systems will place undue stress on water resources in the future. A holistic approach to water quality management, taking the impacts of the mine discharges into account in the context of large salt loads emanating from other point and diffuse sources, will need to be addressed as a matter of priority, and the necessary feasibility studies will need to be initiated immediately.

CHAPTER 12. BUDGET

12.1 BUDGET: PUMPING COSTS TO MAINTAIN WATER LEVELS

Estimates for the costs of pumping water from the Western and Central Basins have been obtained by the DWA, as follows:

12.1.1 Capital costs

Item	Western Basin		Central Basin	
Pumps	1 pump with a capacity to pump 40 MI/d from 150 m	R 1.8 million	3 pumps with a capacity to pump 20 MI/d each from 250 m	R 3 million
Pump installation		R2 million	Dependent on whether water is pumped from 1, 2 or 3 sites	R 2–6 million

12.1.2 Operating costs

The operating costs assume an electricity price of R1,50 per kW/h and the availability of a 6.6 kV feed for the pumps.

Item	Western Basin		Central Basin	
Running costs for pumps		R10 million per annum		R15 million per annum

12.2 BUDGET: TREATMENT COSTS FOR NEUTRALISATION PLANTS

Estimated treatment costs for the construction and operation of limestone/lime neutralisation plants have been provided by Prof. J Maree of Tshwane University of Technology.

12.2.1 Capital costs

	Western Basin		Central Basin		Notes
Unit Cost (per MI/d)	Required Capacity (MI/d)	Cost	Required Capacity (MI/d)	Cost	
R 2 million	20	R 40 million	60	R 120 million	Assumes that the existing plant in the Western Basin will continue operations and that the current infrastructure at Grootvlei Mine will be maintained. Does not include the

					potential reductions in volume which could be brought about by implementing ingress prevention measures
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12.2.2 Operating costs

		Western Basin		Central Basin		Notes
Item	Unit cost (/MI)	Required capacity (MI/d)	Cost (per annum)	Required capacity (MI/d)	Cost (per annum)	
Chemical cost	R 1 200	20	R 8 760 000	60	R 26 280 000	
Electricity	R 100	20	R 730 000	60	R 2 190 000	
Labour	R 100	20	R 730 000	60	R 2 190 000	
Total running cost	R 1 400	20	R 10 220 000	60	R 30 660 000	Assumes that the mining companies in the Western Basin continue to treat water. Does not include the potential reductions in volume that could be brought about by implementing ingress prevention measures

12.3 BUDGET: MAINTENANCE OF THE PUMPING AND TREATMENT INFRASTRUCTURE IN THE EASTERN BASIN

Current costs reported by Grootvlei Mine are R3.7 million per month, including maintenance. This figure should be taken as a working budget, with additional costs likely to restore the pumping infrastructure to full functionality. These costs will be quantified as part of the proposed inspection of the infrastructure at Grootvlei Mine.

12.4 IMPACT OF THE REDUCTION OF WATER INGRESS ON THE COSTS OF PUMPING AND TREATMENT

Reducing water ingress will reduce the eventual pumping and treatment costs owing to the smaller volumes of water required to be pumped and treated. If water ingress prevention measures can be implemented before pumping and treatment is required, this could result in savings on the plant required, in particular the construction costs of treatment plants. This will only be practicable if the ingress prevention measures are implemented before the water in the Central Basin reaches the critical level. In the Western and Eastern Basins, ingress prevention will reduce the current impacts and make the situation considerably easier to manage.

12.5 BUDGET: RECOMMENDED INGRESS PREVENTION MEASURES

Basin	Project outcome	Proposed solution	Critical immediate interventions	Longe- term interventions	Regulatory requirements (if applicable)	Cost estimate – critical immediate interventions	Cost estimate – longer-term interventions	Assumptions
Western	Ingress prevention	Feasibility studies for ingress prevention measures	Assess identified ingress sites/areas, identify solutions	Implement ingress prevention	EIA, Water License and requirements of relevant road authority	R 1 250 000	TBD	Interventions will be relatively limited, canalisation of portions of the Wonderfontein Spruit may be identified as a required measure
Central	Ingress prevention	Canal construction at sites where surface streams cross undermined ground – Boksburg canal	Assess ingress and feasibility of canal construction	Canal construction	EIA, WUL, indemnities, etc.	R 121 061 582	R 0	Canal length = 7 km 80% of canal with impermeable lining (HDPE) 20% of canal with permeable lining (grass)
Central	Ingress prevention	Canal construction at sites where surface streams cross undermined ground – City Deep to Consolidated Mine canal	Assess ingress and feasibility of canal construction	Canal construction	EIA, WUL, indemnities, etc.	R 75 956 438	R 0	Canal length = 4 km 80% of canal with impermeable lining (HDPE) 20% of canal with permeable lining (grass)
Eastern	Ingress prevention	Cowles dam ingress management Eastern: Mine sediments and divert flow around the dam	Assess SAPPI/Golder study, commence engineering feasibility	Obtain authorisations and divert flow/drain dam	EIA, Water License	R 299 683	R 40 653 662	Demolish existing concrete outlet structure Drain dam Construct 2.75 km long temporary diversion canal through empty dam Construct 2.75 km long HDPE plastic-lined canal through empty dam

Basin	Project outcome	Proposed solution	Critical immediate interventions	Long-term interventions	Regulatory requirements (if applicable)	Cost estimate – critical immediate interventions	Cost estimate – longer-term interventions	Assumptions
Eastern	Ingress prevention	South: Blesbok Spruit ingress management Eastern: Unblock or enlarge culverts, divert flow over certain portions	Unblock culverts, assess need to enlarge culverts	Enlarge culverts if needed	To be determined in cooperation with relevant road authority (municipal, provincial, national)	R 343 750	R 0	Immediate: Clear two bridges. No long-term solution suggested, as bridges already exist.
Eastern	Ingress prevention	Central Blesbok Spruit ingress management Eastern: Unblock or enlarge culverts, divert flow over certain portions	Unblock culverts, assess need to enlarge culverts	Enlarge culverts if needed	To be determined in cooperation with relevant road authority (municipal, provincial, national)	R 384 766	R 5 449 219	Immediate: Clear one bridge and one pipe culvert (10 pipes). Long term: Replace pipe culvert with a bridge.
Eastern	Ingress prevention	North Blesbok Spruit ingress management Eastern: Unblock or enlarge culverts, divert flow over certain portions	Unblock culverts, assess need to enlarge culverts	Enlarge culverts if needed	To be determined in cooperation with relevant road authority (municipal, provincial, national)	R 183 594	R 5 843 750	Immediate: Clear three piped culverts (6,4 and 6 pipes respectively). Long-term solution: Replace all three pipe culverts with bridges
Eastern	Ingress prevention	Van Rhyn (ponding) ingress management Eastern: Repair channel that will remove the dam to reduce ponding significantly	Repair channel		Repairs should not require authorisation from regulators	R 34 205 241	R 0	

Basin	Project outcome	Proposed solution	Critical immediate interventions	Longe- term interventions	Regulatory requirements (if applicable)	Cost estimate – critical immediate interventions	Cost estimate – longer-term interventions	Assumptions
Eastern	Ingress prevention	Van Rhyn (direct runoff) ingress management Eastern: Close cracks and stabilise openings	Confirm ingress volumes, feasibility/costing study	Crack sealing, grouting, etc.	Should require no more authorisation than hole closures – landowner's consent	R 68 400	R 6 840 000	Close one large shaft. Close two small vents Close 200 m of cracks
Eastern	Ingress prevention	Largo ingress management Eastern: Close openings	Confirm ingress volumes, feasibility/costing study	Hole sealing, grouting, etc.	Should require no more authorisation than hole closures – landowner's consent	R 148 350	R 49 450 000	Use DC to consolidate sinkholes, then seal with fill over top Assume 180,000m ² of DC Assume 800,000m ³ of earthworks
Eastern	Ingress prevention	Gravelotte (opencast mine, open shaft) ingress management Eastern: Closing of shaft, closing costs for opencast mine too high to be feasible, construct upstream bunds	Confirm ingress volumes, feasibility/costing study	Necessary civil works	Should require no more authorisation than hole closures	R 44 700	R 1 788 000	Close three small inclined openings Close two small vents. Close 10 small openings into workings

Basin	Project outcome	Proposed solution	Critical immediate interventions	Long-term interventions	Regulatory requirements (if applicable)	Cost estimate – critical immediate interventions	Cost estimate – longer-term interventions	Assumptions
Eastern	Ingress prevention	Leeupan ingress management Eastern: Reduce the grey water entering the pan by collecting the water and discharging the water to the sewage reticulation network, Line pan	Assess ingress volumes, alert authorities – municipality/DWA of unauthorised grey water discharges	Determine the need for lining of the pan/other engineering intervention	Lining of pan will require EIA, WUL scoping	R 5 682 951	R 44 662 038	Immediate: Grey water from informal settlement collected in pump station sump and pumped via pipeline to municipal sewage system network, connection point assumed to be 600 mm away. Long term: Pan drained initially by pumping Pan lined with geosynthetic clay liner Pumps installed at low point of liner to pump inflow into pan to nearest stream, assumed to be 2 km away
Eastern	Ingress prevention	New-Kleinfontein canal repair	Repair channel		Repairs should not require authorisation from regulators	R 10 297 172	R 0	0.75 km of canal to be repaired Repairs to be done by demolition of existing concrete and install HDPE-lined riprap canal
Central	Ingress prevention	Canal construction at sites where surface streams cross undermined ground – DRD Canal	Assess ingress and feasibility of canal construction	Canal construction	EIA, WUL, indemnities etc.	R 1 039 950	R 274 546 817	Canal across ingress area 1 = 3.5 km Canal across ingress area 2 = 8.5 km
Central	Ingress prevention	Canal construction at sites where surface streams cross undermined ground – Boksburg canal	Assess ingress and feasibility of canal construction	Canal construction	EIA, WUL, indemnities etc.	R 420 353	R 121 061 582	Canal length = 7 km 80% of canal with impermeable lining (HDPE) 20% of canal with permeable lining (grass)

Basin	Project outcome	Proposed solution	Critical immediate interventions	Longe- term interventions	Regulatory requirements (if applicable)	Cost estimate – critical immediate interventions	Cost estimate – longer-term interventions	Assumptions
Central	Ingress prevention	Canal construction at sites where surface streams cross undermined ground – City Deep to Consolidated Mine canal	Assess ingress and feasibility of canal construction	Canal construction	EIA, WUL, indemnities, etc.	R 263 738	R 75 956 438	Canal length = 4 km 80% of canal with impermeable lining (HDPE) 20% of canal with permeable lining (grass)

12.6 BUDGET: MONITORING

During their deliberations the Team of Experts identified a number of gaps in the current monitoring regime for the three priority areas. A budget to address these gaps is presented below.

	Western Basin	Central Basin	Eastern Basin
Groundwater monitoring	R 3 700 000.00	R 4 000 000.00	R 2 500 000.00
Shaft level monitoring	R 240 000.00	R 400 000.00	R 320 000.00
Surface water quality monitoring	R 100 000.00	R 250 000.00	R 125 000.00
Surface water flow monitoring installations	R 1 500 000.00	R 6 500 000.00	R 2 250 000.00
Data compilation	R 350 000.00	R 350 000.00	R 350 000.00
Seismic monitoring equipment	R 750 000.00	R 1 500 000.00	R 1 000 000.00
Seismic monitoring	R 500 000.00	R 1 000 000.00	R 500 000.00
Meteorological monitoring	R 100 000.00	R 200 000.00	R 100 000.00
Capital costs	R 3 940 000.00	R 9 900 000.00	R 4 370 000.00
Operating costs per annum	R 3 300 000.00	R 4 300 000.00	R 2 775 000.00
<u>Total</u>	<u>R 7 240 000.00</u>	<u>R 14 200 000.00</u>	<u>R 7 145 000.00</u>

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APPENDIX A: DETAILED RISK ASSESSMENT

Risk assessment for the Western Basin

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Decant	Contamination of the surface-water environment.	Certain (already happening)	Decant/discharge of untreated/partially treated water	Very high	Lowering of the water level to the point where all seepage to surface ceases. Water needs to be treated to a quality suitable for discharge before it can be allowed to enter the environment	Risk will be eliminated if suitable measures are taken	
Decant	Contamination of groundwater	Very high	Contaminated water can flow to the local aquifers, contaminating groundwater	Very high	Lowering of the water level to below the ECL (1 530 m a.m.s.l.)	Lowering the water level to this elevation will protect groundwater	

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Decant	Subsidence and sinkhole formation	Low, except in areas where rewatering triggers subsidence on existing features	Acidic mine water flowing from the mine void to adjacent dolomitic aquifers	Moderate to low	The water level in the mine void needs to be lowered to below the ECL (1 530 m a.m.s.l.). Discharge of untreated AMD to the surface, from where it can recharge downstream aquifers must be prevented	Prevention of the flow of AMD to the dolomitic aquifer will protect the dolomite	
Water ingress	Water ingress from mine residue deposits to the mine void	High	Mine wastes, if not properly managed contribute water and pollutants to the mine void and pollute the environment	Very high	Proper water management to prevent infiltration into dumps and minimising seepage Removal of wastes to better managed sites	This risk can be significantly reduced through better waste management practices	Volumes entering the mine void from residue deposits

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Water ingress	Ingress of water to the mine void increases the flow of contaminated water, compounding problems	High	Ground and surface water entering the mine void	High	Better management of surface water in potential ingress areas. The required lowering of the water level in the mine void is likely to expand the area in which water can infiltrate the subsurface and enter the mine workings. Water control via canalisation/pipelines may be required in some stream courses	Reduction of inflow volumes will reduce the volumes of water requiring pumping and treatment	Inflow volumes of surface water flow and groundwater flow
Environment	Sediments will become contaminated with heavy metals and radionuclides	Moderate to low, based on existing sediment sampling data	Contaminated water flowing into streams	Moderate	Contaminated water must not be discharged to river systems. Basic treatment comprising neutralisation and settling will remove most of the heavy-metal and radionuclide load	Prevention of discharge of contaminated water will eliminate downstream risks	

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Environment	Perceived risk to the integrity of the fossil sites in the Cradle of Humankind	Low	AMD entering the Cradle of Humankind (World Heritage Site)	Low	Most fossil sites will not be affected because of their position above the affected aquifers	This risk will be eliminated if downstream pollution is prevented.	

Risk assessment for the Central Basin

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Decant	Decant of water to surface in the low-lying areas around ERPM Mine	High	If pumping ceases the mine void will flood, eventually decanting in the ERPM area (via shafts or the Elsburg Spruit valley in the vicinity of Cinderella Dam)	High	Maintain the water level below the ECL by pumping or other measures	Decant will occur unless the water level is maintained below the decant level	

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Decant	Decant into urban areas and damage to the underground infrastructure and building basements Damage to the buildings/constructed sites	Dependent on the transmissivity of the mine void, <i>i.e.</i> the ability of the void to support different water levels within the basin. This is likely to be exacerbated by compartment-alising dykes and walls erected to direct the flow of ventilation air in the underground stopes	Rising water levels under Central Johannesburg	Unknown, as the exact transmissivity of the underground workings are unknown	Monitoring to pre-empt any impacts on the Centre of Johannesburg Pumping/artificial decant from the void to control the level below the ECL (below the areas accessed by tourists at Gold Reef City)	Maintenance of a lower water level in the mine void by pumping at multiple sites will prevent the decant water from rising to the level of the basements and streets in affected areas	

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Decant	Dissolution/weathering of rocks and subsequent instability	Low	Rising water levels under Central Johannesburg	Very low because of the resistant silicate chemistry of rocks underlying the city	No mitigation required, although monitoring and maintenance of water levels will eliminate risk		
Decant	Impact on groundwater and surface water in the vicinity of ERPM	High	Rising water levels	High	Pumping/artificial decant from the void to control the level below the ECL (150 m below the surface at the South West Vertical Shaft of ERPM)	Maintenance of a lower water level in the mine void will prevent the decant water from rising to the decant level at the lowest-lying part of the basin	

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Water ingress	Water leaking from municipal services adds to the volume of water entering the mine void	High	Municipal water, sewage and storm water reticulation systems in Johannesburg and Ekurhuleni	Moderate to high	Embark on a programme together with the relevant Metro Councils to alleviate risk	This risk could be greatly reduced if proactive maintenance is undertaken on these systems	Location and condition of municipal services — will require intensive interaction with Metro Councils

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Water ingress	Seismic activity/ground tremors, with potential loss of property and injury in densely populated areas and areas with high ground motion amplification	Magnitude 3 events are occurring approximately monthly. Statistically a magnitude 4 event, which can cause damage in a zone of 10–25 km ² , could occur annually. Magnitude 5 events are unlikely but cannot be ignored	Rising water levels will induce an increase in seismic activity	High (M 4 once per year and to continue 3 years after water level is stabilised, M 5 not measured yet but cannot be excluded)	Prevention of rise of water levels. Note that this will require expensive pumping from great depth in perpetuity Seismic monitoring to continue for at least 4 years after the stabilisation of the water level Public information regarding the earthquake awareness (safety measures and process to follow during a sudden occurrence of an earthquake).	Seismic monitoring will provide accurate locations of seismic events and identification of seismically active geological features owing to water lubrication processes. The seismic risk can then be routinely assessed for probability of occurrence of potentially damaging ground motion. Monitoring will assist in the management of potential damage claims.	Evaluation of ground motion amplification owing to site effects

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Water ingress	Increased volume of water that needs to be pumped and treated	Very high	Water ingressing to the basin from the surface at a number of identified points, increasing the rate of flooding	High	Engineering works to reduce ingress will reduce the volume that needs to be pumped and treated	This will reduce the risk, although it will not entirely remove it	Uncertainty still exists on the total volume of ingress, while seasonal variations also need to be taken into account
Water Ingress	Increased volume of water that needs to be pumped and treated	Moderate to high.	Water discharged to the Elsburg Spruit could ingress to the mine void	High, with a consequent risk of round-tripping of water	Discharge point should be downstream of potential ingress area, or discharge should be via an impervious canal	Low risk. provided that mitigation measures are implemented	
Water Ingress	Ingress of water from mine residue deposits to the void	High	Mine wastes provide a source of recharge, which eventually contributes to the flooding of the mine void	Moderate to high	Proper management of mine wastes, including removal to better managed sites	Proper waste management will reduce the risks	

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Environment	Contamination of dolomitic aquifer to the south of ERPM	Moderate to high	Poor quality water decanting/discharged to the Elsburg Spruit will recharge local aquifers	High	Water treatment will mitigate the risk	Low risk, provided that water treatment is maintained and quality is monitored	
Environment	Contamination of ground and surface water	High	Mine wastes produce AMD which can contaminate surface and groundwater resources	Moderate to high	Proper management of mine wastes, including removal to better managed sites Proper surface run-off/storm water management to avoid contact with mine wastes	Proper waste management will reduce the risks	The extent of generation of point source and non-point source pollution

Risk assessment for the Eastern Basin

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Decant	Decant of water to surface in Nigel	High	If pumping ceases the mine void will flood, eventually decanting in the Nigel area	High	Maintain the water level below the ECL by pumping or other measures	Decant will occur unless the water level is maintained below the decant level	
Water ingress	Flooding of the Eastern Basin	Very high	Cessation of pumping at Grootvlei	High	Ensure that pumping continues at Grootvlei until alternative arrangements are in place	This risk remains moderate to high owing to the unsure future of Grootvlei Mine, which is currently in provisional liquidation, and the need for maintenance on the pumps and columns at 3 Shaft	

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Water ingress	Failure of pumps at Grootvlei	High	Inadequate maintenance of pumping infrastructure	High	Ensure that essential maintenance tasks at Grootvlei are undertaken	This risk remains moderate to high owing to the unsure future of Grootvlei Mine, which is currently in provisional liquidation, and the need for maintenance on the pumps and columns at 3 Shaft	
Water ingress	Increase in the volume of water ingressing into the Eastern Basin from the Blesbok Spruit	High	Ponding of water in the Blesbok Spruit	High	Cleaning/enlarging of culverts to ensure continuous flow and prevent ponding will reduce the volume of water entering the mine void	This will reduce the risk, although it will not entirely remove it	

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Water ingress	Ingress of surface water into the underground workings of the Eastern Basin	High	Water enters the basin from the surface at a number of identified points, contributing to the volumes that need to be pumped and treated.	High	Engineering works to reduce ingress will reduce the volume that needs to be pumped and treated	This will reduce the risk, although it will not entirely remove it.	
Water ingress	Flooding of the mine void with AMD	High, although the dolomite tends to neutralise the low pH of the water entering it	Mine wastes, particularly on dolomite, provide a source of recharge, which eventually contributes to the flooding of the mine void	Moderate to high	Proper management of mine wastes, including removal to better managed sites	Proper waste management will reduce the risks	

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Water ingress	Flooding of the mine void with clean dolomitic groundwater, which becomes polluted in the void	High	The configuration of the mine void immediately below the dolomitic aquifer in parts of the basin allows dolomitic groundwater to add to the volume of water which needs to be pumped and treated	High	Interception of shallow groundwater before ingress. This will make clean water available, as well as reducing the need to pump and treat water	Interception of water which would otherwise have ingressed into the mine void will reduce the volumes requiring pumping and treating	
Environment	Negative impact on the quality of the Blesbok Spruit	High	Discharge of untreated water	Moderate to high	Reinstate water treatment at Grootvlei Mine	This risk remains moderate to high owing to the unsure future of Grootvlei Mine, which is currently in provisional liquidation	

Risk category	Risk description and consequences	Probability of occurrence	Risk source	Risk rating	Mitigatory measures	Rating after mitigation	Information gaps
Environment	AMD impacts on the surface environment	High	Mine wastes produce AMD that can contaminate surface and groundwater resources	Moderate to high	Proper management of mine wastes, including removal to better managed sites. Proper surface run-off/storm water management to avoid contact with mine wastes.	Proper waste management will reduce the risks.	