MINE WATER TREATMENT TECHNOLOGY SELECTION TOOL: USERS' GUIDE

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Mine water treatment technology selection tool: Users' Guide

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Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

South Africa faces a costly threat associated with large volumes of contaminated mine water impacting on its natural resources. New legislation requires that mines plan for and manage excess water generated on site during operations and post closure.

Managing mine impacted water during operations and post closure often requires water treatment. Several water treatment options are commercially available. The aim of this project is to develop a tool that will enable a user to select a site-appropriate water treatment technology to meet the project specific needs.

Options reviewed as part of the project include:

- Precipitation/neutralisation treatment options;
- Membrane processes;
- Ion exchange technologies;
- Biological processes;
- Evaporation-based technologies;
- Irrigation options;
- Freezing technologies;
- Other emerging technologies.

Water treatment options must be screened prior to using the tool. Essentially, a treatment option will need to meet the following requirements:

- It must be able to treat both the quantity and quality of water being generated by the mine;
- The output treated water must meet the required treatment specifications.

Some general rules to follow when screening technologies include:

- With large volumes of water greater than 2 Ml/day, passive treatment processes tend to become too large for an active mine; they are more suited to larger volumes post closure.
- With monovalent ions in the feed water, one would require a desalination step. Pre-treatment options will not remove monovalent ions such as Cl, Na, K, etc. from the water.
- Systems such as the HiPro process benefit from economies of scale. Large plants tend to be more cost effective and collaboration between mines within a region is encouraged in order to make these plants more effective.
- Water with high concentrations of metals require a pre-treatment step. Often a two-step process is encouraged in order to separate the metal-rich sludge from the gypsum which can be reused.
- Biological processes work best with neutral or neutralised water.
- Ion exchange processes become less viable for high salinity waters due to the large volumes of chemicals required.

Water quality analysis includes:

- Physical and organoleptic parameters – colour, odour, total dissolved solids, conductivity, pH, alkalinity and acidity;

- Macro-determinants – phosphate, calcium, sodium, chloride, fluoride, magnesium, potassium, sulphate, zinc and silica;
- Micro-determinants – heavy metals and cyanide;
- Organic determinants – dissolved organic carbon, e-coli and heterotrophic plate count.

The selection tool evaluates options on a common platform under four dimensions:

- Environmental;
- Economic;
- Social;
- Technical.

The tool is an Excel-based application with flexibility in allowing the user to select criteria, select between two and ten treatment options, weight the criteria and input both quantitative and qualitative information. The data are then evaluated and results computed.

The option selected should satisfy the four dimensions equally well and the highest score is not necessarily the most appropriate option. The tool should be used to guide and inform the decision-making process.

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CHAPTER 1: INTRODUCTION

South Africa is a water scarce country, and its water resources need to be carefully managed to allow for sufficient and equitable distribution to all its citizens, as well as to the natural environment (Chivenge, et al., 2015); (Pahlow, et al., 2015). Although mining has long been a cornerstone of the economy, the impact on water resources of environmental problems associated with poorly managed mining has been neglected in the past, and the country currently faces an urgent, dangerous and costly threat from large volumes of mine water, of dangerously poor quality (McCarthy, 2010).

New legislation requires that mines plan for and manage excess water generated on site during operations and post closure.

The aims of the project were to:

1.1.1.1 Develop a list of evaluation criteria for mine water treatment technologies through a consultative process;

- Develop an evaluation matrix based on the selection criteria identified;
- Review and document mine water treatment technologies available at the time of conducting the study;
- Develop a spreadsheet-based tool for use by industry to evaluate treatment options;
- Provide a checklist for users and technology providers to ensure that technologies are evaluated on a common platform when using the tool.

CHAPTER 2: BACKGROUND

Mine impacted water (MIW), and specifically acid mine drainage (AMD) treatment facilities are planned and implemented by the mining industry, including the gold, coal, platinum and precious metals sectors. MIW and the management thereof continues long after production on mines has ceased and it is thus essential that a sustainable solution for MIW management is selected.

A number of locally developed and imported treatment technologies are available in South Africa. The most appropriate technology has to be project specific. Various factors, including life cycle costs, feed water quality and quantity, target water quality, waste generation, environmental aspects, implementation risks, regulatory approval aspects and buy-in by interested and affected parties, amongst other factors, all influence the selection of the most appropriate technology.

At present technology selections are often based on capital costs and existing systems. People feel more confident in implementing processes that have been tested and are running in similar applications. The technology evaluation tool developed here includes the three pillars of sustainability: the environment, social setting, and economic efficiency – in order to select a balanced sustainable solution to the mine water problem. An additional important factor to be taken into account when selecting a treatment option is ensuring that the option is technically sound. A technically sound theme was added to the selection tool.

This tool is intended to be used by industry to rate and rank alternative and emerging treatment technologies from the perspective of supporting technology research and development.

2.1 LEGISLATION RELATED TO MINE WATER

Current South African mining-related legislation has been summarised by Mey and van Niekerk (2009). The Minerals Act (Act No. 50 of 1991) contained specific requirements for the environmental management of mines in terms of environmental management program reports (EMPR). In 2002, the Minerals and Petroleum Resources Development Act No. 28 (MPRDA) was introduced, which requires a comprehensive environmental management plan (EMP). An EMP includes public participation and financial allowances for post-closure environmental and water liabilities. The National Water Act (Act No. 36 of 1998) (NWA) makes provision for the issuing of licences by the regulator for different water uses.

The National Environmental Management Act (Act No. 8 of 2004) (NEMA) stipulates the activities requiring a full environmental impact assessment (EIA). The National Environmental Management Waste Act (Act No. 59 of 2008) (NEMWA) addresses the fragmentation in waste legislation. Although the legislation in place can be said to be of a very high standard, its implementation is not always practical in terms of time and resources for the studies required as well as the approval process. Potential adjustments to the process to facilitate more efficient and expedited water treatment processes could include the establishment of less strict (perhaps temporary) guidelines, monitoring and/or fining schemes with more responsibility placed on the water user, and a wider variety of options which could include irrigation and/or evaporation.

2.2 MINE IMPACTED WATER

MIW can be classified into one of the following categories: acidic, sodium rich, or calcium/magnesium type. The main component responsible for the formation of acid or neutral mine water is pyrite (FeS_2). The presence of alkali (Na^+) or alkali earth metal (Mg^{2+}, Ca^{2+}) carbonates in the ore determines whether the water is acidic, sodium or calcium/magnesium type. Mine water is acidic when FeS_2 is stoichiometrically greater than alkali or alkali earth metal carbonates present in the ore. If smaller, the H_2SO_4 formed as a result of FeS_2 oxidation will be neutralised with Na_2CO_3, $CaCO_3$ or $CaMg(CO_3)_2$, resulting in a mine water rich in sodium and/or calcium and/or magnesium.

The formation of AMD can be attributed to the occurrence of the following events:

- Dissolution of limestone/dolomite up to its solubility level in natural ingress water;
- Pyrite oxidation by bacterial action as a result of oxygen-rich ingress water passing through broken pyrite-containing rock within the mine environment and producing acidity, iron (II) [Fe(II)], sulphates and other salts;
- Partial neutralisation of free acid due to natural alkalinity contained in the mined and broken rock media;
- Alternating contact of pyrite-rich rock with water and oxygen when the water level fluctuates as a result of water being pumped out at a constant rate, whilst the water recharge varies with seasonal rainfall (Maree, et al., 2013).

Mine water typically contains four main components, namely:

- Free acid;
- Metals contributing to acidity (Iron (Fe), Aluminium (Al));
- Anions (Sulphate (SO_4^{2-}), Carbonate (CO_3^{2-}));
- Other dissolved metals (Calcium (Ca), Magnesium (Mg), Manganese (Mn), Sodium (Na), etc.).

Depending on the amount of alkali in the ore strata that contributes to neutralisation or partial neutralisation, mine water can be classified into three groups:

- Acidic mine water, predominantly rich in H^+ and Fe^{2+}, where the pyrite content in the ore strata exceeds the alkali content (e.g. Witbank area, Witwatersrand Central and Western Basins);
- Ca^{2+}/Mg^{2+}- rich mine water, where $CaCO_3$ or dolomite in the ore strata is sufficient to neutralise the oxidised pyrites (e.g. Middelburg area, Wits Eastern and Far Eastern Basins);
- Na^+-rich mine water, where Na_2CO_3 in the ore-bearing rock is responsible for neutralisation of the oxidised FeS_2 (e.g. Secunda area).

2.3 ENVIRONMENTAL IMPACT OF CONTAMINATED MINE WATER

The distribution of the major mining areas across the water management areas (WMAs) of South Africa is shown in Figure 1. Mining activity spans 11 of the 19 WMAs with coal and gold mining being most dominant. A large proportion of the coal deposits and a majority of the gold deposits lie within the Vaal River catchment. The upper catchments of the Vaal and Olifants rivers are extensively underlain by coal deposits.

The gold and coal mineral deposits within South Africa are most prone to acid generation during mining activity and pose a severe strain on the environment in the form of AMD and associated water quality impacts.

In terms of the report of the Inter-Ministerial Committee on Acid Mine Drainage (IMC, 2010), an analysis of the currently known mine drainage sources in South Africa has identified the following mining areas as a priority:

- 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.

With reference to the above listed areas, critical mine drainage related problems are known to exist in the Western and Central Basins where, respectively, limited and no pumping is taking place. Uncontrolled discharge has occurred in the Western Basin, while the Central Basin is currently flooding and is expected to discharge in 2017/18. Measures are being implemented to deal with these AMD problems. The Eastern Basin is also considered an AMD priority area, due to the lack of adequate measures to manage and control the problems related to AMD. It is of critical importance to implement intervention measures before problems become more serious.

Severe water-related problems, including numerous AMD discharges, have been reported in the Mpumalanga Coal Fields. This is considered a vulnerable area and the impact of mining and AMD does pose a threat specifically in the upper reaches of the Vaal and Olifants River systems. Follow-up action and assessment is required, particularly in view of the expansion of coal mines in the area and the regional-scale impacts already reported. The other large gold-mining areas listed, namely the Free State, KOSH, Far West Rand and Evander Gold Fields, are currently being mined and water is pumped from these basins. However the full extent of AMD is still not fully understood. Localised AMD impacts in the O'Kiep Copper District in the Northern Cape have also been reported (IMC, 2010). Mining areas affecting water quality are mainly in northern KwaZulu-Natal, the Free State, North West, western Mpumalanga and Gauteng (DWA, 2010).

Although localised studies on the impact of AMD have been performed by government departments, science organisations and academic institutions, these studies have been highly focussed. The exact extent and quantifiable volumes of AMD generated within key mining areas on a regional basis is thus not available. Investigations thus far have focussed on specific AMD issues and related impacts and mitigation measures. In an effort to obtain an indication of the extent of, and potential for, mine drainage generation within the key mining areas identified, discussions with Department of Water and Sanitation officials that manage these areas were undertaken. In addition, catchment-related studies and reports were reviewed to support understanding of the current status.

An estimate of the potential mine drainage generated in the mining areas most susceptible to AMD is provided in Table 1, and Table 2 indicates the volumes of MIW observed in some of the most closely monitored areas.

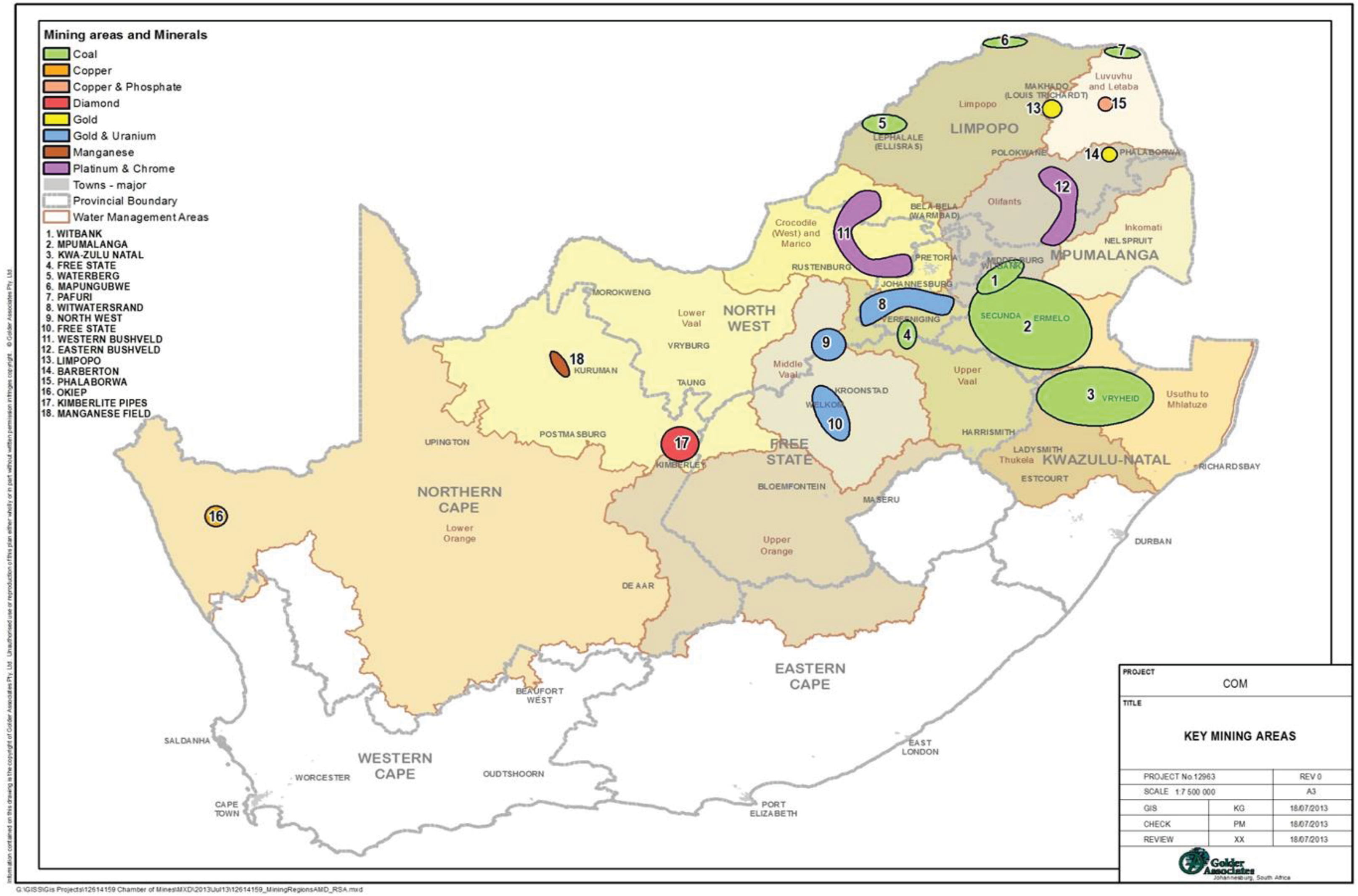


Figure 1: Distribution of major mining areas in South Africa

Table 1: Estimate of AMD generated within mining areas most susceptible to AMD

Mining Area/Basin	Water Management Area	Major mineral mined	Mining type	Potential volume of MIW generated
West, Central and Eastern Goldfields	Upper Vaal	Gold and uranium	Mainly underground	High to very high
Klerksdorp Gold Field (KOSH) and Free State Gold Fields	Middle Vaal WMA	Gold and uranium	Underground	Moderate
Barberton Green Stone belt	Inkomati WMA	Gold	Underground and artisanal	Low
Pietersburg, Murchison Green Stone belt	Luvuvhu and Letaba WMA	Gold	Underground and artisanal	Low
Giyani Green Stone belt	Luvuvhu and Letaba WMA	Gold	Underground and artisanal	Low
Evander/Ermelo Coal Fields	Upper Vaal WMA	Coal	Opencast and shallow underground	High
Highveld Coal Fields	Upper Vaal WMA	Coal	Opencast and shallow underground	High
Witbank Coal Fields	Olifants WMA	Coal	Opencast and shallow underground	High
Free State Coal Fields	Upper Vaal and Middle Vaal WMAs	Coal	Mainly underground	Moderate
KZN Coal Fields	Usutu to Mhlatuze WMA, Thukela WMA	Coal	Mainly underground	Moderate
Waterberg Coal fields	Limpopo WMA	Coal	Mainly underground	Low
Mapungubwe and Mopane Coal fields		Coal	Opencast and underground	Low
Pafuri Coal Fields	Luvuvhu and Letaba WMA	Coal		Low
Bushveld Complex	Olifants and Crocodile (West) and Marico WMAs	Platinum and chrome	Underground	Low
Phalaborwa Complex	Olifants WMA	Copper and phosphate	Opencast and underground	Low
O' Kiep Copper District	Lower Orange WMA	Copper		Low

Table 2: Volume of mine water produced in the various basins in South Africa (Rukuni et al., 2016)

River	Basin	Flow (Ml/d)			Mine Water/River Water (%)
		Mine Water	Total Mine Water	River Water	
Vaal			320	10 800	
	Central	60			
	Eastern	110			3.0
	Far Western	150			
Crocodile			30	650	
	Western	30			4.6
Olifants			130	2 728	
	Mpumalanga	130			4.8
Total			480	14 178	3.4

2.4 EXISTING INITIATIVES TO ADDRESS MINE IMPACTED WATER

Given the high cost of treating and pumping MIW, it is important that cost-effective technologies or methods are identified to prevent uncontrolled discharge of MIW resulting in the salinisation and contamination of surface or ground water at all scales of mining operations.

An expert team appointed to advise the Inter-Ministerial Committee on AMD recommended controlling the AMD associated with mining on the Witwatersrand through the following actions, amongst others:

- Installation of pumping facilities in each of the mining basins to maintain the water level below the environmental critical level (ECL) (further discussed in section 1.5.1);
- Neutralisation of excess mine water in the short term;
- Desalination of excess mine water in the medium to long term (DWA, 2012).

The Trans-Caledon Tunnel Authority (TCTA) was appointed by the Department of Water and Sanitation (DWS; formerly Department of Water Affairs (DWA)) to implement a neutralisation programme, and in June 2011, a project to manage the neutralisation of mine water in the Western, Central and Eastern Basins was commissioned (Creamer, 2012). Limestone treatment for neutralisation of free acid, followed by additional lime treatment for removal of iron(II) and other metals was implemented. A due diligence study of the Witwatersrand mining basins estimated the capital cost of AMD neutralisation plants for the three basins at R924-million (van Vuuren, 2011).

Based on proven technology, the High Density Sludge (HDS) process was recommended for neutralisation and reverse osmosis (RO) for desalination. A study was commissioned to identify the most cost-effective solution for desalination (Aurecon, 2013).

In Mpumalanga, three mine water desalination plants are in operation:

- The eMalahleni plant was initially designed to treat 25 Ml/d of mine water, and the capacity has been increased to 50 Ml/d. The capital cost of the first phase was R400 million (R40 million/Ml/d), and the second phase R500 million. The desalination process has a water recovery of 99%.
- A second desalination plant has been constructed at Optimum Colliery, with a capacity of 15 Ml/d at a cost of R800 million.

- A third plant was commissioned in 2015 at Middelburg Colliery, with a capacity of 25 Ml/d.

The three plants, with a total capacity of 90 Ml/d, cost a total of R 2,950 million, and operate at a running cost of R15/m^3. The annual running cost amounts to R493 million. A significant quantity of the 75 Ml/d mine water that is treated to potable standard at eMalahleni and Optimum is sold to the local municipalities. The balance is discharged into the Olifants River (Figure 2).

2.5 ENVIRONMENTAL CRITICAL LEVEL

Environmental critical level (ECL) 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 (DWA, 2010) The DWS recommends that water levels are to be held at or below ECLs by means of pumping.

A key step in managing MIW is reducing the load reporting to the environment. Pumping MIW with the aim of protecting groundwater is likely to be costly. In addition, it may cause further pyrite oxidation in larger MIW volumes. Table 3 (page 9) provides indicative capital and running costs for water pumped from the three basins based on the recommended ECLs (150 m below surface for Western Basin, 200 m for Central Basin and 400 m for Eastern Basin) (Makgae, et al., 2013).

Table 3: Cost of pumping water from underground to surface at current ECL levels

Parameter	**Western Basin**	**Central Basin**	**Eastern Basin**	**Total**
Flow(Ml/d)	30	60	108	198
Head, h (m)	150	200	400	302
Electricity Cost:				
Pump efficiency (%)	0.5	0.5	0.5	0.5
Energy to lift water (kJ)	3 678 750	9 810 000	35 316 000	48 804 750
Power, P_h (kW)	1 022	2 725	9 810	13 557
Power cost (R/kWh)	0.50	0.50	0.50	0.50
Electricity cost (R/m^3)	0.41	0.55	1.09	0.82
Electricity cost (R/a)	4 475 813	11 935 500	42 967 800	59 379 113
Capital Costs:				
Pump cost (R/kW)	16 000	16 000	16 000	16 000
Pump capital cost (R)	16 350 000	43 600 000	156 960 000	216 910 000

Currently no pumping costs are incurred in the Western Basin, but it is estimated to require a once-off capital investment of R16.3 million and an annual electricity cost of R3.7 million. In the Central Basin, the capital and electricity costs are estimated to amount to R43.6 million and R11.9 million per year respectively. For the Eastern Basin, the capital and electricity cost has been estimated to be R216 million and R48.8 million per year respectively. If water is pumped to a level of 30 m below the uncontrolled discharge level instead of to the ECL level, the total capital cost is estimated to reduce from R216.9 million to R21.6 million (Table 4) for the three basins, and the electricity cost from R59.5 million to R5.9 million per year (Makgae et al., 2013).

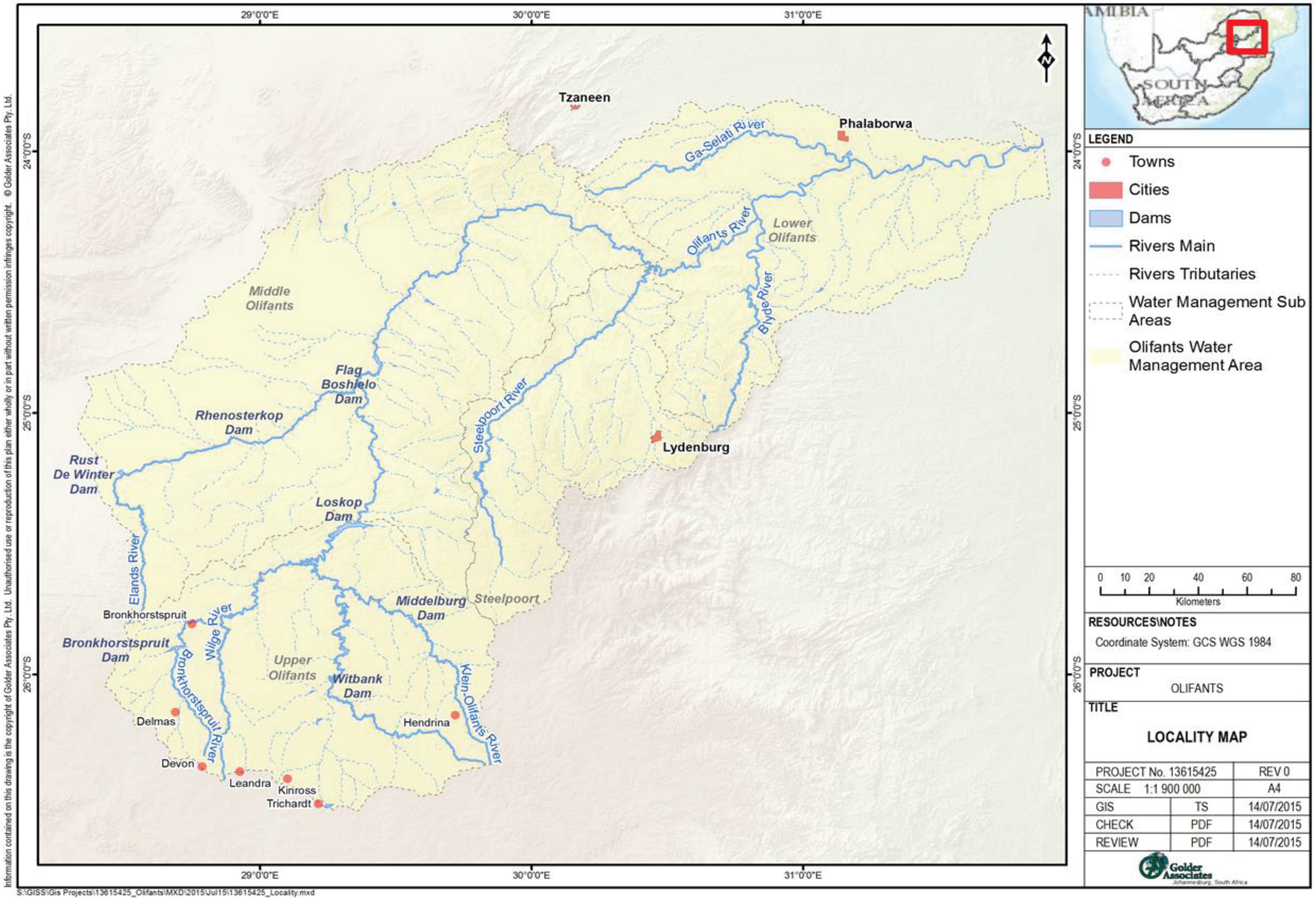


Figure 2: Location of the Olifants River Water Management Area and the boundaries of the five water management regions (after Sing and Van Veelen, 2001)

Table 4: Pumping cost of water from 30 m below surface to the surface in each basin

Parameter	**Western Basin**	**Central Basin**	**Eastern Basin**	**Total**
Flow(Ml/d)	30	60	108	198
Head, h (m)	30	30	30	30
Electricity Cost:				
Pump efficiency (%)	0.5	0.5	0.5	0.5
Energy to lift water (kJ)	735 750	1 471 500	2 648 700	4 855 950
Power, P_h (kW)	204	409	736	1 349
Power cost (R/kWh)	0.50	0.50	0.50	0.50
Electricity cost (R/m^3)	0.08	0.08	0.08	0.08
Electricity cost (R/a)	895 163	1 790 325	3 222 585	5 908 073
Capital Costs:				
Pump cost (R/kW)	16 000	16 000	16 000	16 000
Pump capital cost (R)	3 270 000	6 540 000	11 772 000	21 582 000

$$P_h = \frac{q \times \rho \times g \times h}{(3.6 \times 10^6)} \quad [1]$$

where

P_h = power (kW)

q = flow capacity (m^3/h)

ρ = density of fluid (kg/m^3)

g = gravity (9.81 m/s^2)

h = differential head (m)

Alternative approaches to maintaining mine water at the ECL are to allow uncontrolled discharge within a contained area at the lowest point, or to pump the water to a shallow level below the discharge point. This water can then be treated for reuse or discharge to the environment.

Covering the exposed ore with water is likely to minimise the formation of AMD as a result of pyrite oxidation. Pyrite oxidation can be minimised in two ways:

- Keeping oxygen away from pyrite-rich broken rock;
- Ensuring that ingress water flowing over pyrite-rich, broken rock is kept to a minimum.

Both of these options can be achieved by allowing the mine water to rise to the level at which it discharges, or to near this uncontrolled discharge level in cases where a buffer volume is required underground, to allow water storage during rainy seasons. Water can be pumped from a level sufficiently deep to prevent uncontrolled discharge during rainy periods.

2.5.1 Treatment technologies

Various treatment options are available for MIW. These will be discussed further in this report. The technologies will be categorised under the following functions:

- Precipitation process (pre-treatment; neutralisation; metal removal; chemical desalination);

- Desalination (evaporation, precipitation, ion exchange, membrane processes);
- Biological treatment;
- Waste management (brine treatment; sludge processing).

Information on mine water treatment processes was obtained from public literature. An overview of technologies for the various mine water types is presented in Figure 3.

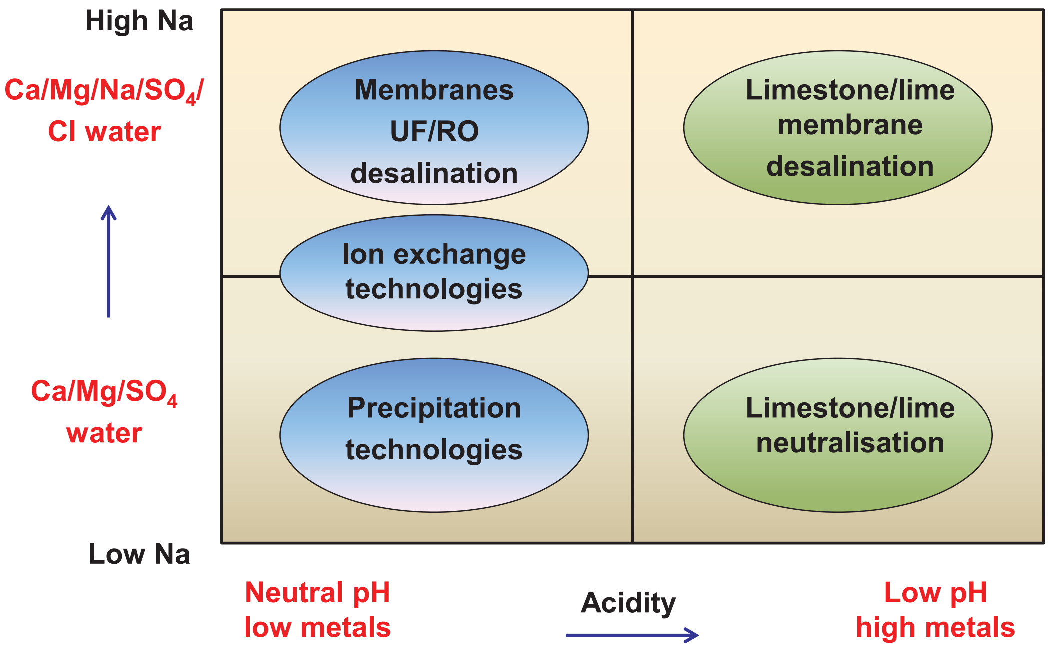


Figure 3: Typical mine water types with preferred technologies (Annandale et al., 2011)

The review included discussions with technology suppliers, and reviews of existing processes and publications (notably Bowell, 2004; Lorax, 2003). The technologies were evaluated according to the following criteria:

- Limitations of the system in terms of:
    - Flow
    - Incoming water quality
    - Treated water quality;
- Operational requirements;
- Existing applications;
- Information gaps;
- Maturity of the technology;
- Known applications;
- Resource requirements;
- Target pollutants;

- By-products produced;
- Gaseous emissions;
- Waste production;
- Skill levels required for operation and maintenance.

The individual technologies were not the sole focus, as it became clear that many of the competing technologies do not differ substantially. It is possible that different technologies such as reverse osmosis, ion exchange, Savmin and biological sulphate removal all have a capital cost in the range R15-R20 million/(Ml/d) and depending on the feed water quality can produce treated water of acceptable quality.

CHAPTER 3: SCREENING PROCESS

This chapter guides the user in the selection of the types of technology that would be applicable for their own situation. The following information is required before starting to use the tool:

- Estimated volume of water requiring treatment;
- Water quality of the stream requiring treatment (refer to Appendix A for recommended sampling list);
- Water quality requirements for the end user of the treated water stream.

3.1 GENERAL RULES

These are general rules to follow when screening technologies:

- With volumes of water greater than 2 Ml/day, passive treatment processes tend to become too large for an active mine; they are more suited to larger volumes post closure.
- With monovalent ions in the feed water, one would require a desalination step. Pre-treatment options will not remove monovalent ions such as Cl, Na, K etc. from the water.
- Systems such as the HiPro process benefit from economies of scale. Large plants tend to be more cost effective and collaboration between mines within the region is encouraged in order to make these plants more effective.
- Water with high concentrations of metals requires a pre-treatment step. Often a two-step process is encouraged in order to separate the metal-rich sludge from the gypsum which can be reused.
- Biological processes work best with neutral or neutralised water.
- Ion exchange processes become less viable for high salinity waters due to the large volumes of chemicals required.

3.2 WATER QUALITY ANALYSES REQUIRED

Ideally, one would recommend at least a year’s worth of monthly water quality data. Analysing for the constituents listed in subsections 3.2.1 to is recommended. If the product water is intended for human consumption, the most recent version of South African National Standard 241 must be used.

3.2.1 Physical and organoleptic parameters

Colour measurements of water are carried out on filtered samples. Colour can be an indication of contamination by natural minerals, such as ferric hydroxide, or organic substances such as humic acid or algae. This can be analysed for on the first sampling round and a second random sampling round.

Odour in water is often the result of volatile organic compounds in the water. The Threshold Odour Number method can be used to determine the odour. This can be analysed for on the first sampling round and a second random sampling round.

Total dissolved solids (TDS) is an indication of the ions in the water. It serves as a useful value to confirm that the major contaminants in the water are being analysed for. The sum of the concentrations of individual anions and cations measured should be approximately equal to the measured TDS value. A significant difference can indicate that some anions or cations in the water are not being analysed for or errors in the analysis.

Conductivity is the ability of water to conduct an electric current. It is sensitive to variations in dissolved solids, mostly mineral salts. Conductivity levels correlate to TDS readings. Conductivity can be measured on site and compared to the reading obtained from the laboratory.

The pH value is an indication of the acid (H^+)/alkali (OH^-) balance of a solution. Acidity and alkalinity are the base and acid neutralising capacities of the water. The pH value does not correlate to the acidity or alkalinity concentrations of the water. In the case of mine water, the acidity is linked to the metal concentrations (typically iron, manganese and aluminium) in the water. Alkalinity is typically linked to the concentrations of carbonate, bicarbonate and hydroxide in the water. Water with low acidity or alkalinity has a low buffering capacity and is susceptible to changes in pH.

3.2.2 Macro-determinants

Ammonia occurs naturally in water bodies, arising from the breakdown of nitrogenous organic and inorganic matter in soil and water. In mining, it can also be linked to explosives used. Substantial loss of ammonia is possible through volatilisation with an increase in pH above 9.

Organic nitrogen compounds in water can lead to fouling of membranes. The organic nitrogen compounds in the water should be taken into consideration in the selection of the membranes.

Phosphorus in the water can, together with nitrogen compounds, lead to fouling of membranes.

Calcium is a divalent ion, readily dissolved from rocks rich in calcium minerals.

Sodium is a highly soluble monovalent ion. The monovalent ions will not be removed in the pre-treatment phase.

Chloride, like sodium, is a monovalent ion and cannot be removed in pre-treatment processes.

High fluoride concentrations in the water combined with calcium ions can lead to calcium fluoride scaling of membranes.

Magnesium can be successfully removed by RO or precipitated as magnesium hydroxide in the pre-treatment process.

Potassium is a monovalent ion. Potassium in wastewater generally arises from industrial waters.

Sulphate concentrations in MIW are typically high. Sulphates can be removed in pre-treatment steps and desalination processes.

High zinc concentrations in water can lead to fouling or scaling of membranes.

High silica concentrations are undesirable for RO due to the risk of scaling associated with silica. A combination of lime and magnesium hydroxide in the pre-treatment step as well as the antiscalants used in the process should prevent scaling.

3.2.3 Micro-determinants

Metals, including aluminium, antimony, arsenic, cadmium, chromium, cobalt, copper, iron, manganese, nickel, selenium and vanadium can lead to fouling or scaling of membranes.

Cyanide concentrations are monitored due to its high toxicity.

3.2.4 Organic determinants

The concentration of dissolved organic carbon (DOC) indicates the concentration of organic matter in the water being treated. High concentrations of organic matter can lead to algal growth in the clarifiers and on the membranes. The pre-treatment process must effectively reduce the DOC concentrations to acceptable levels.

Escherichia coli concentrations are used as an indication of possible faecal contamination of water. Very low *E. coli* concentrations are expected in mine water.

The heterotrophic plate count is an indication of heterotrophic bacteria in the water, although these bacteria are not necessarily harmful to humans.

CHAPTER 4: SELECTION CRITERIA

The aim of the treatment selection tool is to provide a basis for ensuring that all options being considered are evaluated on the same platform. This chapter discusses the process followed in compiling the selection criteria for the tool.

4.1 DIMENSIONS

The three pillars of sustainability, *viz.* environment, economic and social were taken into consideration when developing the criteria. A technical dimension was added to ensure that the option is technically sound.

Themes have been allocated to each of the four dimensions. The themes provide an indication of the overall aspects that will be evaluated. Specific select criteria are included for the themes.

4.1.1 Environmental dimension

The following themes have been selected for the environmental dimension (Table 5):

- Mass and energy inputs;
- Impacts of the system;
- Solid outputs of the system;
- Gaseous outputs from the system;
- Liquid outputs from the system.

4.1.2 Economic dimension

The following themes have been selected for the economic dimension (Table 6):

- Net project value;
- Project performance; Impacts to the organisation.

4.1.3 Social dimension

The following themes have been proposed for the social dimension (Table 7):

- Health and safety;
- Quality of life;
- Local and economic benefits;
- Corporate citizenship.

4.1.4 Technical dimension

The following themes have been proposed for the technical dimension (Table 8):

- Adaptability;
- Complexity;
- Uncertainty.

4.1.5 Selection criteria

Selection criteria were specified for the themes presented above. Tables x to x provide the selection criteria, the description and scoring thereof, and the rationale for including these in the decision process.

4.2 TREATMENT SELECTION TOOL

A treatment selection tool has been set up on Excel and included with this report. The tool is designed for selecting an option from technologies that meet the basis of design. Options not meeting the basis of design requirements are fatally flawed and should not be considered further.

CHAPTER 5: contains the users' guide for the tool.

4.3 ENVIRONMENTAL DIMENSION

The environmental dimension focuses on resource consumption, waste production, and risks to the environment. The indicators proposed for the environmental dimension are presented in Table 5.

Table 5: Indicators proposed for the environmental dimension

Theme	Indicator	Description	Significance to mine	Importance for the theme
1. Energy (inputs to the system)	Energy consumption / generation	Estimates the net energy consumption of the option	An energy efficient treatment option should aim for process optimisation, and is likely to: ▪ minimise distribution losses; ▪ reduce waste of resources/energy; ▪ improve generation efficiency throughout the system; and ▪ recover waste for reuse. South Africa is currently facing energy constraints and, at times, generators and alternative energy sources may need to be used to keep the treatment option active. Energy costs are also likely to increase in the coming years and energy efficient technologies can aid in cost recovery, sustainability of operation and maintenance and responsible energy use (Tee et al., 2015). A mine water treatment option which promotes energy efficiency, produces saleable by-products from the treatment process, and can be used to generate electricity, is more likely to lower the energy consumption costs of a mine (Tee et al., 2015).	Water and wastewater treatment facilities are often energy intensive. In a country facing energy constraints, any energy-intensive practice has an impact on the environment, society and the economy. A mine water treatment option which is energy efficient will benefit the environment, society and the economy by: ▪ Reducing air pollution and greenhouse gas (GHG) emissions by decreasing the use of non-renewable fossil fuel resources for the production of energy; ▪ Reducing smog, acid rain and airborne particulate matter that can cause respiratory and other health impacts to the public and the environment; ▪ Reducing energy consumption costs by increasing water efficiency, especially on pumps that have high energy consumption, thus shifting energy use away from peak demand times and generating electricity from by-products such as biogas; ▪ Reducing the dependability of energy from the national grid and improving in-house security of energy; and ▪ Supporting economic growth through job creation and market development by investing in long-term energy efficient technologies.

Theme	Indicator	Description	Significance to mine	Importance for the theme
2. Input materials (inputs to the system)	Recycled input materials (consumables)	Estimates the percentage of input materials that are recycled	Recycled input materials are likely to reduce waste volume, energy consumed during the treatment process and the amount of raw materials consumed (This will aim to promote a closed loop system in the mine water treatment process, thereby reducing costs to the mine and promoting production efficiency.	Reducing the quantity of consumables and chemicals used in the process is likely to reduce the amount of raw materials consumed and emissions that may be produced. The recycling of input materials in general should reduce mining and forestry impacts in the production of raw materials. As a result, there is a reduction in: "the depletion of raw materials and natural resource consumption, energy use in production, greenhouse gas emissions, environmental burdens due to transportation and helps preserve landscape and landfill areas, which in itself, reduces the production of harmful methane, and contamination to land, air and water".
	Quantity of consumables used	Measures the amount of consumable materials required by each option (membranes, etc.), i.e. number to be replaced over 10 years	Reducing the amount of raw materials consumed will reduce costs to the mine and promote production efficiency.	
	Volume of chemicals used	Measures the volume of chemicals required	Lower quantities of chemical inputs to the process will reduce both costs and safety risks on the site and on its transportation routes.	
3. Land area requirement (impact of the system)	Site footprint	Measures the size of the option site footprint	Land requirements will influence the selection of a treatment option, as this will influence purchase and preparation costs, and could reduce impacts of the mine in terms of the environment and the neighbouring communities.	The use of a smaller site footprint could reduce detrimental impacts on the environment and society. Minimising an activity's footprint on land and the environment could result in reduced natural resource consumption, contamination of groundwater, surface water, soil, biodiversity and other potential environmental assets and processes. Indirect and cumulative impacts on surrounding communities, wetlands, ecosystems, could also be influenced by the site footprint size.

Theme	Indicator	Description	Significance to mine	Importance for the theme
4. Ecological integrity (impact of the system)	Impacts on surrounding environment of general operations, mechanical disturbance, spill of waste or input chemicals, or system failure	Evaluates the likely impact on the receiving environment caused through general operations, mechanical disturbance, system failure or spill of waste or input chemicals.	The mine should consider a treatment option which is likely to avoid, minimise or contain risks of spill or failure and consequent impacts on the receiving environment by use of safety systems, staff awareness, adequate mitigation measures or pollution control mechanisms in cases of system failure. Risks to the environment could include contaminated water and soil, harmful air emissions, and risks to local ecosystem function.	Ecological integrity of an ecosystem allows for the support and maintenance of biological communities such as plants, animals and microorganisms and their interactions, as well as the physical elements of the ecosystem such as soils, air, water, etc. It also contributes to ecosystem resilience – the capacity of ecosystems to absorb disturbances without undergoing fundamental change. Impacts on an ecosystem caused through a spill, mechanical impact or general operations can greatly affect its ecological integrity and have serious consequences such as disruption of watershed processes, harm to wildlife, and impact on the economic stability of the communities that depend on the ecosystem.
5. Solid outputs (outputs from the system)	Nature/ hazard of solid waste	States the waste classification of solid waste (quality/level of hazard)	Quantity and quality/classification of waste to be discussed first – not straight to recycling.	Solid waste produced by the treatment process could be hazardous, corrosive, ignitable, reactive and toxic causing significant impacts to the environment if discharged. Solid waste from treatment processes could also include sludge, which could be hazardous, but could also require a large land area for drying/treatment/disposal. In line with the waste hierarchy, the solid waste that is generated could potentially be reused in
	Quantity of solid waste	Measures the amount of solid waste generated	Quantity and quality/classification of waste to be discussed first – not straight to recycling.	

Theme	Indicator	Description	Significance to mine	Importance for the theme
	Solid output reuse	Measures the percentage of the solid waste that will be reused for other purposes	The effective collection and separation of waste can result in products which can be reused, recycled or sold in terms of the National Environmental Management Waste Act, Act 59 of 2008 (NEMWA), rather than being disposed of at a landfill site. This minimises the quantity of solid waste output. This could reduce costs to the mine and promote a treatment process which is environmentally friendly. For all waste outputs, NEMWA Regulations, GNR 921, must be adhered to.	the system or in other processes. This will reduce the need to transport waste to landfill, and requirements for raw materials. .
6. Gaseous outputs (outputs from the system)	Greenhouse gas (GHG) emissions	Estimates the quantity of GHG emitted by the option	Note on potential impacts of GHGs – why are they a concern? The management and/or monitoring of GHG and AQ emissions must be in accordance with the National Environmental Management: Air Quality Act, 39 OF 2004 (NEMAQA) minimum requirements/ listed activities, Government Notice, Regulation 248. The mines' emission targets are to be aligned with the stipulation limits. This will reduce environmental, health and safety concerns to the surrounding area and will reduce financial costs and environmental liability to mine.	Examples of GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), sulphur dioxide (SO_2), oxides of nitrogen (NO_x), carbon oxide (CO) and non-methane volatile organic compounds (NMVOC). Greenhouse gas emissions contribute to climate change, which has been shown to cause increasing overall average annual temperatures, global sea level rise, the melting of polar ice caps, increasing numbers of extreme weather events, unpredictable weather patterns, fires, and greater impacts on ecosystems and their functionality. These higher temperatures could also impact human receptors

Theme	Indicator	Description	Significance to mine	Importance for the theme
	Air quality	Assesses the impact of gaseous emissions upon air quality in the vicinity of the site		in terms of respiratory and cardiovascular illnesses, the spread of tropical diseases and possibly certain types of cancers Gaseous emissions will impact the air quality in the vicinity of the site, and perhaps a far wider area, depending on wind patterns. They could potentially also have indirect and cumulative impacts on the overall air quality in the surrounding area. As a result, gaseous outputs from the system may affect the health of humans, plants and animals on, near and within some distance of the site.
7. Liquid outputs/ discharge (outputs from the system)	Nature/ hazard of liquid waste	Assesses the quality of the liquid waste	The National Water Act, 36 of 1998 (NWA) and NEMWA stipulate the regulations for the quantity, quality, reuse and recovery of liquid waste. Liquid wastes from the treatment process could include sludge, brine and other effluents. Quality of liquid waste that can be discharged according to the Waste Classification Guidelines. It is preferable to select an option which produces no liquid waste, or liquid waste that is not toxic or harmful.	Impacts of liquid waste on the environment could include the contamination of groundwater, surface water and soil, as well as disruption of ecosystem processes. The minimisation and recycling of liquid waste produced will reduce negative impacts on the environment, as will selection of a technology which does not produce large volumes of hazardous waste. Also, in line with the waste hierarchy, liquid wastes that are generated from the treatment process can be reused and recovered in the system or in other processes where possible. This will reduce the need to

Theme	Indicator	Description	Significance to mine	Importance for the theme
	Quantity of waste liquid produced	Measures the amount of liquid output generated by the option	The NWA and NEMWA stipulate the regulations for the quantity, quality, re-use and recovery of liquid waste. Liquid wastes from the treatment process could include sludge, brine and other effluents. It is preferable to select an option which minimises the production of liquid waste.	transport waste to landfills and natural resource consumption.
	Liquid output reuse	Measures the percentage of the liquid waste that will be reused for other purposes	The effective separation of liquid waste outputs can allow for reuse and possibly resale, rather than being disposed of at a landfill site. This may also result in reduced costs at the mine and promote a treatment process which is environmentally friendly.	

4.4 ECONOMIC DIMENSION

The economic dimension focuses on direct and indirect costs associated with the project. The indicators proposed for the economic dimension are presented in Table 6.

Table 6: Indicators proposed for the economic dimension

Theme	Indicator	Description	Significance to mine	Importance for the category
1. Economic performance	Capital Expenditure (CAPEX)	Measures the total CAPEX for each option	The mine will aim to select an option which is low on capital costs when the project/plant is commissioned. CAPEX is incurred before the mine water treatment plant becomes operational.	The treatment option with the lowest overall project life cycle cost, that also meets the required environmental, social and technical criteria, will usually be selected. Life cycle costing takes into account the CAPEX, OPEX, capital replacement costs, closure costs, and potential financial recoveries. It is important that these mine water treatment costs are considered during the operation of the mine as well as that they are allowed for in the contributions to the closure fund, to allow for continued operation of the water treatment plant post mine closure.
	Operational Expenditure (OPEX)	Measures the total OPEX for each option over an agreed time period (e.g. cost per annum)	Maintaining low OPEX during the operational life of the project (which is likely to continue post closure) is important. It should be cautioned however that low CAPEX processes can in some cases incur high OPEX costs, and the two need to be considered together with all the other costs over the life of the plant.	
	Capital replacement costs	Estimates the potential replacement costs for consumables, e.g. membranes, over a 20-year time period	Capital replacement costs can include, for example, replacement of RO membranes, worn pumps or electrical and instrumentation components. Capital replacement costs are typically incurred at intervals depending on the operational life of the various components, with the capital replacement costs typically increasing towards the middle and end of the life of the water treatment plant.	
	Financial recoveries	Estimates the potential recovery of costs through sales of by-product, water, etc.	A treatment option which recovers costs from its process allows the mine to offset overall costs of treatment, and may even generate profit for the mine.	
	Closure costs	Measures the costs associated with closure of water treatment site	Closure costs associated with the mine water treatment plant site should be budgeted for and minimised. This should take potential social, environmental or reputational damage into account.	

Theme	Indicator	Description	Significance to mine	Importance for the category
2. Contractual	Contractual agreements	Assesses the type of contract that the supplier is willing to sign with the mine, e.g. operational guarantees, build-own-operate, etc.	If a technology supplier is willing to sign a contractual agreement which ensures their responsibility for meeting design specifications and provision of additional services, this could minimise the risks and costs to the mine. Such an agreement will typically allow for an initial extended performance assessment period before sign-off that commissioning was completed successfully, as well as ongoing operational penalties and incentives for poor or good performance respectively.	Simple, clear and cost-effective contractual agreements will improve the attractiveness of the treatment option.
3. Construction	Ease of obtaining necessary permits	Measures the costs associated with obtaining necessary permits and potential delays	Lower costs associated with less complicated permitting processes (consultant costs, meeting time, transport required, documentation), will render a treatment option more attractive. This may influence the selection of a new technology, as opposed to one which has been tested (and permitted) in the past. Delays in the approval process can also lead to cost and time implications for the mine.	Selection of a treatment option should take into account the full permitting process, anticipate potential delays in authorisation processes, and allow for minimal disruption of existing operations (and associated costs) at the site during project installation.
	Interference with activities on site	Measures the economic cost of disruption of other routine site activities during the implementation of the option. Applicable when construction will take place on an operational site	A treatment option which is easily installed within a short period of time with minimal impacts to existing operations is preferred.	
4. Potential for fines, penalties and surcharges	Potential for fines, penalties and surcharges associated with environmental and social permitting	Evaluates the likelihood of potential legal action being taken against the proponent through implementation of the option or incurred through malfunction/failure, which could result in financial penalties.	Financial penalties could be imposed due to harmful failure or malfunction of the treatment technology and non-compliance to the conditions of the authorisations/permits for operation/construction of the treatment technology. Selection of a technology which minimises the exposure of the mine to such fines will be preferable.	Selection of a low risk (low hazard chemicals/waste), highly reliable technology, and regular monitoring and inspection will avoid fines, penalties and surcharges, thereby reducing potential costs to the mine.

4.5 SOCIAL DIMENSION

The social dimension focuses on potential impacts to both the public and employees. Indicators proposed for the social dimension are presented in Table 7.

Table 7: Indicators proposed for the social dimension

Theme	Indicator	Description	Significance to mine	Importance for the category
1. Health and safety	Public health and safety	Assesses the potential adverse impacts on public human health and safety (permanent and temporary residents).	Risk to public health and safety, e.g. in terms of mechanical risk such as unsafe terrain, equipment or vehicles, or in terms of toxicity of gases, liquids or solids, must be avoided at all times, and a treatment technology with low health and safety risks or which can contain risks, will be preferable. Secondary impacts in terms of incidents related to human health and safety include reputational damage and costs of care or treatment.	Mine water and the chemicals/equipment required for the treatment thereof could be hazardous and pose a health and safety risk to site staff that are involved in the treatment process, and to the public (should access not be adequately controlled, or should a spill/release of emissions extend beyond the site). The proponent should have an effective corporate social responsibility programme in place as well as a social labour plan to provide the community and staff with adequate knowledge about water treatment and the risks

Theme	Indicator	Description	Significance to mine	Importance for the category
	Workers' health and safety	Evaluates the potential impact of the option on the health and safety of the staff and contractor staff (accidents, time off, illness, etc.) – does not include health risks of hazardous chemicals. Evaluation to be based upon the track record of the option in similar circumstances.	Risk to worker health and safety, e.g. in terms of mechanical risk such as unsafe terrain, equipment or vehicles, or in terms of toxicity of gaseous, liquid or solid waste, must be avoided at all times, and a treatment technology with low health and safety risks or which can contain risks, will be preferable. Secondary impacts in terms of incidents related to human health and safety include reputational damage and costs of care or treatment.	of coming into contact with contaminated water or other hazardous chemicals. The proponent should also have clearly communicated emergency procedures in place, for staff, visitors and the surrounding community, if there is a potential for a spill or release that requires emergency action. The mine must monitor and measure the quality of the water after treatment and only release it if it is fit to be released or distributed for use. The mine must inspect the mine water circuits to make sure that there is no leakage of untreated,

Theme	Indicator	Description	Significance to mine	Importance for the category
	Hazardous materials	Assesses the nature and volume of hazardous chemicals used (input materials, not as waste).	Hazardous chemicals used in the treatment process could be harmful to humans, animals or the local ecosystem, e.g. acid or flammable chemicals. Hazardous chemicals that emit gases could furthermore be inhaled by staff, and emissions which reach beyond the site could impact on the surrounding community. A safety risk assessment or an environmental assessment will highlight potent significant impacts and will recommend mitigation measures to be undertaken to avoid, prevent or minimise the occurrence of the impact. A treatment option that requires fewer hazardous chemicals in the treatment process will reduce potential risks to workers and the surrounding communities, thereby reducing potential social impacts of the mine.	contaminated water that comes into contact with the public or the environment. The mine water treatment process may also pose risks to the health and safety of workers. These risks may result from fumes, high temperatures, hazardous materials, potential mechanical injuries, etc. The proponent must also provide workers with the necessary personal protective equipment (PPE) to ensure that they do not come into contact with potential impacts to their health and safety. The mine must adhere to the Occupational Health and Safety Act, (OHS), Act 82 of 1993, NEMA, NEMWA and NWA regulations when assessing the extent of health and safety impacts to the public and workers.

Theme	Indicator	Description	Significance to mine	Importance for the category
2. Impacts on local community	Local suppliers and contractors	Assesses the economic benefit that the option will bring to the immediate local community through sourcing of goods and services through local procurement practices, especially within medium, small and micro-enterprises.	A treatment option which makes use of locally manufactured/sourced materials and equipment will provide economic benefits to the local community.	The implementation of a mine water treatment plant is likely to benefit local communities as well as the mine. The proponent should aim to employ local staff and source resources and materials locally, which will not only be cheaper and more efficient but also create livelihoods amongst the local community and increase their economic status. Workers can also reside at their homes with their families, which will reduce transport costs. Support from the local community for the treatment option is of great importance. The proponent could be exposed to reputational risk and long-term, complex public participation processes (resulting in delays in permitting), and sensitive community liaison during operations, should the option not benefit the local community. The public participatory process is outlined in the NEMA EIA Regulations, 2014. Negative community perceptions can delay the permitting
	Local job creation	Assesses the number of local jobs created.	Local job creation will allow for a mutually beneficial relationship between neighbouring communities and the mine.	
	Employment diversity	Assesses the employment of individuals who are from previously disadvantaged backgrounds.	An option which employs people from previously disadvantaged communities will be preferable.	

Theme	Indicator	Description	Significance to mine	Importance for the category
	Community perception	Assesses the community's known or anticipated perception of the option.	The construction and operation of a treatment option could cause visual, odour, traffic and noise impacts on the local community. It could also impact on cultural sites or sense of place for the community. These potential impacts may change the community’s perception about the mine water treatment option, which may affect the permitting process and ongoing community liaison into the operational and closure phases.	process, as well as affect ongoing relations with the community into the operational and closure phases of the project. Reputational risk will also be an important factor to consider.
	Impacts of construction work on the local community	Assesses the potential disruption and corresponding impact on the community during construction	Construction impacts on the local community could include noise, odours, traffic, lighting and visual impacts as well as impacts of heritage significance associated with local community and the area.	

4.6 TECHNICAL DIMENSION

The technical dimension has been included to ensure that the option selected is technically sound and can meet the treatment requirements. The indicators proposed for the technical dimension are presented in Table 8.

Table 8: Indicators proposed for the technical dimension

Theme	Indicator	Description	Significance to mine	Importance for the category
1. Adaptability	Robustness	Assesses the flexibility and adaptability of the option to changing feed water quality associated with environmental and seasonal effects, in particular shock loadings.	Mine water qualities are likely to change over time. Treatment plants that are very rigid in terms of the load that can be treated often require skilled staff and large feed water storage facilities in order to maintain a specified feed water quality to the plant. Failure to work within the specified feed water quality can lead to: ▪ System failure; ▪ Damage to equipment; ▪ Poor quality product; and/or ▪ A large quantity of waste. This can lead to social, environmental and economic impacts.	The environment is susceptible to change through varying seasons and environmental conditions. Treatment technologies should be adaptive to these changes in order to be efficient. If the treatment option is not adaptable, it could result in damage to certain treatment plant components, increased operational costs and negative environmental impacts should the target treated water quality and/or quantity not be met. A treatment option which is flexible, adaptable and easily upgradable is therefore a preferred technology option.

Theme	Indicator	Description	Significance to mine	Importance for the category
			Additional processes may also be required to treat water if the option is not flexible and adaptable to changing feed water quality.	
2. Adaptability	Upgradability	Assesses the ease of upgrading the option to meet future increased (or decreased) flow rates.	Flows can increase as the mine footprint increases or as rainfall patterns change, and an easily upgradable option is likely to result in minimal impacts to normal operations when upgrades are required. This indicator assesses whether units can be easily added to increase capacity.	
3. Complexity	Ease of site establishment	Assesses the level of effort required to establish the site for the option – accessibility, terrain, geotechnical conditions, source of fill material, etc.	Ease of preparation of the site for construction should keep costs and construction time to a minimum, as well as minimising impact on ongoing operations. Factors further influencing the ease of site establishment could include: ▪ Foundation requirements; ▪ Electrical requirements;	A treatment option which is easily established, constructed, operated, maintained and decommissioned is preferred. Complexity of any of these areas could result in increased requirements in terms of labour, technical skills, maintenance systems and procedures or costs.

Theme	Indicator	Description	Significance to mine	Importance for the category
			▪ Siting large structures including reactors, storage facilities and waste facilities.	
	Decommissioning complexity	Assesses the level of effort required for decommissioning.	Decommissioning complexity will depend on underground infrastructure, electrical network, presence of hazardous material and solid waste, health risks, complexity of demolition works, additional off-site operations, fugitive emissions control, etc. Containerised systems are, for example, easily decommissioned and are able to be moved to new sites as opposed to large concrete structures which could result in high decommissioning costs.	
	Electrical system complexity	Assesses the complexity of the electrical system required for powering the treatment option.	This indicator takes into consideration peak loads and average power consumption, requirements for larger sized equipment, single-phase versus three-phase loads, etc. In times of power outages, normal operational conditions	

Theme	Indicator	Description	Significance to mine	Importance for the category
			cannot always be maintained and lengthy shut-down, maintenance and start-up procedures may need to be followed before the plant can be put back into operation, e.g. settling of solids in reactors and clogging of pipelines. A treatment option which has an easily operable electrical system, and is adaptable to power outages will be advantageous to the mine.	
	Operation and maintenance complexity	Assesses O&M complexity and required frequency.	The mine water treatment technology may be operational long after mine closure. Minimal O&M requirements are preferred. Availability of required skills is considered, as well as the impact upon operations should repairs require long lead times.	
	Design complexity	Assesses the level of design complexity associated with the option.	More complex designs may lead to extensive staff training requirements and continuous requirements for upgrades and	

Theme	Indicator	Description	Significance to mine	Importance for the category
			updates, as well as unforeseen issues arising in later project stages.	
	Construction complexity	Assesses the level of construction complexity associated with the option.	More complex construction has the potential to lead to delays and problems during operation. Delays in commissioning of the treatment option may result in high socio-economic risk.	
4. Uncertainty	Likelihood of approval by regulator	Assesses the likelihood of approval of the proposed option by the regulatory agencies, based upon proven/tested capacity to meet the discharge regulations/requirements in similar environments.	A treatment option with a proven full-scale track record, and with which the authorities have experience, is less likely to cause delays in the approval process.	A treatment option which has not been well tested in the proposed environment could have technical uncertainties and could require down-time for adjustment and modification/rectification of the technology. Technical support teams may also not have sufficient experience with newer technologies, which are more uncertain than tried and tested technologies. A treatment option with less uncertainty will result in reduced technical risks and will be preferable to implement.
	Technical support	Assesses the availability of technical support from the supplier(s), based upon previous	Technology with a strong support base (preferably locally) is favoured. Newer treatment processes may not have been tested, and technical	

Theme	Indicator	Description	Significance to mine	Importance for the category
		experience and recent interactions.	staff may be less able to operate the technology. This may result in time and operational cost constraints to the mine.	
	Durability	Assesses the long-term durability of the treatment process. Assessment to be based upon proven or tested performance in similar environments.	The more durable the treatment option, the less maintenance, time constraints and capital replacement costs to the mine. Tried and tested treatment technologies are also likely to be more durable than newer treatment technologies.	
	Technical uncertainty /reliability	Measures the confidence associated with the option through proven previous implementation and measurement. Appropriate measures can be recommended to reduce technical uncertainty, such as small-scale trials.	A treatment option which has been tried and tested in similar industries and environments, which treats similar feed water, (not necessarily mine waters e.g. food industry), and has gone through sufficient lab and pilot skill investigations, is preferable. Independent reviews and recommendations of the technology can also add to its reliability and determine uncertainties.	

CHAPTER 5: USERS' GUIDE

The steps to be followed when using the tool to select a treatment option is described in this chapter.

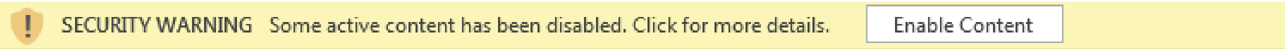
5.1 PROCESS TO BE FOLLOWED

The following steps need to be taken when selecting a treatment option:

1. Develop a basis of design (BoD) for the treatment plant.
    a. In a new operation, use predictive modelling and geochemical investigations to determine the anticipated flows and water qualities to be treated. Models can also be used to estimate a date when treatment would be required. For existing operations, use historical data and predictive modelling and geochemical studies to understand the current situation and how this may change over the long term.
2. Screen options to determine which options will be applicable.
3. Consult with suppliers and issue requests for quotations with the BoD and a list of information requirements.
4. Launch tool.
5. Select evaluation criteria.
6. Populate weightings. These are based on your corporate requirements and specific project requirements.
7. Populate evaluation sheet:
    a. Ensure that units are consistent for quantitative data.
    b. A workshop approach is recommended for qualitative data.
8. Submit evaluation.
9. Interpret results.

5.2 LAUNCHING THE APPLICATION

The mine water treatment option selection tool operates on pre-defined, back-end macro content that requires a security pass-through to allow the content to run. Figure 4 illustrates a typical warning that may appear depending on the current security settings:

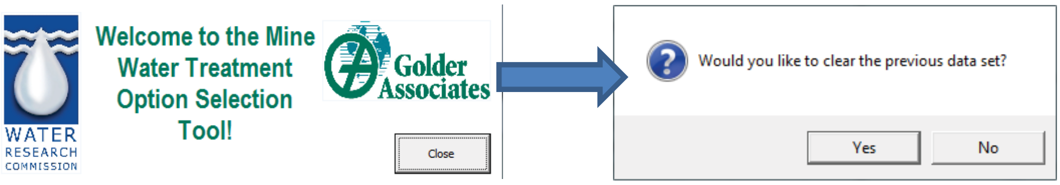


SECURITY WARNING Some active content has been disabled. Click for more details.

Figure 4: Typical security warning for macro content to be enabled.

In order to use the mine water treatment option selection tool, it is recommended that the content be enabled.

Once the content is enabled a splash screen (Figure 5) will be shown (which will automatically close after 5 seconds) which is followed by a question and requires user input. The user can decide whether to keep the prior data set used or to start a new selection.



Welcome to the Mine Water Treatment Option Selection Tool!

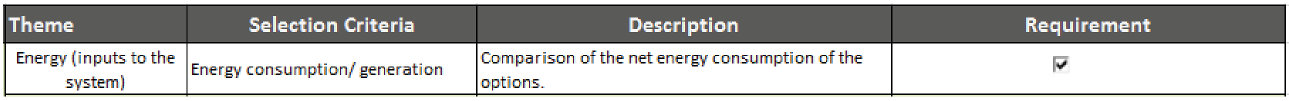
Would you like to clear the previous data set?

Figure 5: Initial splash screen and required user inputs

5.3 SELECTION CRITERIA

5.3.1 Selection criteria form

The user will be brought to the “Selection Criteria” sheet where a checkbox can be seen. The user is required to check the relevant checkboxes to be evaluated. Figure 6 shows a typical line in the requirement selection list.

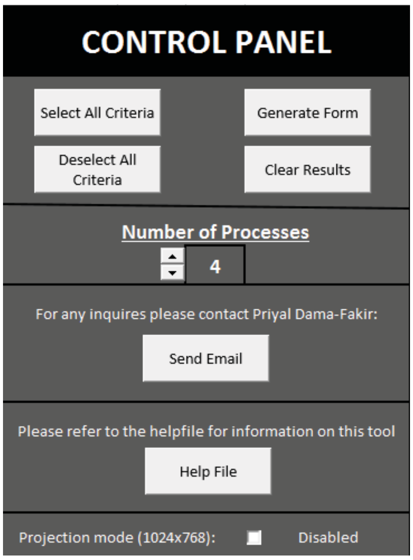


Theme	Selection Criteria	Description	Requirement
Energy (inputs to the system)	Energy consumption/ generation	Comparison of the net energy consumption of the options.	☑

Figure 6: Requirement selection list

5.4 CONTROL PANEL

A control panel is available and located next to the selection criteria requirements. Figure 7 shows the current layout of the control panel and Table 9 describes each control panel function and the usage for each function.



CONTROL PANEL

Number of Processes: 4

For any inquires please contact Priyal Dama-Fakir:

Please refer to the helpfile for information on this tool

Projection mode (1024x768): ☐ Disabled

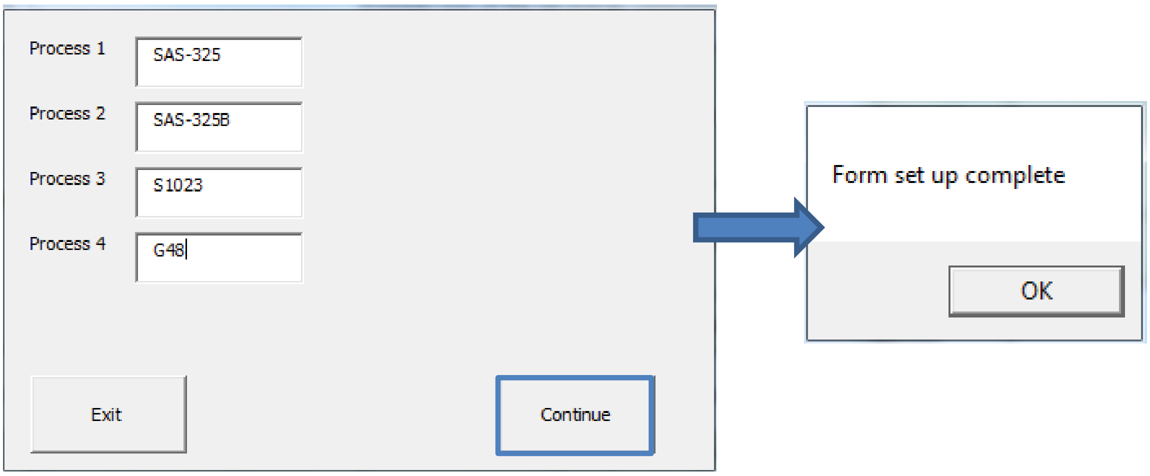
Figure 7: Control panel for the selection criteria

Table 9: Control panel functionality descriptions

Control Panel Function	Description	Usage
Select All Criteria	Selects all requirement checkboxes	Select if the user would like all the checkboxes to be checked.
Deselect All Criteria	Deselects all requirement checkboxes	Select if the user would like all the checkboxes to be unchecked.
Generate Form	Generates evaluation form based on requirements checked	Once the desired requirements are selected, the user must run this function to continue the evaluation.
Clear Results	Clears previous results	This function will remove sheets and results generated from a previous run of this application.
Number of Processes	Adjusts the number of processes to be evaluated	Allows the user to increase or decrease the total number of processes to be evaluated. This can be done by typing in a number or using the spin box control. There is a lower limit of 2 and an upper limit of 10 processes that can be entered.
Help File	Opens a help file	Launches the help file. This file is located in the root folder of this application.
Projection Mode	Adjust graph projection over a projector	This function displays completed charts in a different format to fit on projected screens better. This option is based on projector resolution of 1024x768. If the projector can output in HD then this option should be left unmarked.

5.5 EVALUATION FORM GENERATION

In order to continue with the evaluation once the desired requirements have been marked, the “Generate Form” function found in the control panel should be run. The user will be presented with a screen similar to Figure 8. Names should be given to each process in question. The “Continue” function should be run to proceed to the next step of the evaluation. There will be a short delay after running this function. Once completed a message prompt will appear to notify the user that the form generation has been completed.


Process 1 SAS-325
Process 2 SAS-325B
Process 3 S1023
Process 4 G48

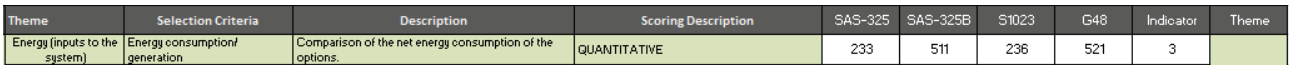
Form set up complete

Figure 8: Process names screen

An “Evaluation” spreadsheet will appear with the marked requirements populated. The user is required to fill in the necessary values as seen in Figure 9. The scoring description will indicate what requirements are expected to be inputted.

Populate the weighting columns based on your corporate requirements. For less important criteria, select 1. Select 2 for criteria with average importance and 3 for criteria that are of high importance. Only three options have been provided to ensure that a balanced result can be obtained.

Once the evaluation sheet has been updated, the “Submit Evaluation” function should be run. This function is found to the far right of the form.



Theme	Selection Criteria	Description	Scoring Description	SAS-325	SAS-325B	S1023	G48	Indicator	Theme
Energy (inputs to the system)	Energy consumption/ generation	Comparison of the net energy consumption of the options.	QUANTITATIVE	233	511	236	521	3	

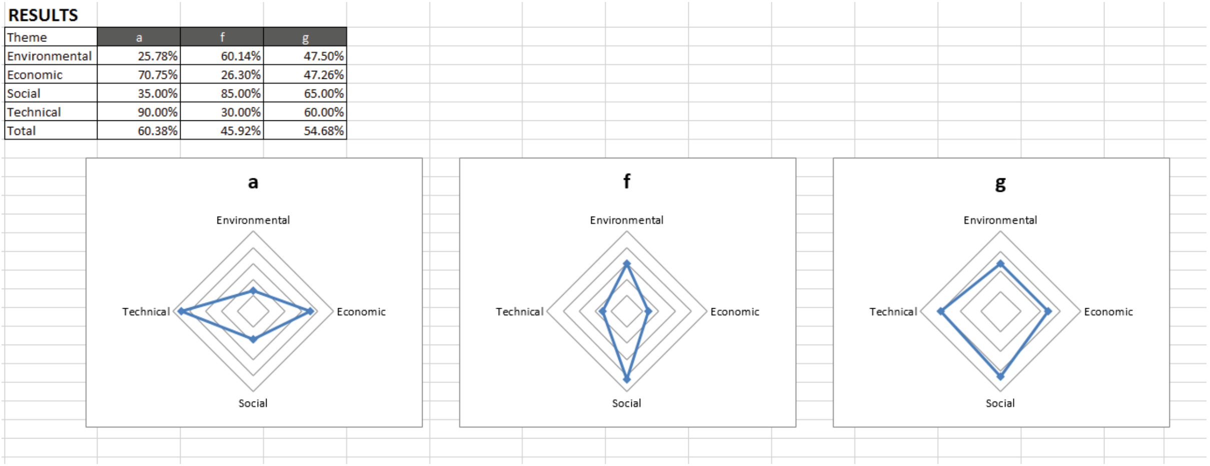
Figure 9: Typical line in evaluation scoring

5.6 RESULTS

After an evaluation has been submitted, a series of result pages will be available for analysis. Projection mode (Figure 7) impacts the “Results” page such that the charts do not overlap each other over projected screens. A “Print to PDF” feature exists on all pages of graphical results; this allows a user to save graphical results to a PDF for future reference.

5.7 INTERPRETATION OF RESULTS

A snapshot of results obtained is presented in Figure 10. It can be noted that while option 1 obtained the highest overall score, it is not the most desirable option from a sustainability point of view and option g is preferred as it is a more balanced result.



RESULTS

Theme	a	f	g
Environmental	25.78%	60.14%	47.50%
Economic	70.75%	26.30%	47.26%
Social	35.00%	85.00%	65.00%
Technical	90.00%	30.00%	60.00%
Total	60.38%	45.92%	54.68%

Figure 10: Results obtained from the mine water treatment selection tool.

CHAPTER 6: SURVEY OF MINE WATER TREATMENT TECHNOLOGIES

6.1 PRECIPITATION/NEUTRALISATION TREATMENT

All precipitation treatment processes rely on chemical precipitation, through the production of sparingly soluble salts (solubility < 0.1 M) to remove unwanted components from the saline mine water. Precipitation treatment processes are generally only effective at removing multivalent ions from water, with the extent of multivalent ion removal limited by the concentration of monovalent counter-ions. Elevated concentrations of sodium or chloride cannot be removed.

The following types of treatment are explored in this section:

- Lime neutralisation;
- Limestone neutralisation;
- Lime/limestone neutralisation;
- The SAVMIN^{TM} process;
- Barium sulphate precipitation.

Lime treatment is normally used as pre-treatment for neutralisation and metal removal. Adding lime to AMD rich in sulphate and calcium will result in the formation of gypsum:

$Ca(OH) + H_2SO_4 \rightarrow CaSO_4.2H_2O$ [2]

Due to the relatively high solubility of gypsum, which depends on the composition and ion strength of the solution, only partial sulphate removal is achieved. Typically 1500-2500 mg/l of sulphate can be removed.

6.1.1 Conventional treatment with lime

Figure 11 shows the conventional lime treatment process configuration. It allows for mixing, aeration, and removal of solids. Unfortunately, the settling rate of solids is slow, and the process results in a large volume of solid waste which is difficult to dispose of (Pretorius, 1998).

6.1.2 Recycled sludge process

During this process, a portion of the settled sludge is first brought into contact with the AMD before the addition of lime. Due to the “seeding” effect, a denser sludge is produced (Kostenbader and Haines, 1970).

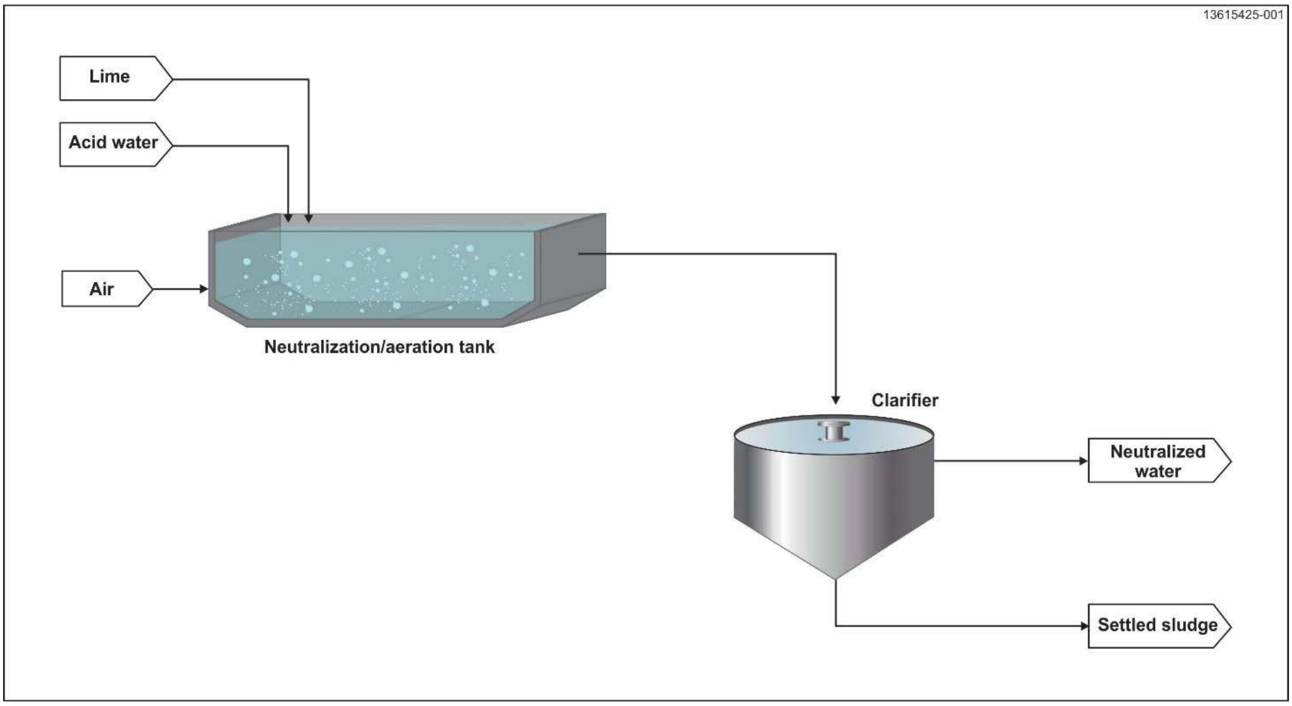


Figure 11: The conventional process for acidic water neutralisation

6.1.3 High Density Sludge (HDS) process

The HDS process is widely used for neutralisation of acidic effluents (Osuchowski, 1992). Figure 12 illustrates the stages of the HDS process, as follows:

- pH correction/sludge conditioning;
- Neutralisation/aeration;
- Solid/liquid separation.

The pH correction stage makes use of a reaction tank for the preparation of a lime solution and a sludge conditioning tank which receives both the recycled settled sludge from the settling tank underflow and the lime solution. The lime dosage in the pH correction stage is such that the pH of the final treated water is pH 8. The conditioned sludge from the pH correction stage overflows into the neutralisation/aeration tank. This tank is fitted with a mixer and/or aerator to keep the solids in suspension, to mix the conditioned sludge with the acid water entering the tank, and for aeration. In this tank, ferrous iron is oxidised to ferric iron. The neutralised and oxidised effluent overflows to the clarifier where sludge is separated from the liquid. A polyelectrolyte can be dosed to the clarifier to promote flocculation. In this process, several metals can be oxidised, such as ferrous to ferric hydroxide (pH 7.2), manganese to manganese dioxide (pH >9), or precipitated, such as manganese hydroxide (pH >11) and aluminium hydroxide (pH 6.5) (van Tonder and Günther, 1998).

Due to metal precipitation, the HDS process generates little excess alkalinity (50-100 mg/l as $CaCO_3$), even at high lime dosages (high pH). The characteristics of the sludge change at pH levels greater than 9; gelatinous sludge forms that is difficult to settle, even with polymers. Large sludge particles are produced through recirculation of a portion of the settled sludge (Kostenbader and Haines, 1970), which results in better sludge settling (Bosman, 1974).

The HDS process has the following advantages over the conventional process (Osuchowski, 1992):

- Sludge with a density ten times higher than that of the conventional process is produced. As a result, smaller sludge drying and disposal facilities are required.
- The sludge settles faster, therefore a smaller clarifier is required with a saving on the clarifier of approximately 38%.

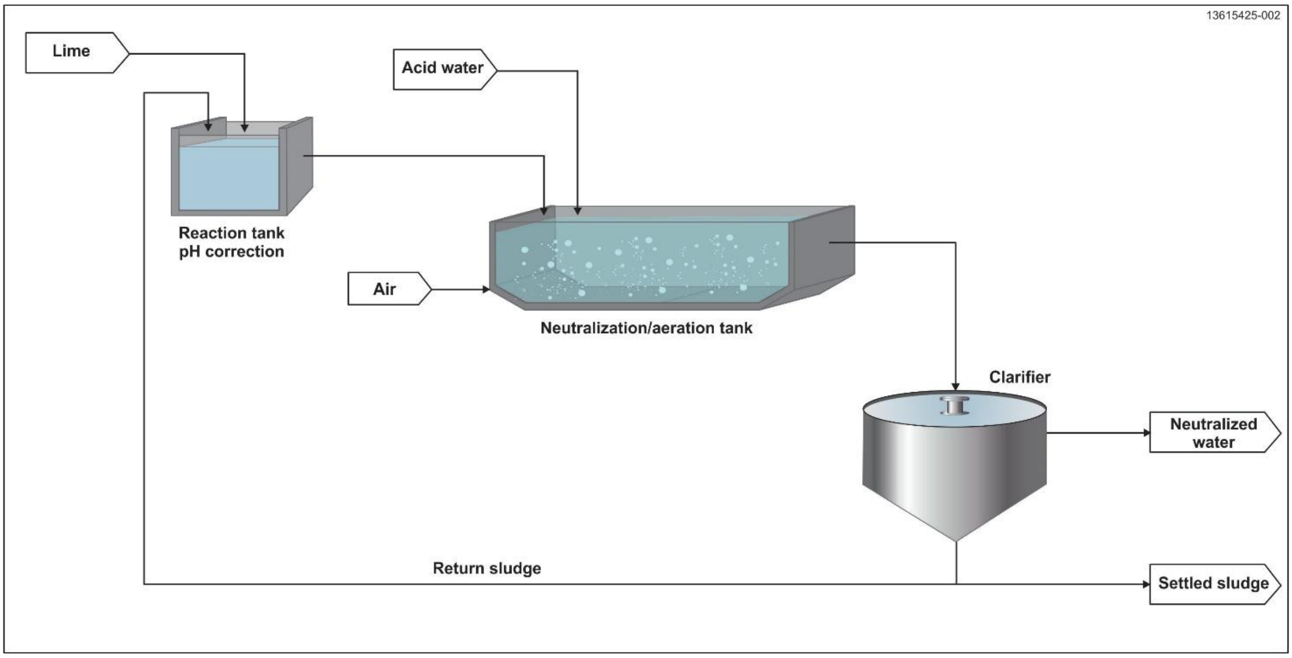


Figure 12: The High Density Sludge process

6.1.4 Limestone neutralisation

The first full-scale implementation of limestone neutralisation of acid mine water was carried out in 2001 at Landau Colliery by Anglo Coal (Günther, et al., 2003), where lime was replaced with limestone for neutralisation during the HDS process to save on alkali cost. The saving amounted to 55%, or R4.5 million per annum (Günther, et al., 2003). Limestone was previously not considered an effective alkali due to its limited solubility and the armouring of rock limestone particles, which resulted in poor utilisation of the limestone (Renton & Brown, 1995). The limestone slurry can also be used to neutralise acid leached from the unwashed coal in the coal processing plant.

6.1.5 Limestone/lime neutralisation

The integrated limestone and iron(II)-oxidation process allows for the oxidation of iron(II) when limestone alone is used for neutralisation in the first stage (Maree and du Plessis, 1994; Maree et al., 1996) (Figure 13). Powdered limestone is used for iron(II)-oxidation at pH 5.5, neutralisation of free acid, metal precipitation (e.g. Fe^{3+} and Al^{3+}) and gypsum crystallisation. All reactions are achieved in the same reactor. The novelty of this development lies in the fact that conditions were identified in which iron(II) can be oxidised at pH 5.5 by the addition of limestone. Limestone, the cheapest alkali, is used for neutralisation of the bulk of the acid content. Carbon dioxide (CO_2) is produced and stripped off through aeration and transported to the third stage. Lime is used in the second stage to allow for precipitation of magnesium and other metals, and the sulphate associated with these metals. The solubility product of gypsum controls the level to which sulphate is removed. In the third stage, $CaCO_3$ precipitation occurs when the CO_2 that is produced in the first stage makes contact with the high pH of the water from the second stage. This occurs at pH 8.3. The $CaCO_3$ is pure enough to be sold as a by-product, or it can be recycled to the first stage to supplement the limestone addition (Maree et al., 1996). This process offers benefits such as:

(i) The treated water is under-saturated with respect to gypsum;

(ii) if the feed water contains aluminium, sulphate removal is not only achieved through gypsum crystallisation, but also through ettringite ($3CaO.3CaSO_4.2Al_2O_3$) formation as it precipitates in the pH range 11.3 to 11.4.

The equipment consists of low-cost mixed or aerated reactors and clarifiers. A number of process configurations exist, each with specific advantages or disadvantages. The process is robust and proven, but the resultant water quality normally fails to meet the standards that would allow for river discharge or reuse. The process also produces large volumes of mixed precipitate sludge waste that requires long-term disposal. The process can be used as an effective metals removal pre-treatment step prior to desalination processes, such as RO or ion exchange. Limestone can be used for complete removal of iron(II) within 90 min reaction time. Lime can therefore be used for removal of metals (Maree et al., 2013).

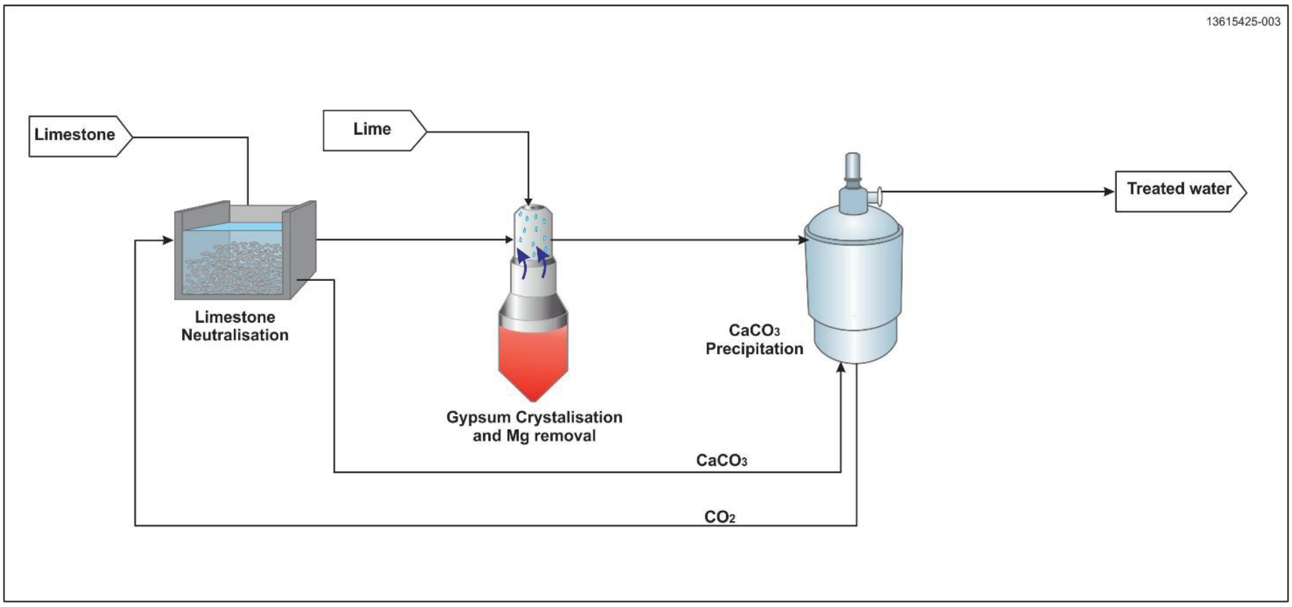


Figure 13: Lime/limestone neutralisation process

6.1.6 The SAVMIN^{TM} process

The SAVMIN^{TM} process involves the removal of metals and sulphate from contaminated mine water at ambient conditions (van Rooyen, 2015). Water treated through the SAVMIN^{TM} process can meet the standards for drinking water in South Africa. The process comprises four stages, as illustrated in Figure 14. These are explained below:

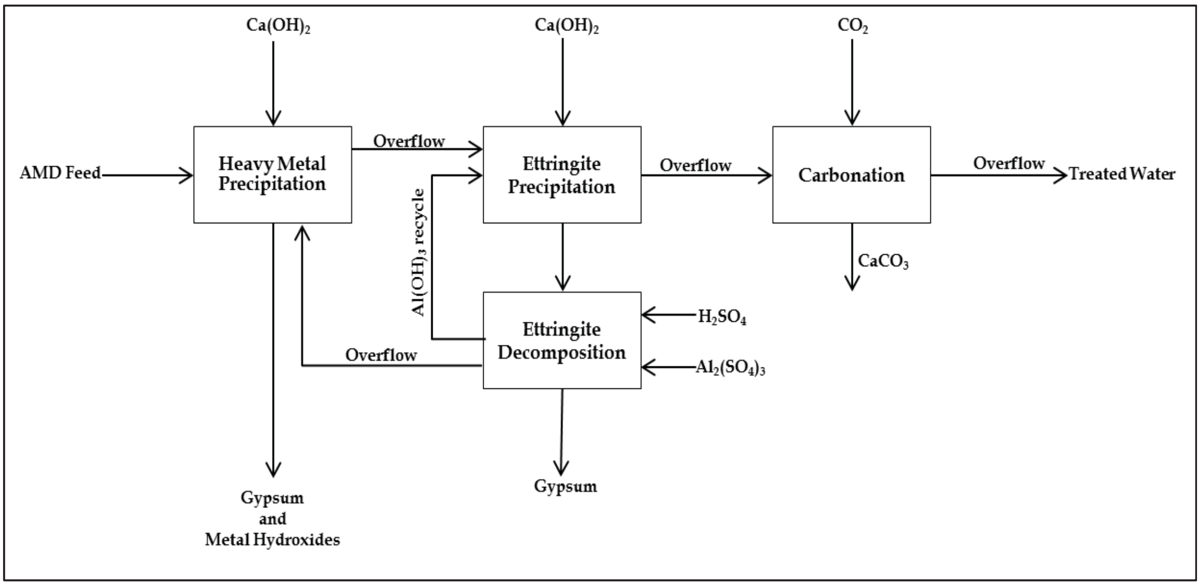


Figure 14: The SAVMIN^{TM} process block flow diagram

- **Stage 1 – Metal precipitation**: Mine water is treated with lime to raise the pH to a value between 10 and 11.5. Gypsum and metals, as hydroxides, are precipitated. The combined metal hydroxides and gypsum solids are separated from solution and leave the process as waste. Further treatment of the metal hydroxides and gypsum waste might be required, however this does not form part of the SAVMIN^{TM} process. In some cases this waste may need to be disposed of in a properly lined hazardous waste disposal site.

- **Stage 2 – Ettringite precipitation:** pH is raised further and aluminium hydroxide is added to the gypsum-saturated solution from Stage 1, which results in the removal of calcium and sulphate from solution by the formation of an insoluble calcium aluminium sulphate salt called ettringite ($3CaO.3CaSO_4.Al_2O_3.31H_2O$).

- **Stage 3 – Carbonation:** The overflow solution is treated with carbon dioxide to lower the pH and cause the precipitation of calcium carbonate, which is then separated from the treated water. The calcium carbonate can either be collected as a by-product or disposed of as waste. The solution from Stage 3 is the product, clean water.

- **Stage 4 – Ettringite decomposition**. Ettringite is decomposed with the addition of H_2SO_4 to produce aluminium hydroxide and gypsum. $Al_2(SO_4)_3$ is also added to make up for aluminium losses in the system.

As shown in Figure 14, sulphuric acid and make-up aluminium sulphate are added to the ettringite slurry (underflow from Stage 2). The pH of the stream is decreased to a value between 6.0 and 9.0. Aluminium hydroxide precipitates, together with gypsum, which ultimately reports to the solids. The recovered aluminium hydroxide is separated from the gypsum solids and recycled to Stage 2. The ‘clean’ gypsum is recovered as by-product or waste. The overflow, saturated in gypsum, is recycled to Stage 1.

Trials at the Stillfontein plant in South Africa successfully treated 500 m^3 of water with a sulphate concentration of 800 mg/l to < 200 mg/l.

6.1.7 Barium sulphate precipitation

The removal of sulphate by barium carbonate was originally demonstrated more than 40 years ago (Kun, 1972), with researchers in later years also illustrating this successfully (Maree, 1989; Trusler et al., 1988; Adlem, 1997). Slow reaction rate and the high cost of $BaCO_3$ are problematic (Kun, 1972). Wilsenach showed that the cost problem can be overcome by recycling barium through roasting of barite to form BaS and then purging with CO_2 to reform $BaCO_3$ (Wilsenach, 1986). The process is shown in Figure 15.

It should be noted that if magnesium is present in the feed it needs to be removed with lime as $CaCO_3$, because the high solubility of $MgCO_3$ prevents the dissolution of $BaCO_3$. Since lime dosing results in $CaCO_3$ precipitation, it allows for higher Ba^{2+} concentrations in solution.

The slurry from the reactor is directed to a thickener where clean water can be decanted and recycled in the mine or process operation. The thickened slurry is filtered, dried and treated to recycle barium and collect sulphur. In a modification of this process a two-stage fluidised bed reactor system has been proposed to overcome the low reactivity of $BaCO_3$. A weakness of this process is that $CaCO_3$ and $BaSO_4$ are mixed, and need to be separated either before or after the kiln stage (Maree, 1989).

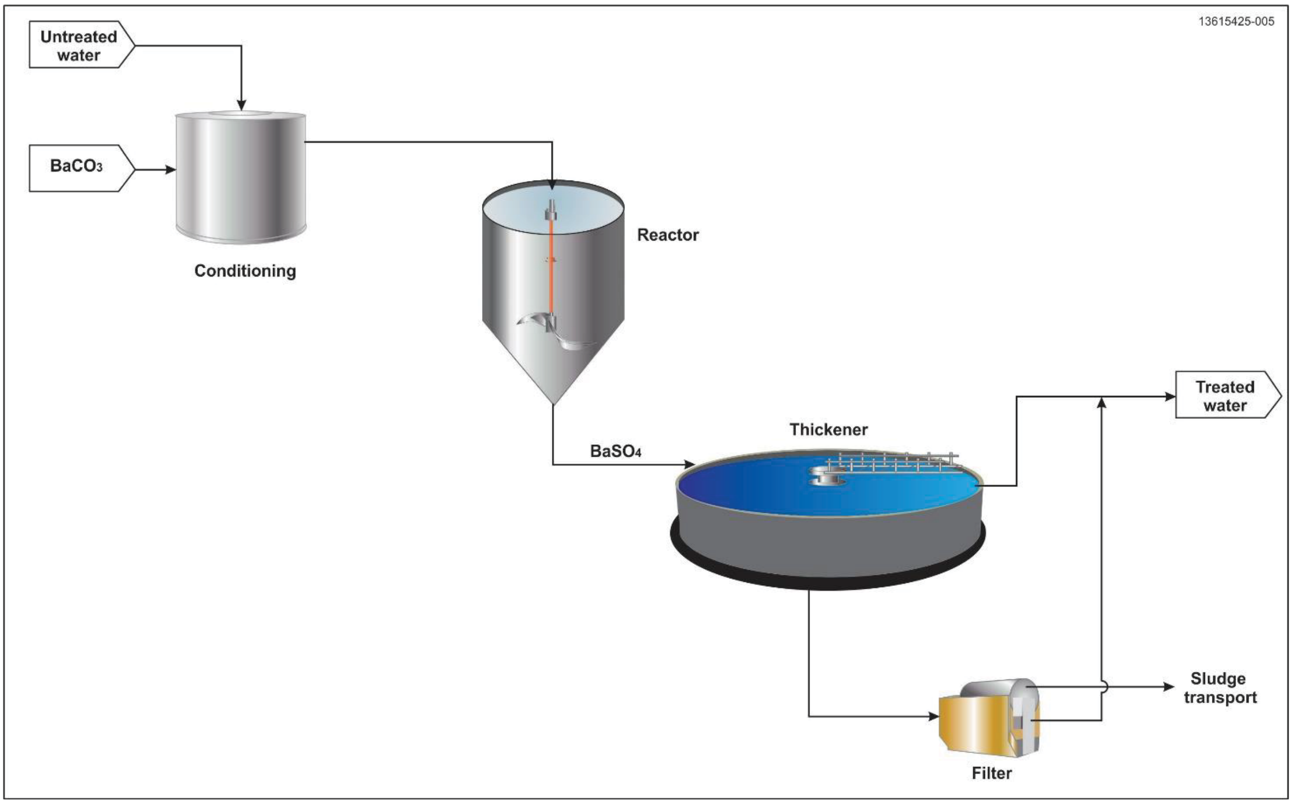


Figure 15: Process flow diagram of the barium carbonate process (Maree and du Plessis, 1994; Hlabela et al., 2007)

BaS has been proposed as an alternative to $BaCO_3$ (Maree, 1989; Bosman, et al., 1990). In the case of BaS, sulphide needs to be stripped from the treated water. The H_2S gas that is stripped off can be brought into contact with Fe^{3+} to recover sulphur. A possible flow sheet for this process is provided in Figure 16.

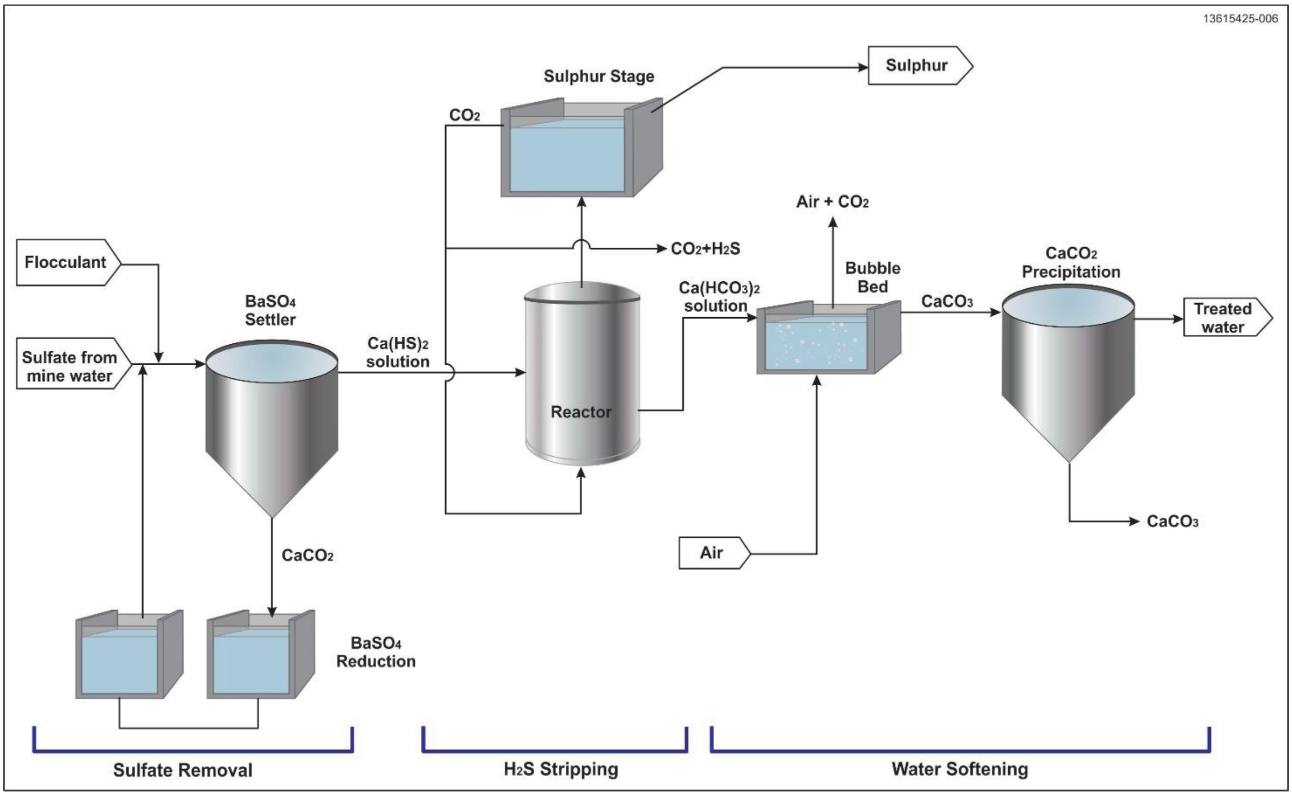


Figure 16: Schematic flow diagram of the BaS process (Maree, et al., 1989)

Sulphate removal can also be achieved by dosing $Ba(OH)_2$ (Adlem et al., 1991; Bowell, 2004; 2004). The necessity for complex water treatment associated with the $BaCO_3$ and BaS processes would then be eliminated. No long retention times or stripping of H_2S as in the BaS process would be needed (such as in the $BaCO_3$ process). Because of the cost of barium and its environmental toxicity it is advantageous to have a barium recovery plant to recycle barium salts.

Sulphate can be removed from solution with all three barium salts, BaS, $BaCO_3$ and $Ba(OH)_2$, from high levels to within regulatory standards. In the case of BaS and $Ba(OH)_2$, acidic solutions can be treated directly, although in practice some lime treatment is required for acidic solutions to prevent metal hydroxide sludge from being mixed with $BaSO_4$. The $Ba(OH)_2$ process also removes Mg and NH_3. Thus, the overall TDS are lowered, as well as the concentration of deleterious elements. A benefit of the process is that by-products are created which can be sold to offset treatment costs, e.g. in the $BaCO_3$ and BaS processes, S, NaHS and $CaCO_3$ can be commercially produced.

6.2 MEMBRANE PROCESSES

Membrane processes use a physical membrane barrier to help separate the charged ions from the clean water, producing two effluent streams, one with low dissolved solids concentration and the other with a high dissolved solids concentration.

The following technologies are discussed in this section:

- Reverse Osmosis and nanofiltration;
- Electrodialysis;
- Vibration Shear Enhanced Process;
- Multi-Effect Membrane Distillation (MEMSYS).

6.2.1 Reverse osmosis and nanofiltration

6.2.1.1 Reverse Osmosis

Reverse osmosis (RO) removes most of the dissolved solids from brackish or saline feed water and can treat water to a very good quality. Pre-treatment for RO often involves limestone and/or lime dosing (see section 1.7) and aeration for the neutralisation of acidic water and the removal of metals. Neutralisation is then followed by stringent filtration using either sand and cartridge filters, or ultrafiltration (UF), before RO. This process uses pressure to drive water through a semi-permeable membrane, leaving the ions behind. A clean water stream (permeate) and a concentrated brine solution (retentate) result. RO is capable of rejecting bacteria, salts, sugars, proteins, particles, dyes, and other constituents that have a molecular weight of greater than 150-250 daltons.

RO has the ability to produce treated water with a very low TDS concentration; however, this is expensive (in terms of capital and operational costs) and reduces the quantity of water recovered. Generally, a recovery of 50%-80% can be achieved with a single stage RO plant, and this can be increased to 95% with multiple stage RO, thereby greatly reducing the waste brine volume and the cost of brine disposal. Multiple stage RO can achieve water recoveries of greater than 99%, depending on the feed water quality (Figure 17). These high water recoveries are achieved when the feed water consists of predominantly divalent ions that can be precipitated from the preceding stage's brine before being treated in the next RO stage. Multiple stage RO systems can also contain nanofiltration membranes to allow monovalent ions to pass through the membrane (see section below) and increase the overall water recovery by reducing the production of brine.

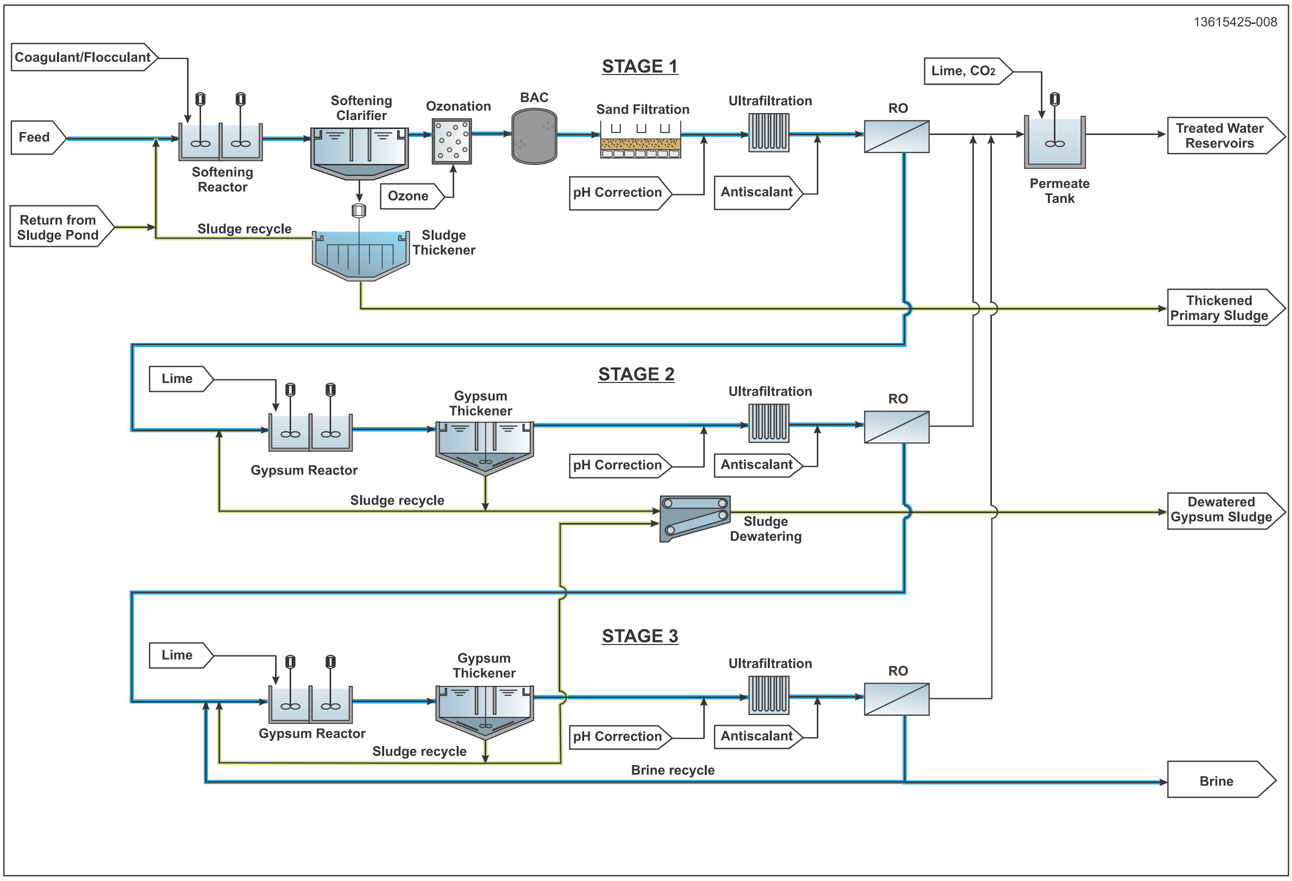


Figure 17: Example of a reverse osmosis/ultrafiltration membrane treatment process

Tubular RO systems, which have regular flow direction reversal and make use of sponges for cleaning, can be used for highly scaling water streams that cannot be treated in conventional spiral wound RO systems.

The sludge and brine waste streams which are a by-product of the RO process require long-term disposal due to their hazardous nature and high concentration of dissolved salts.

6.2.1.2 Nanofiltration

Nanofiltration (NF) has the same pre-treatment requirements as RO and similar challenges with regard to waste disposal. However, the brine volume is lower, as NF only separates the multivalent ions, while it allows monovalent ions to pass through the membrane. It must be noted that a solution with a mixture of monovalent ions and divalent ions, for example sodium sulphate, will behave like a divalent solution as the retained multivalent salt has to remain charge neutral and will therefore not allow the sodium to go through the membrane.

The use of NF is viable if divalent ions are the main ionic constituents in the feed water to be treated.

6.2.1.3 High Recovery Precipitating Reverse Osmosis (HiPRO®) Process

The High Recovery Precipitating Reverse Osmosis (HiPRO®) process consists of three stages, each configured with pre-treatment, Ultrafiltration and RO (Figure 18) (Karakatsanis and Cogho, 2010; Günther et al., 2008). The treated water produced by each stage is of potable water quality. The brine from each stage becomes the feed for the next stage. Partial sulphate removal is achieved through precipitation of gypsum during lime dosing in the pre-treatment stages. The final RO stage is mainly used for removal of soluble sodium sulphate and sodium chloride, resulting in 98% water recovery.

In the pre-treatment stage, limestone is used for removal of H_2SO_4 (free acid), Fe^{3+}, Al^{3+} and Fe^{2+} (partially) when the feed water has a low pH. Lime is used for removal of remaining Fe^{2+}, Mn and other metals present in low concentrations, or O_3 is used for removal of Fe and Mn, where only low levels of Fe and Mn are present in the feed. Solids are removed in the pre-treatment clarifier. An anionic polymer flocculant is added to promote solids agglomeration. Clarification is followed by sand filtration prior to further treatment via ultrafiltration (UF). Pre-treatment during Stages 2 and 3 differs from that in Stage 1 because the pH is raised enough for precipitation of magnesium hydroxide; removal of the magnesium counter-ion and the addition of calcium with the lime results in additional gypsum precipitation. In the reactors the sludge is kept in suspension by means of large agitators. Hydrocyclones are used to draw off large sludge particles. Small particles in the overflow are introduced into the respective Stage 2 or 3 Clarifier. The coarse sludge from the underflow of the Hydrocyclones is subsequently dewatered by means of a Vacuum Belt Filter.

Ultrafiltration is the final solids removal process before the RO step. Each UF skid is intermittently backwashed in order to remove the entrained solids. The backwash water from the sand filters and the UF skids is collected in the plant's drain sump and further treated. Anti-scalant and sulphuric acid are dosed upstream of the UF in Stage 1 to prevent scaling of RO membranes with gypsum or calcium carbonate. In the case of Stages 2 and 3 where the water has an elevated pH after pre-treatment, anti-scalant is dosed after the UF process, as well as sulphuric acid for pH correction.

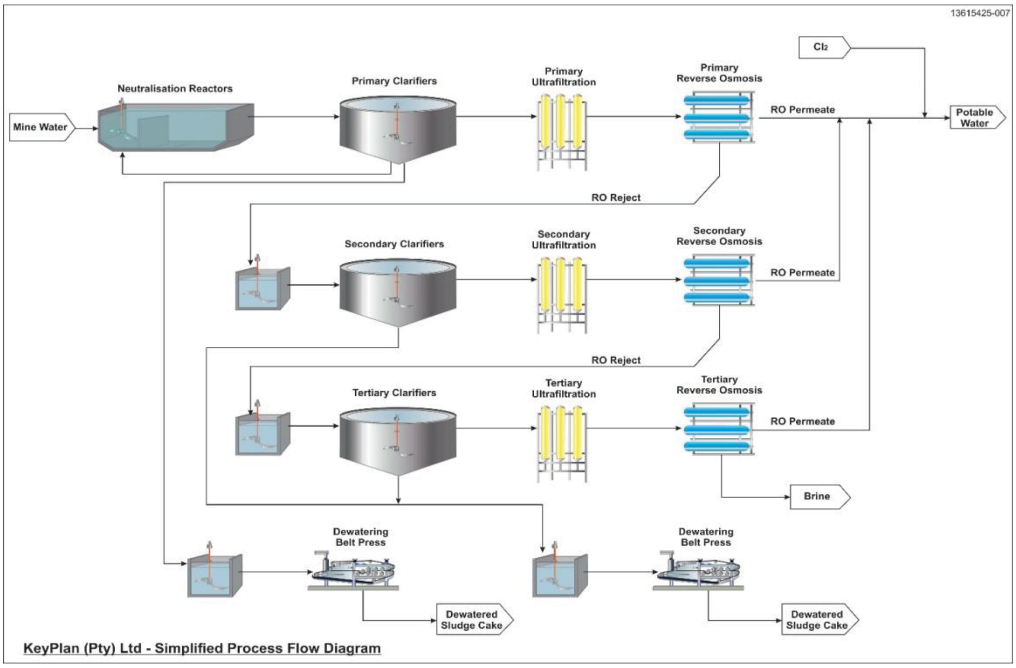


Figure 18: Process configuration for the KeyPlan HiPRO® process (Karakatsanis and Cogho, 2010)

RO is the final treatment stage. The $CaSO_4$ saturation level of Stage 1 RO feed water typically amounts to 90% to 95%, but the recovery is limited by the $CaCO^3$ scaling potential. The maximum Stage 1 RO recovery is usually around 70% (feed water quality dependent). The Stage 1 RO design in some cases has made use of Nanofiltration (NF) membranes to allow for some of the monovalent bicarbonate ions to pass into the permeate. The benefits of this were:

(i) Stability is provided to the low salinity permeate;

(ii) The lower concentrations of bicarbonate in the reject will place less demand on lime in the Stage 2 Precipitation Reactors.

The Stage 2 and 3 RO designs are usually at increasingly lower recoveries due to the higher $CaSO_4$ saturation levels in the feed water. The permeate stream from each RO skid is collected in a common treated water tank. The reject from each stage is routed to the next stage, while a small amount of Stage 3 reject is passed on to the brine pond. Mixed sludge, gypsum and brine are produced as waste streams.

6.2.2 Electrodialysis (ED, EDR)

Electrodialysis (ED) and electrodialysis reversal (EDR) involve the transport of ions across water-tight membranes that allow electrons to flow through them (Figure 19). Direct electrical current is passed across a stack of alternating cation and anion selective membranes in this process. Anions are attracted to the anode but cannot pass through anion-impermeable membranes, and are thus concentrated. Cations move in the opposite direction and are impeded by cation-impermeable membranes. The initial water stream is split into two streams; one becomes concentrated in salts and becomes the brine stream, while the other is depleted of salts and forms the clean water stream. The process is greatly improved by the use of current reversal. The anode and cathode can be periodically changed. This way the potential for membrane fouling is reduced and facilitates regeneration of the membrane by self-cleaning.

Electrodialysis requires the same neutralisation and metals removal pre-treatment steps as RO. The suspended solids removal requirements are, however, not as stringent, and normal filtration is sufficient.

In the EDR process, the reversal refers to the reversal of the polarity of plates and membranes that provides a self-cleaning capability by changing the direction that ions migrate through the membranes. The reversal of ion flow aids in the prevention of slime and other build-up and lowers the requirement for pre-treatment chemicals. The main operating cost of EDR is the energy input for the transport of the ions across the membranes. The energy input required by EDR is almost directly proportional to the ionic concentration of the feed water. Therefore EDR is typically more cost competitive compared to conventional RO at lower feed water TDS concentrations. It must be noted that EDR will only remove ionic species and thus if the feed water is high in organic compounds or non-ionic species, some form of filtration prior to the EDR unit will be required.

ED and EDR processes can produce water of a very good quality, similar to ion exchange (discussed in section 6.3) or RO. As with conventional ion exchange or RO, ED and EDR produce brine that requires long-term disposal or volume reduction, followed by crystallisation, and then disposal of the crystallised salts.

The EDR process is not sensitive to effluent temperature or pH. This is a major advantage over RO techniques. The capital costs of EDR are also reduced due to lower working pressures. Scaling by $CaSO_4$ can occur if there is inadequate pre-treatment. At Beatrix gold mine, a water recovery of 80% was achieved during a pilot plant study. The feed water has high Fe, Mn, Na and Cl as well as sulphate (Juby and Pulles, 1990).

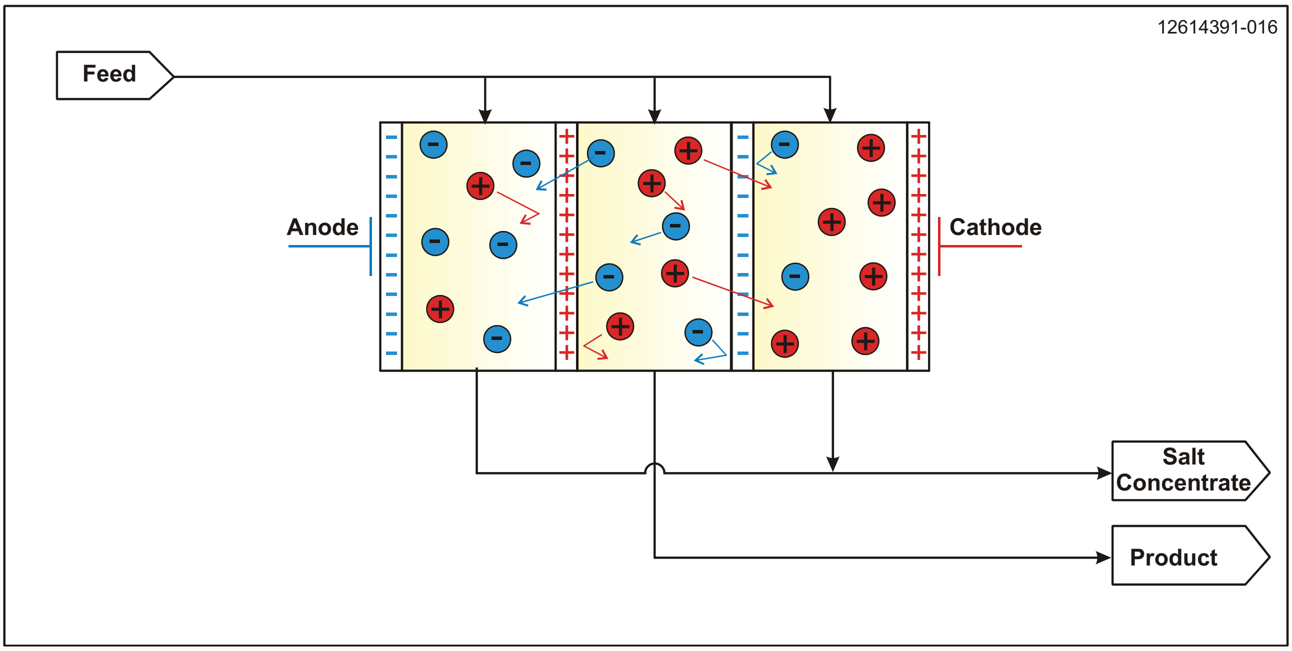


Figure 19: Illustration of the ED process

6.2.3 Vibration Shear Enhanced Process

The Vibration Shear Enhanced Process (VSEP) is based on conventional RO, but uses torsional vibration of the membrane surface, creating high shear energy at the membrane surface (Figure 20). This enhances throughput (98% water recovery) and reduces colloidal fouling, hence reducing the level of pre-treatment required (possibly eliminating it). It achieves very high reductions of colour, turbidity, iron, etc. and VSEP has the potential to replace most of the RO pre-treatment requirements, resulting in lower operating costs and less brine. However, it is imported from the United States of America, and exchange rates may make it prohibitively expensive. Units are modular and portable. However, a small brine stream that requires disposal still remains.

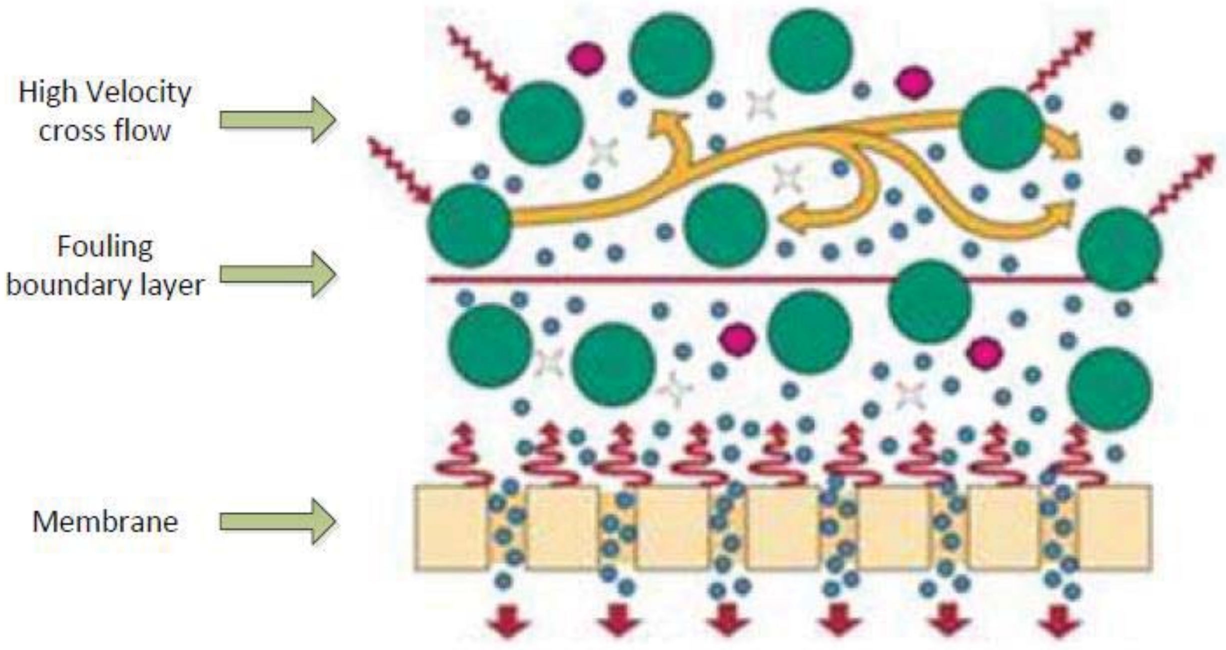


Figure 20: VSEP membrane (New Logic Research, Inc, 2012) (New Logic Research)

6.2.4 Multi-effect Membrane Distillation (MEMSYS®)

The Multi-effect Membrane Distillation System (MEMSYS®) is similar to the multi-stage flash distillation process in that it makes use of waste heat and reduced pressures to vapourise the water (Figure 21). The process also makes use of hydrophobic membranes which allow the water vapour to pass through, keeping the concentrated salt behind. The water vapour, which has passed through the membrane, then condenses on a plastic surface and is recovered, whilst the concentrated brine is fed to the next stage. Studies indicate that concentrations of up to 15 g/l TDS can be achieved using this process.

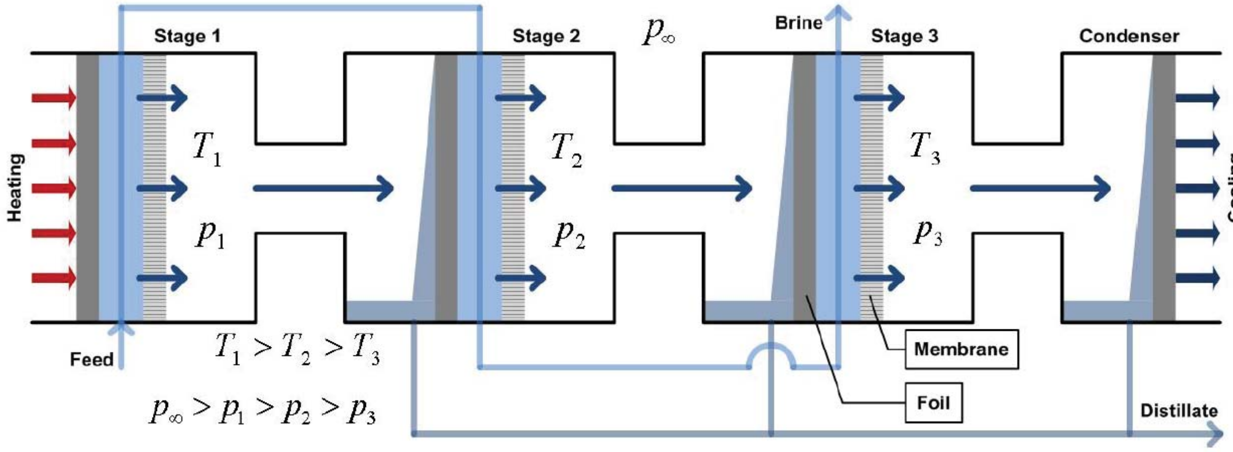


Figure 21: Multi-effect Membrane Distillation System (MEMSYS®)

6.3 ION EXCHANGE TECHNOLOGIES

Ion exchange (IX) technologies rely on the exchange of one charged ion with another to remove unwanted constituents from mine water. When the exchanged ions are hydrogen (the cation), and hydroxide (the anion) the water is desalinated as the hydrogen and hydroxide combine to form water. The ion exchange media, whether natural or synthetic resins, are normally regenerated using acids and alkalis. The spent regenerant solutions which contain the ions removed from the water as well as some excess regenerant, typically require disposal if they are not beneficiated further. Ion exchange technologies are generally effective at removing all charged ions from the feed water, and as such can effectively desalinate water with high concentrations of sodium and chloride, as well as remove some more problematic metals like uranium.

The following technologies are discussed:

- Conventional Ion Exchange;
- GYP-CIX;
- KNeW.

6.3.1 Conventional ion exchange

Conventional IX is used widely, particularly for boiler feed water demineralisation or water softening. It is based on the use of tested combinations of process equipment and the lowest cost regenerants that produce soluble spent regenerant solutions, typically hydrochloric acid and sodium hydroxide. The spent regenerant solutions either require disposal in brine ponds or further volume reduction treatment using thermal evaporation processes, and disposal of the final salts as hazardous waste.

6.3.2 The GYP-CIX

The GYP-CIX process uses the same principles as conventional ion exchange, except that the process configuration is based on reactors with fluidised resin beds and a fluidised bed regenerator. This process configuration implies that the capital costs are higher, but allows for the use of low-cost sulphuric acid and lime as the regenerants while producing gypsum as a by-product.

Previously, the limitation to using sulphuric acid and lime for the ion exchange process was the scaling or fouling effect during regeneration due to the calcium sulphate produced during the regeneration process. This fouling has been minimised by the fluidised bed configuration and the precipitation does not destroy or limit the performance of the resin.

6.3.3 KNeW

In the KNeW process (Potassium Nitrate ex Waste, patented by Trailblazer Technologies) (Bewsey, 2013; 2015), AMD is neutralised with Na_2CO_3 to precipitate metals, calcium and magnesium, followed by resin treatment for removal of dissolved solids (Figure 22). The remaining cations (mostly sodium) are removed on cation resin and anions (SO_4 and Cl) in the anion resin (R-OH). The cation resin is regenerated with HNO_3 to produce a metal nitrate solution. Residual metals are removed as metal carbonate (mainly $FeCO_3$, $CaCO_3$ and $MgCO_3$) for use as a soil ameliorant. The $NaNO_3$ solution is mixed with equimolar KCl, heated to evaporate water to exceed the solubility of NaCl (NaCl is less soluble than KNO_3), followed by cooling to 35°C to crystallise KNO_3 which is a primary fertiliser. The anion resin is regenerated with ammonia to produce ammonium sulphate. Methanol addition is used to precipitate a pure $(NH_4)_2SO_4$ from the chloride contaminant. Ammonia is recovered by increasing the pH with NaOH to above 12. The feasibility of the KNeW process is dependent on the sale of by-products. Figure 23 shows a pilot plant operation near Krugersdorp.

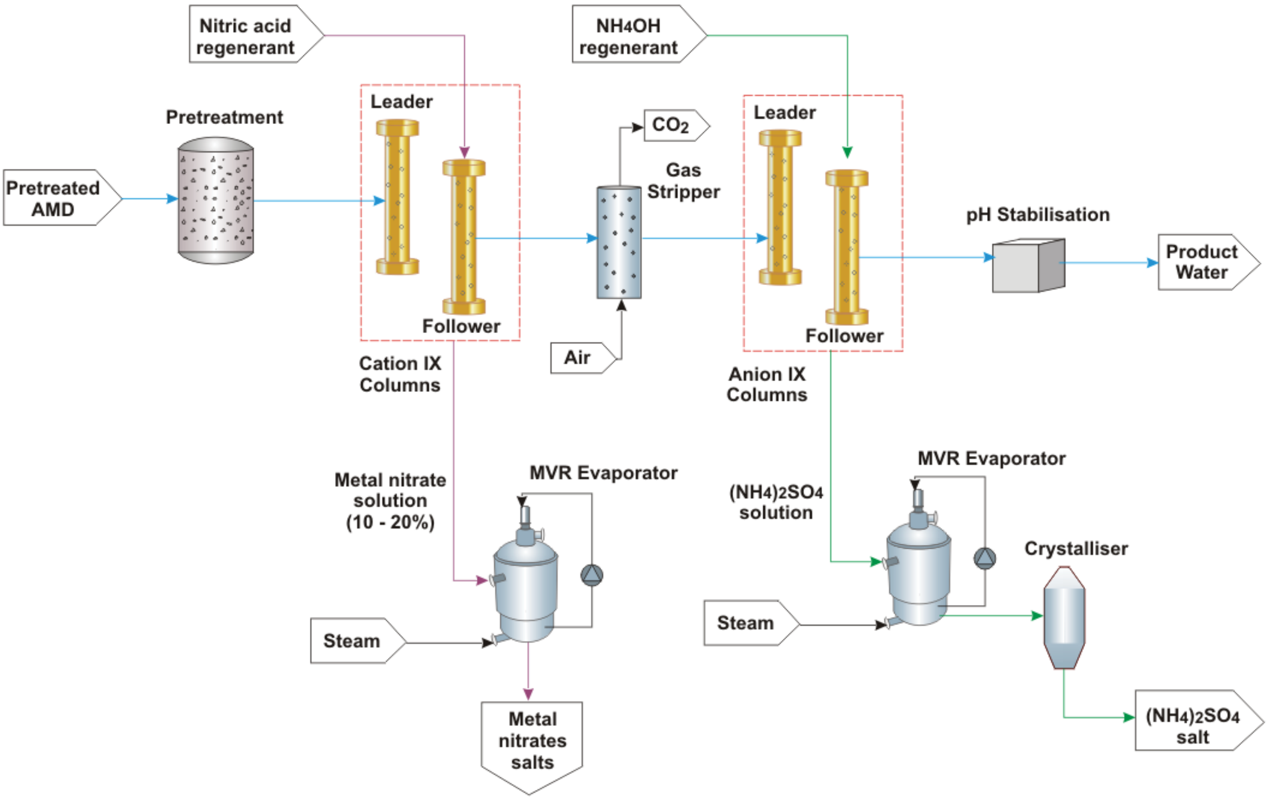


Figure 22: Example of a beneficial by-product recovery ion-exchange process

Figure 23: KNeW pilot facility in Krugersdorp (Bewsey, 2015)

6.4 BIOLOGICAL PROCESSES

The most widely used active treatment process for AMD is based on chemical neutralisation and hydroxide precipitation of metals (Lanouette, 1977; Peters et al., 1985; Veeken and Rulkens, 2003). Chemical treatment is often associated with high chemical costs and large volumes of sludge that must be disposed of (García et al., 2001; Tichý et al., 1998). Sulphide precipitation of metals however offers benefits compared to hydroxide precipitation, such as lower effluent metal concentrations, faster sludge settling rates and the potential to recover valuable metals (Whang et al., 1982; Peters et al., 1985; Boonstra et al., 1999; Jalali and Baldwin, 2000; Veeken and Rulkens, 2003; Aurecon, 2013). Chemical sulphide precipitation has not been widely used for AMD treatment, most likely due to the high cost of chemicals (Lanouette, 1977; van Houten and Lettinga, 1995). Several researchers have investigated the use of biological processes for AMD treatment and metal recovery (for reviews, see Gadd, 1992; White et al., 1995; Mallick, 2002).

Several biological processes can generate alkalinity, which can neutralise (Johnson, 2000). Biological processes include photosynthesis (Robb and Robinson, 1995; van Hille et al., 1999; Johnson, 2000), denitrification (Kalin et al., 1991; Johnson, 1995), ammonification, methanogenesis and reduction of iron and sulphate (Kalin et al., 1991; Johnson, 1995; White et al., 1997; Johnson, 2000). Biological sulphate reduction appears to be the most promising biological process for AMD treatment due to combined removal of acidity, metals and sulphate, and metal recovery (for reviews, see (Hulshoff Pol, et al., 2001; Lens, et al., 2002).

6.4.1 Biological sulphate reduction

Sulphate-reducing prokaryotes (SRP) produce hydrogen sulphide and alkalinity. The metal precipitation reaction releases protons, thus adding to the acidity of the water. The acidity that is generated is neutralised by OH^- or HCO_3^- produced during sulphate reduction. This results in precipitation of metals as hydroxides (e.g. $Fe(OH)_3$) or as carbonates (e.g. $CaCO_3$) and neutralisation of H^+ (Christensen et al., 1996; Dvorak et al., 1992).

The reduction of sulphate to hydrogen sulphide is carried out by anaerobic microorganisms, including the bacteria *Desulfovibrio* and *Desulfotomaculum*. These organisms have a respiratory metabolism in which sulphates, sulphites and/or other reducible sulphur compounds serve as the final electron acceptors, leading to the production of hydrogen sulphide (Chappelle, 1993). The organic substrates for these bacteria are generally short chain acids such as lactic and pyruvic acid. In nature, these short chain substrates are provided through fermentative activities of other anaerobic bacteria on more complex organic substrates (Gould et al., 1994). A wide variety of organic substrates have been investigated for this purpose including molasses, sewage sludge, straw, newspaper, sawdust, manure, silage, and wastes from the food and beverage industry.

Sulphate reduction can be utilised in situ for the treatment of AMD due to the natural occurrence of SRP under anaerobic conditions. Under anoxic conditions, sulphate may be removed from mine waters as stable sulphide precipitates with low solubility (Arnesen, 1991). Flooded underground mine workings and open pits can be anoxic, and as such provide a suitable environment for the implementation of a sulphate reduction system in the presence of an organic substrate. Alternatively, a dedicated reactor can be used or anaerobic conditions created in a passive system, such as a constructed wetland. Sulphate reduction occurs naturally in mine workings as indicated by the presence of sulphides (H_2S odour) in many mine water discharges (Huang and Tahija, 1990).

6.4.2 Constructed bioreactors

Figure 24 illustrates a constructed anaerobic bioreactor that uses bacterial reduction of sulphate and iron to precipitate metals as metal sulphides. During water treatment, a uniform flow rate is required to be effective. The removal of sulphate is dependent on the energy source and residence time (Dill et al., 1994). Product gas can be effectively used as a reliable energy source (Maree et al., 1991; Du Preez et al., 1992).

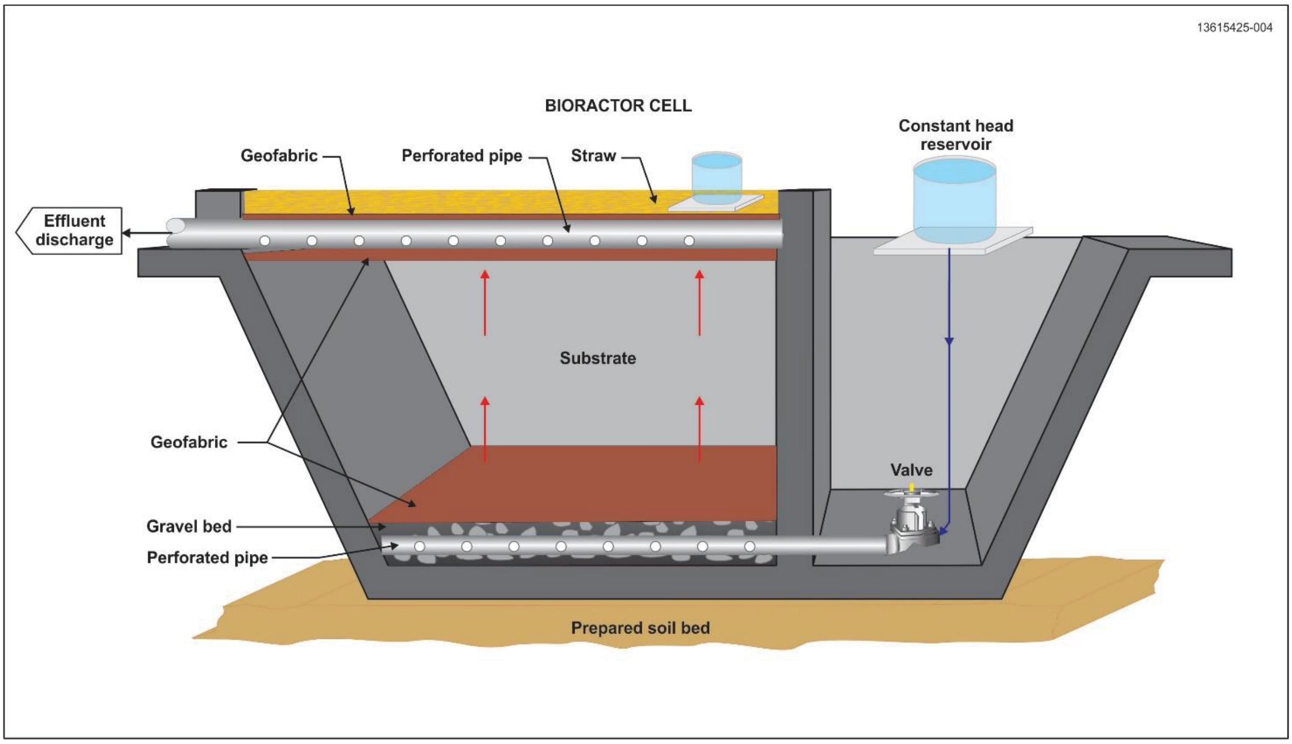


Figure 24: Schematic diagram of an upflow anaerobic bioreactor

6.4.2.1 Paques Technology

Paques commercialised the Upflow Anaerobic Sludge Blanket (UASB) technology (Figure 25) for the anaerobic treatment of wastewater as developed by Lettinga (Lettinga, 2015a; 2015b). This treatment concept enables industrial used water to be purified, and produces renewable energy, fertilisers and soil conditioners. This technology has been widely used by industry and municipalities. Paques BV has been active in the commercialisation of anaerobic technologies since 1980 (Paques, 2015a), and since 1990 also the sulphur technology (Paques, 2015b). The SULFATEQ™ process removes sulphate to less than 300 mg/l and convert it into hydrophilic (non-clogging) elemental sulphur. It also recovers valuable metals such as copper, nickel and zinc as marketable metal sulphides. It is a two-step process (Figure 26). In the first step, sulphate is reduced biologically to dissolved sulphide in high-rate bioreactors. Alcohol or hydrogen gas is used as an energy source. In the second step sulphide is oxidised to elemental sulphur with air and separates it from the liquid. Valuable metals can be recovered.

The first full-scale application for groundwater treatment with SRB was realised in 1992 by Paques BV at the site of Nyrstar Budel BV (Paques, 2015c) (Figure 27). This installation uses an organic energy source (electron donor). For a more concentrated sulphate solution and high load applications, a system with hydrogen gas is preferred (Figure 28).

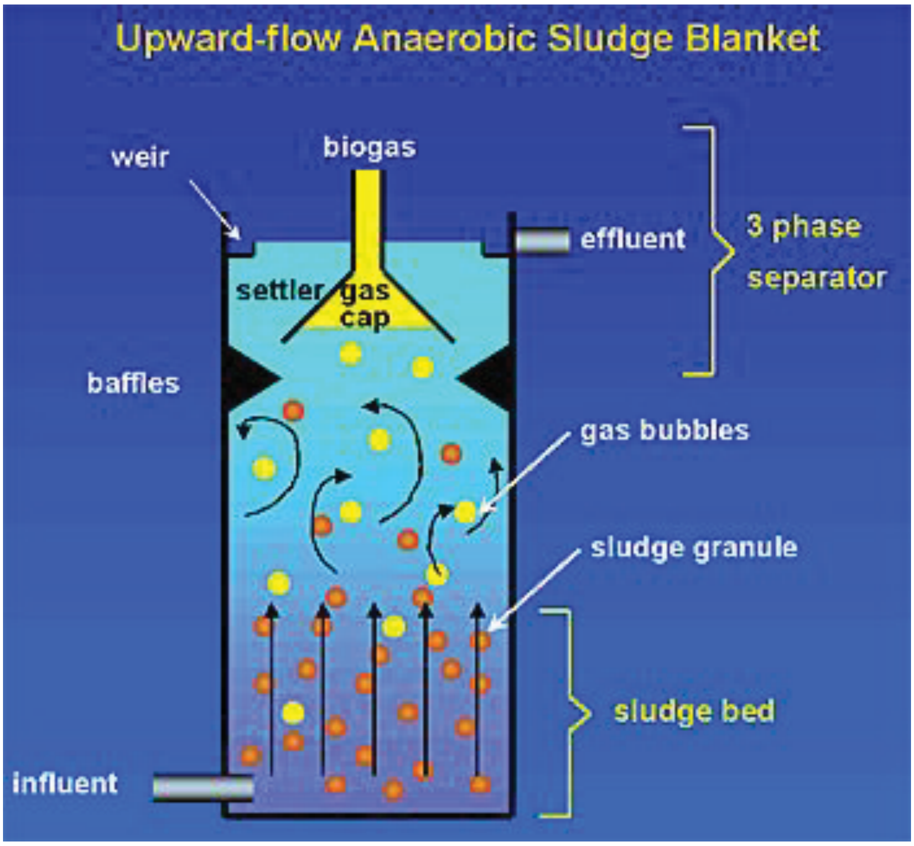


Figure 25: Upflow anaerobic sludge blanket reactor

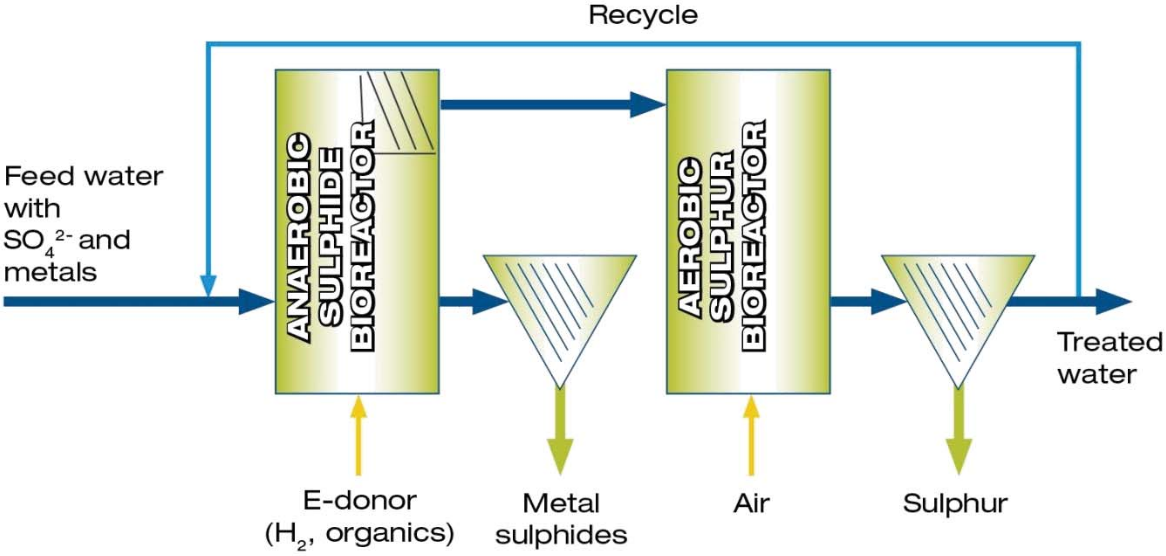


Figure 26: Process configuration of the SULFATEQ™ process

Figure 27: First full-scale biological sulphate reduction installation

Figure 28: Full-scale biological sulphate reduction installation with hydrogen gas as electron donor

In 2002, Anglo Coal contracted Delkor to build a 3 Ml/d biological sulphate removal plant, based on the Paques process for treatment of mine water, at the Navigation Section of Landau Colliery in Witbank, South Africa (Anglo, 2015) (Figure 29). It reduced the sulphate concentration in the mine water from 2300 to 180 mg/l. This plant operated from 2002 to 2005, at which time the energy source became too expensive and the water could be treated at a lower cost at the nearby eMalahleni Water Reclamation Plant.

Figure 29: Biological water treatment plant at Landau Colliery

6.4.2.2 The Rhodes BioSURE® Process

The BioSURE process, developed by the Environmental Biotechnology Group (EBRU) of Rhodes University, was introduced at Grootvlei Gold Mine by ERWAT (East Rand Water Care Company). The BioSURE process uses waste material such as primary sewage sludge as the electron donor source. A 10 Ml/d plant was built. The application of this technology is limited by the availability of sewage sludge or other low-cost organic waste as a source of carbon and energy. A benefit of this technology is that it provides an option for the co-disposal of sewage sludge, reducing the cost of landfilling solid waste (Rose, 2013).

The BioSURE® process exploits the hydrolysis of organic material as a carbon source for biological sulphate reduction with accompanying sulphide production, metal precipitation and alkalinity generation. The process was successfully scaled up to a 10 Ml/d plant located at ERWAT's Ancor waste water treatment works (WWTW) in Springs, Gauteng, treating mine water from Grootvlei Mine utilising primary sewage sludge (PSS) as an electron and carbon donor, with final sulphate concentrations of < 250 mg/l. Integration of the plant with the Ancor WWTW for effluent polishing and access to PSS, as well as access to neutralised MIW from the HDS process at Grootvlei made this a unique application of the technology.

6.4.2.3 *The VitaSOFT Process*

The VitaSOFT process (Joubert and Pocock, 2016) was developed in response to further development requirements that were identified during the development and full-scale demonstration of the Rhodes BioSURE® process. Further work was required to implement the BioSURE process elsewhere, in particular where the MIW has a high acidity, low pH, high concentrations of dissolved metals and a sulphate concentration in excess of 2000 mg/l. One of the disadvantages of BioSURE is its reliance on PSS, which may not always be available, as well as on a continuous supply of iron hydroxide, and the associated disposal requirements for large amounts of iron sulphide sludge. VitaSOFT (Figure 29) addressed these shortcomings and developed a more robust process with broader and more flexible application potential. Maize silage was identified as an alternative carbon source, with advantages over PSS such as long shelf life, a higher percentage biodegradability, and lower nitrogen content.

Sufficient alkalinity could be generated in the biological sulphate-reducing process to neutralise acidic MIW and precipitate contaminating metals as sulphides without the need for an upstream HDS process. Biological iron oxidation was used as a means to regenerate the iron hydroxide required for sulphide removal, so that a constant supply would not be required. Finally, the effluent of the biological sulphate-reducing process could be softened and stabilised by removal of calcium carbonate as magnesium hydroxide, to decrease the salinity of the water in order to meet the final effluent standards for discharge.

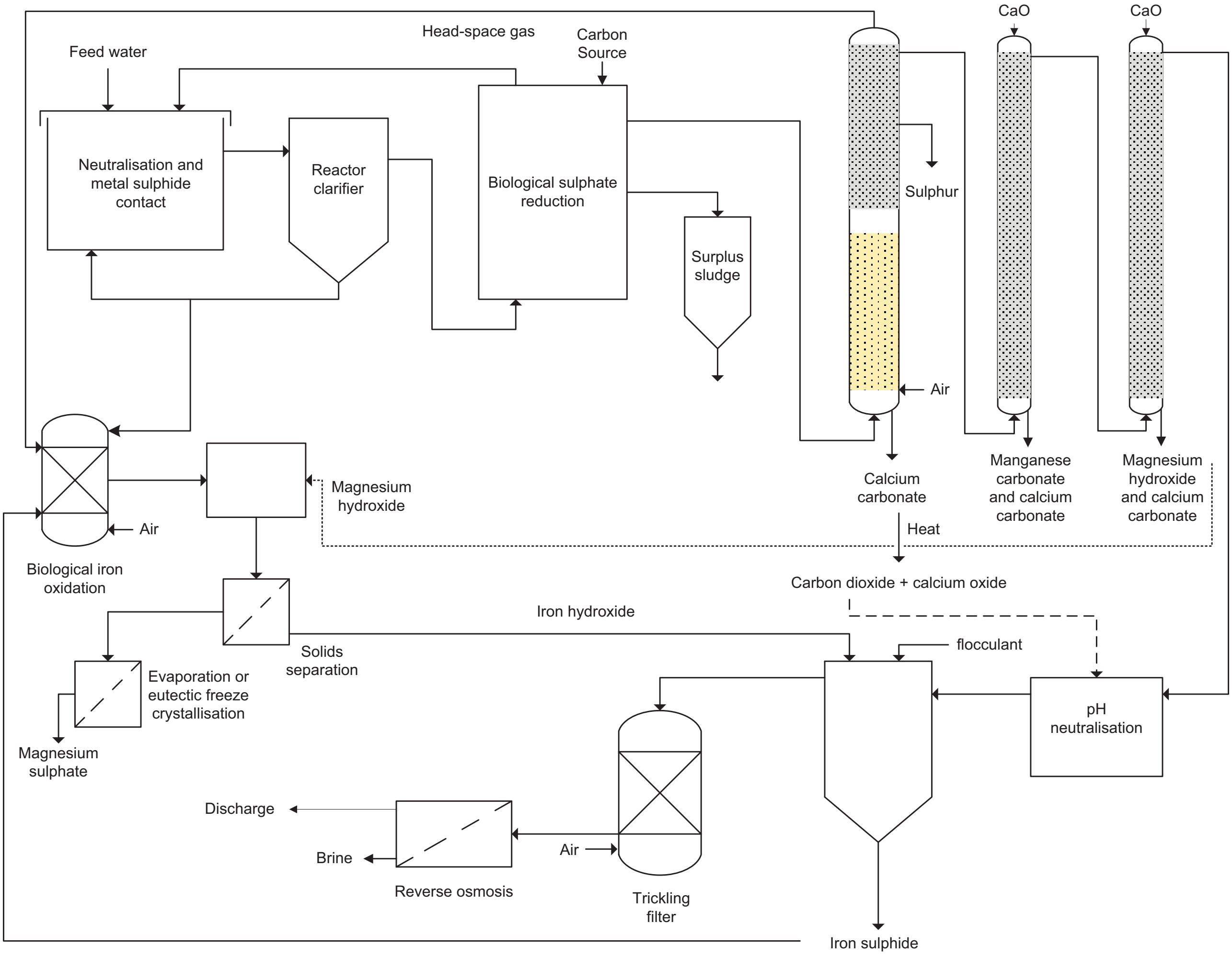


Figure 30: Biological water treatment plant at Landau Colliery

The technology provider (VitaOne8) demonstrated that maize silage was a valid alternative to PSS as a carbon source for biological sulphate reduction (BSR), which can be applied either as a supplementary carbon source where PSS is available, or as a primary source where there are no alternatives. The lower nitrogen content of silage compared with PSS resulted in a lower ammonia concentration in the BSR effluent. The implication of this is that there is no requirement for integration of the process with a WWTW, or for an alternative nitrification/denitrification step. An integrated biological sulphide oxidation reactor was introduced into the process. A substantial portion of the sulphide was removed biologically as elemental sulphur, minimising the requirement for iron hydroxide.

Sufficient alkalinity was generated biogenically between the biological sulphate-reducing and sulphide-oxidising processes to not only neutralise the incoming MIW, but also to precipitate all the calcium in the water as calcium carbonate without the need for lime addition. Lime was only required for the removal of manganese and magnesium in a two-stage process. The cost saving of lime and limestone is therefore two-fold; there is no requirement for an upstream HDS process, and less lime is required for desalination than would typically be required without the contribution of the biogenic alkalinity. Biological iron oxidation was successfully demonstrated as a viable means to regenerate iron hydroxide from iron sulphide.

6.4.3 In situ reactors

Waters rich in sulphate can be treated in situ because SRP occurs naturally. Fixed bed reactors and in-pit reactors have been utilised, but stirred reactors with a suspended solid medium have also been proposed, with the aim of achieving higher reduction rates through improved operating conditions and reactor utilisation (Huang and Tahija, 1990; Arnesen, 1991; Robins, 1997).

6.4.4 Constructed wetlands

Constructed wetlands have been introduced at closed mines in which it is difficult to contain the acid effluent (Machember et al., 1993; Younger et al., 2002). Rees and Bowell (1999) studied the removal of sulphate in a wetland on pilot scale in the Pelenna valley. The design discharge flow rate was 3 l/s at pH 5.6. The total iron content was 21.7 mg/l and the sulphate content was 459 mg/l. Sulphate has decreased over the ten-year period of the project.

6.4.5 Permeable reactive barriers

Acid can be removed from water in an aquifer by passing the water through a permeable reactive barrier (PRB), a reactive zone in which material is introduced so that it can react with the problematic constituents. Examples of such material are limestone for neutralisation, and organic material for biological sulphate removal. Although no specific PRB has been developed for sulphate treatment, reduction in high levels of sulphate in groundwater at an Ontario mine site has been reported (Benner et al., 1999). In this system, a mixture of gravel and compost was used to create a BSR zone that precipitated iron sulphide at a rate of sulphate removal of 14 mg/l/day over a three-year period. A major limitation on the application of such a system is the requirement for stoichiometrically equivalent amounts of reduced metals to sulphide ions in order to limit sulphur dispersion.

Passive systems can be implemented at the foot of a tailing pile or at seeps to intercept a smaller flow of water at the contaminant source. Passive systems can also be used to implement biologically and chemically mediated processes. Little operation and maintenance is required which is advantageous for remote sites.

Many MIWs require removal of acidity, acid generating potential, and/or metals. Passive bioreactor systems promoting sulphate-reducing bacterial activity can mitigate all three of these issues. However, the presence of iron and aluminium in passive bioreactor systems has been problematic due to clogging by Fe and $Al(OH)_3$ precipitates (Zaluski et al., 2006). Clogging of passive bioreactor systems can result in failure long before the organic substrate in the bioreactors has been depleted. Figueroa et al. (2007) investigated a two-stage passive treatment system for effective removal of iron and aluminium, and Hedin et al. (1994) recommend pre-treatment for feed water containing O_2, Fe and Al concentrations above 1 mg/l prior to treatment using wetlands or vertical flow reactors (similar systems in terms of design). One strategy to mitigate the clogging of bioreactors is to pre-treat the water with a limestone drain. The dissolution of limestone results in reactions that consume protons and thus increase both alkalinity and pH, resulting in the precipitation of dissolved iron and aluminium.

Anaerobic passive bioreactor systems have been constructed at numerous sites in the United States and Canada. The success of these systems has varied. The performance efficiency of constructed anaerobic wetlands receiving mine drainage has been observed to vary seasonally and with wetland age (Weider, 1992). Ordonez et al. (2000) were unable to achieve sulphate-reducing conditions in a pilot-scale wetland. A field-scale passive bioreactor constructed in West Fork, Missouri, has effectively removed lead from mine water; however, periodic roto-tilling and back flushing has been required to keep the cells from clogging (Gusek et al., 2000). In addition, trials at sites in Colorado and Wyoming indicate that problems do occur when water at near freezing temperatures is treated in a passive treatment system (Farmer et al., 1995; Reisinger et al., 2000).

Design criteria for passive bioreactor treatment systems are inconsistent, e.g. the specifications for organic substrate, inorganic material fractions and physical, chemical and biological characteristics.

6.5 EVAPORATION-BASED TECHNOLOGIES

Evaporation-based technologies rely on evaporation and subsequent condensation of vapour to produce product water which is low in TDS. The remaining solution contains the concentrated mixed salts and typically requires long-term disposal in brine ponds if it cannot be disposed of to the sea. Evaporation-based technologies are effective at removing all salts, including monovalent salts, such as sodium and chloride, from the water and can produce potable quality water. However, constituents having similar boiling points to that of water are not effectively removed during distillation. Such impurities include many volatile organic contaminants, certain pesticides, ammonia and volatile solvents. These compounds are typically not present in mine water.

Evaporation-based technologies include:

- Multi-stage flash distillation (MFD);
- Multi-effect distillation;
- Rapid spray distillation;
- Mechanical vapour compression/recompression (MVC or MVR);
- DewVaporation;
- Forced evaporation.

6.5.1 Multi-stage flash distillation (MFD)

Multi-stage flash distillation systems have been used commercially for desalination for many years. In the multi-stage flash process, the feed water is pumped through multiple heat transfer units, each of which is maintained at a lower pressure than the previous unit (Figure 31). Vapour generation or boiling caused by reduction in pressure is known as “flashing”. As the water enters each stage through a pressure-reducing nozzle, a portion of the water is flashed to form a vapour. In turn, the flashed water vapour condenses on the outside of the condenser tubes and is collected in trays. As the vapour condenses, its latent heat is used to pre-heat the feed water that is being sent to the main heater, where it will receive additional heat before being introduced to the first flashing stage. When the concentrated water reaches the lowest pressure stage, it is pumped out.

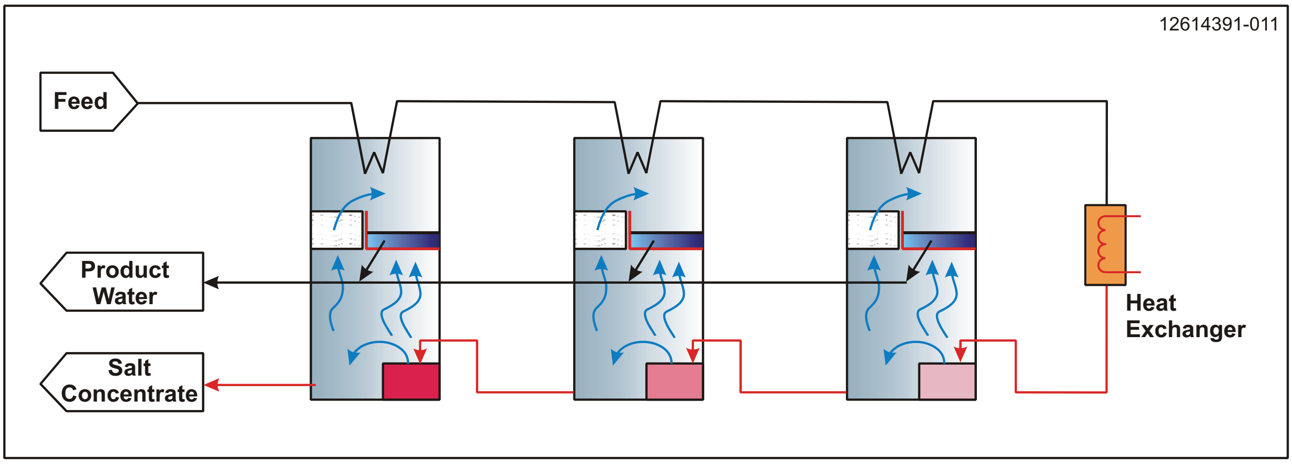


Figure 31: Illustration of a multi-stage flash distillation process

The reuse of the heat of vapourisation from one stage to pre-heat the subsequent stages substantially reduces the overall energy requirement of multi-stage flash distillation compared to single-stage distillation. Pre-treatment may consist of suspended solids removal and de-aeration.

6.5.2 Multi-effect distillation

The multi-effect distillation (MED) process is similar to multi-stage distillation in that it consists of multiple stages. Several boilers are arranged in series, each operating at a lower pressure than the preceding one. In a three-stage vertical tube distiller, after the feed water is pre-heated, it enters the heat exchanger in the last stage and progressively warms as it goes through the heat exchangers in the other stages (Figure 32). As the water moves through the heat exchangers it condenses the water vapour emanating from the various stages. When the progressively warmed feed water reaches the first stage, it flows down the internal periphery of the vertical tubes in a thin film, which is heated by steam. The feed water to the second stage comes from the bottom of the first stage. As for multi-stage flash distillation the reuse of the heat of vapourisation from one stage to pre-heat the subsequent stages substantially reduces the overall energy requirement of multi effect distillation compared to single stage distillation.

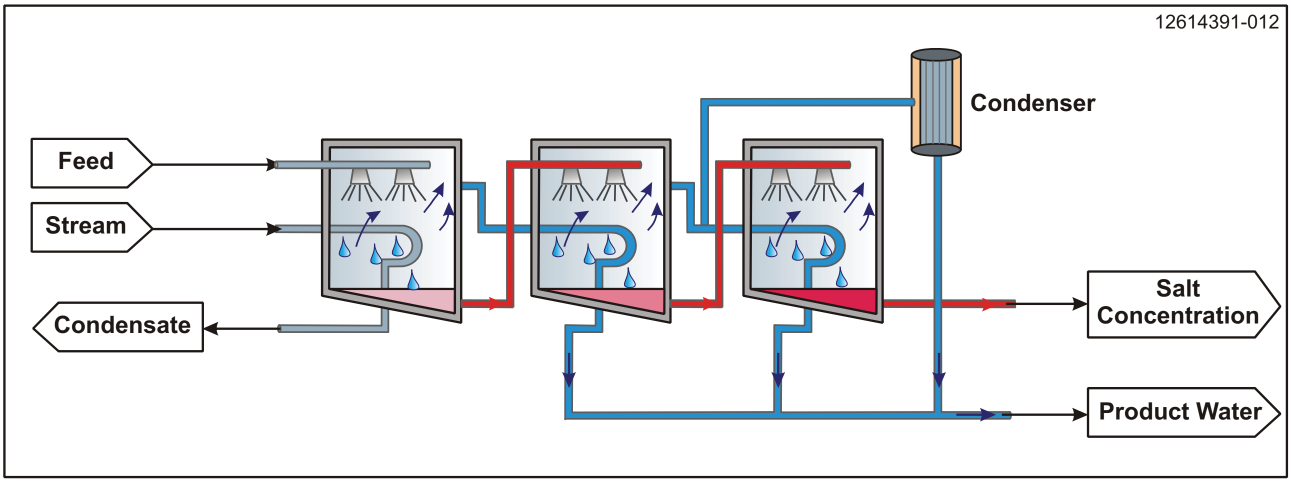


Figure 32: Illustration of a multi-effect distillation process

6.5.3 Rapid spray distillation

Rapid spray distillation is a relatively new technology that uses a rapid spray system to eject salt-contaminated water at high velocities to create water droplets of a specific size and nature (Figure 33). Depending on various parameters, liquid is converted to vapour within milliseconds of ejection, allowing for solids to be flashed or separated from solution. The resulting pure vapour is condensed and collected with 95% recovery.

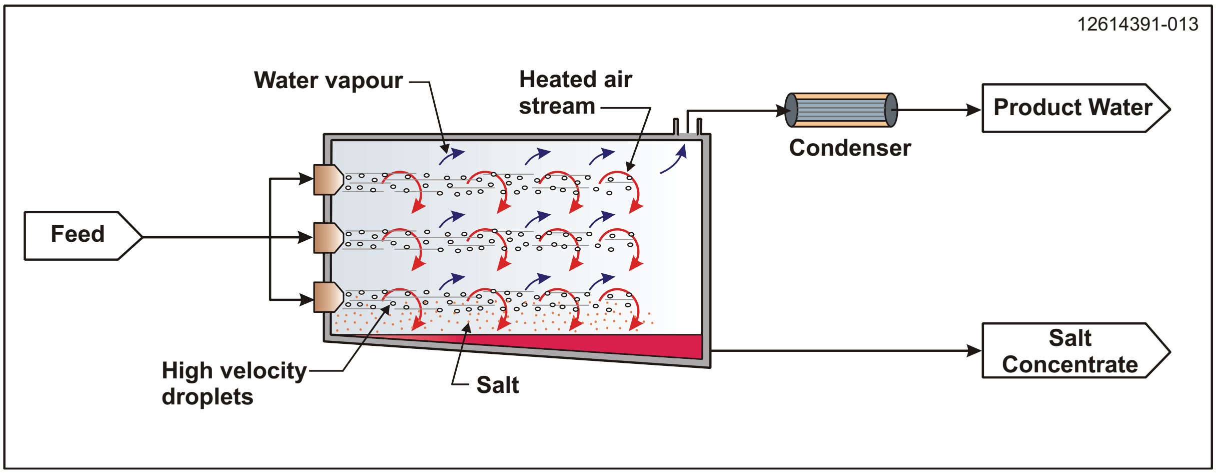


Figure 33: Illustration of a rapid spray distillation process

6.5.4 Mechanical vapour compression

Mechanical vapour compression (MVC) is an evaporation method which uses a compressor to compress, and thus increase, the pressure of the steam produced (Figure 34). Since the pressure increase of the steam also generates an increase in the condensation temperature of the steam, the same steam can serve as the heating medium for the liquid being concentrated from which the vapour was generated. This makes this evaporation method very energy efficient. When this compression is performed by a mechanically driven compressor, the evaporation process is referred to as MVC or MVR (mechanical vapour recompression).

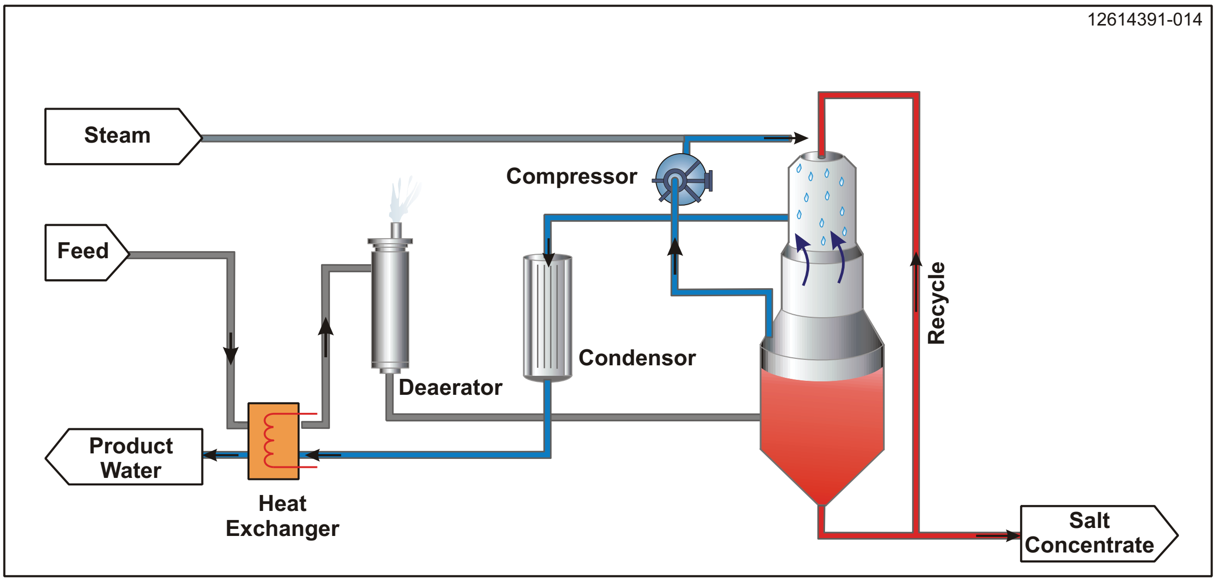


Figure 34: Mechanical vapour compression process

6.5.5 DewVaporation

DewVaporation is a patented process that makes use of waste heat at atmospheric pressures to evaporate water. The general concept is similar to that of multi-stage distillation, as it reuses the heat of condensation to promote evaporation of the incoming stream (Figure 35). However, the process is different from conventional evaporators as temperatures below 100°C are used and evaporation takes place off the surface of the liquid and not from a heated metal surface, thus reducing scaling. Due to the lower temperature, plastic-based construction materials are used, eliminating corrosion problems and lowering costs.

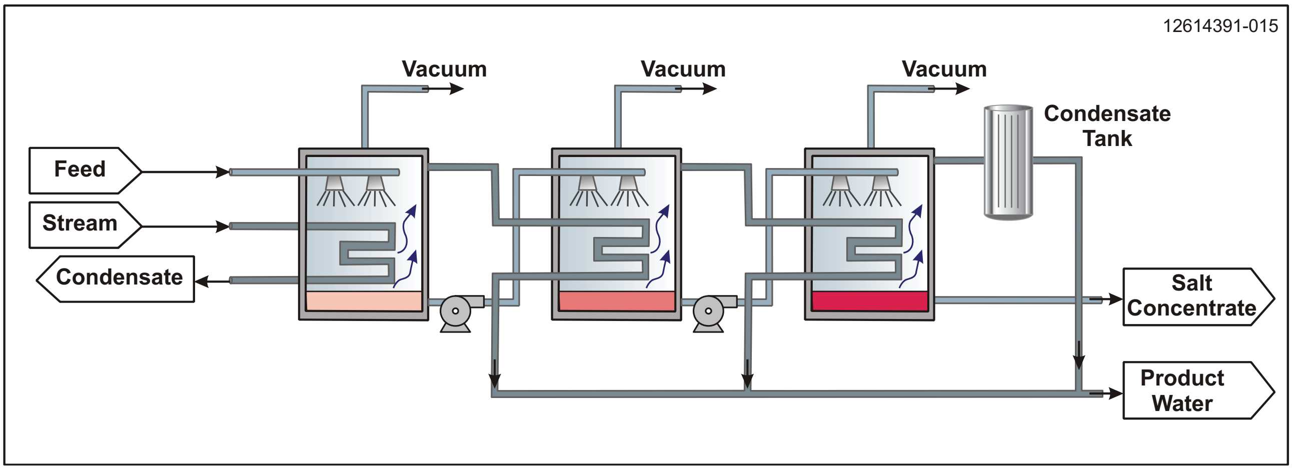


Figure 35: DewVaporation process

6.5.6 Forced evaporation

Evaporation from conventional evaporation ponds is widely used to separate pure water from hazardous waste, and this greatly reduces the volume of waste for further treatment or storage. Convectional pond evaporation systems are driven by heat energy, and with sufficient energy, molecules on the surface will evaporate. The quantity of water that will evaporate in the system will be directly proportional to the net heat absorbed from all sources, less the heat losses. The two most significant sources of heat in forced evaporation are solar radiation and the sensible heat extractable from moving air.

Pond evaporation is usually slow, and is often limited to land availability and the limitations of the cost of constructing additional evaporation ponds and the added cost of clean-up and revegetation (Dama-Fakir and Toerien, 2010). *Forced* evaporation however is currently finding its way into mine water management. It allows for evaporation rates beyond those of traditional approaches such as evaporation ponds and irrigation. The general concept is similar to that of evaporation ponds, except that forced evaporation makes use of a high-pressure water stream and an air fan to push the water through evaporator nozzles to produce fine droplets that will increase the surface area exposed to air, and hence improve evaporation rates as the air stream blows the droplets over the pond.

Most of these evaporators are compact and equipped with fine nozzles, a high-pressure pump and an air fan to give the water droplets enough residence time for evaporation. Mechanical evaporators can offer 70% evaporation rates. The units currently available on the South African market are operating at a 50% evaporation rate, with each unit evaporating approximately 22.5 m^3/h, at an estimated unit cost of R1.70/m^3. Figure 36 shows a picture of mechanical evaporators at a mine closure site.

Figure 36: Mechanical evaporator equipped with a booster pump

The major advantage of the mechanical evaporator is improved evaporation rates due to increased surface area, with the heat energy for evaporation taken from the surrounding air. In many applications, the positive process efficiencies and economic impacts of mechanical wastewater evaporation were outweighed by the potential environmental impacts of spray and salt crystal drift towards adjacent public areas, leading to public concern. Spray drift and off-target salt losses are the inherent problems of conventional air-assisted fine droplet mechanical evaporators. Due to concerns for environmental safety and process efficiency, it is important to maximize the amount of water evaporated and deposited back into the source or target site. A current solution to this is the installation of drift barriers.

An effect of forced evaporation is the concentration of the wastewater, which is likely to require further treatment with other processes as described in previous sections.

Evaporation is energy intensive if dependent on electrical power. In the case of forced evaporation solar energy can be used, but the technique is influenced by the following parameters:

- Humidity of the air;
- Air temperature;
- Water temperature;
- Droplet size;
- Time in the air as vapour;
- Salt content;
- Wind speed;
- Drifting of small water droplets and salt crystals.

6.6 IRRIGATION WITH MINE IMPACTED WATER

Some MIW is acidic but most of it is circumneutral, or, if acidic, it can be neutralised through water-rock interaction. The main limitation of MIW for agricultural use is an undesirable concentration of sulphate salts and metals, chiefly iron, and to a lesser extent, manganese, aluminium and trace elements. The possibilities of irrigating land and producing crops with MIW, primarily after it has been neutralised with lime but also as a form of land treatment in which raw mine water is applied to soils or mine tailings that have been preconditioned with slaked lime or limestone to achieve in situ neutralisation and sequestration of many of the contaminants, have been long explored (van der Laan et al., 2014). Supplementary treatments were also explored using aluminium sulphate and locally mined ferromanganese wad, currently used for uranium recovery in gold mines.

Mine water can be used cost-effectively to irrigate vegetation on mine tailings, or to irrigate salt-tolerant crops such as ryegrass, maize, wheat and soybean on agricultural land. Following irrigation the salts in the water become concentrated and the dominant ions, calcium and sulphate, precipitate as gypsum. About 60% of applied salts are retained within the soil when irrigating with neutralised mine water. Irrigating with neutralised AMD can result in wheat yields of around 9 tonnes/ha and soybean yields of 5 tonnes/ha, when grown in rotation (i.e. the yields do not differ from those obtained while irrigating with surface water). Even under worst case scenarios in which farmers have to pay for the infrastructure to deliver the mine water to their farms, an income of > R240 000/year can still be realised for a 40-hectare farm.

Clay soils and mine tailings have further capacity to retain many of the other salts present in the water. Results from this study indicate that 75%-90% of salts can be removed when raw mine water is applied to mine tailings or clay soils. The use of aluminium sulphate – which works synergistically with lime – as part of the pre-treatment process potentially has several benefits, including smaller, more economical treatment plants.

While RO has been proposed for treating mine water in the Vaal Basin, it is expensive, energy intensive and, like other processes, leaves a saline residue which requires disposal. By contrast, irrigating with chemically treated water enables its immediate productive use. The socio-economic benefits could be far reaching. In addition, South Africa currently is not well positioned to provide electricity for RO or other energy-intensive treatment methods and will need to accept the high carbon footprint indefinitely. A life cycle assessment comparing conventional RO with the irrigation option together with RO of the smaller volumes of irrigation return flows demonstrated significantly lower impacts for the latter option in terms of global warming potential, non-renewable resource (fossil fuel) depletion and acidification potential.

6.7 FREEZING TECHNOLOGIES

When water freezes, it generally forms ice crystals that are pure, leaving behind a more concentrated salt solution. The ice can be separated and allowed to melt to produce a product with low TDS. The removal of water from the brine results in an equilibrium shift within the solution, resulting in salts crystallising out of the solution. Since ice is less dense than water and brine, it floats to the surface, while the denser salt crystals settle to the bottom. The pure water (ice) and salt crystals can be separated according to density.

Freezing water involves the use of only about one sixth of the energy required to evaporate water, since the heat of fusion for ice is six times less than the heat of evaporation. In addition, the temperature change required is generally in the region of 20-30°C to freeze water from room temperature, whereas to boil it requires a temperature change of 70-80°C. Freezing-based technologies can therefore be more energy efficient than evaporation-based technologies. These include:

- Eutectic freeze crystallisation;
- Hybrid ice technology.

6.7.1 Eutectic freeze crystallisation

The eutectic temperature is the temperature at which a solute crystallises out of solution when cooled to that temperature. For a specific feed water quality profile, the various salts have unique eutectic temperatures, and at a temperature of -25°C all salts within the solution crystallise (Figure 37). At the same time water crystallises for removal as ice.

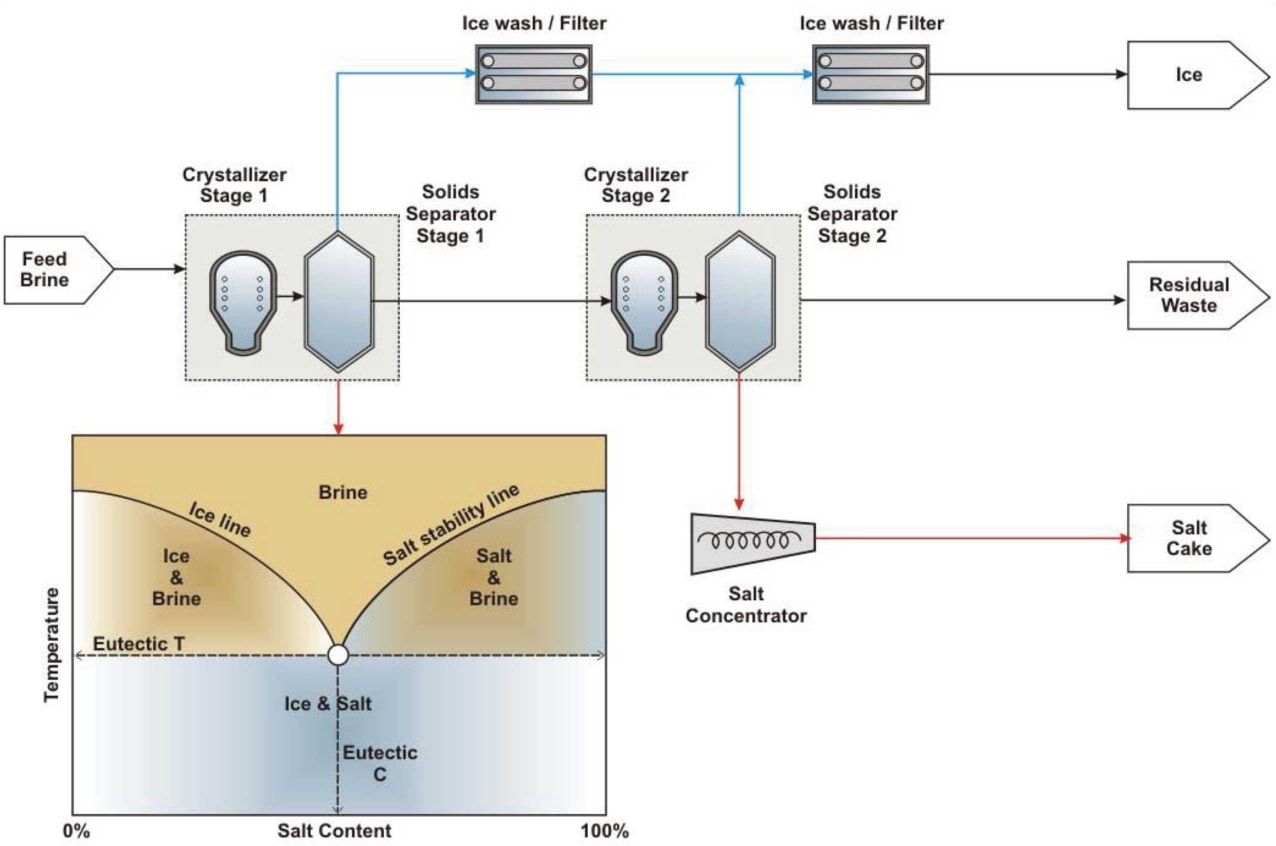


Figure 37: Eutectic freeze crystallisation

When employing multiple units, this process enables the recovery of numerous relatively pure salts from a brine mixture as well as low TDS water. In order to improve efficiency, a fluidised bed-type configuration is sometimes used in the freezing/crystallisation section, with low energy settling sections away from the fluidised zone for the removal of ice and salt crystals respectively. The salt crystals may become included within, or entrained with, the ice crystals and not always separate effectively in the settling zones. This can result in the carry-over of a portion of salt, and thus the water recovered in the form of ice may not meet drinking water standards. It will however be of a quality that can be returned to the feed stream of a typical mine water treatment plant.

6.7.2 Hybrid Ice technology

The waste heat produced in the cooling step is used in a vacuum evaporator to evaporate the concentrate, leaving behind a concentrated waste salt. With the HybridICE process, a mixed salt is recovered. In the case of mine water, this is not likely to be saleable and would need to be disposed of at a hazardous waste facility.

6.8 EMERGING TECHNOLOGIES

A number of emerging technologies which fall outside of the categories described so far are presented below. Although these may result in lowered water treatment costs, they may still produce brine that requires responsible disposal:

- Forward osmosis desalination;
- Carbon nanotube desalination;
- Biomimetic desalination using Aquaporin proteins;

- Nano-electrochemical processes;
- Sludge processing.

6.8.1 Forward osmosis desalination

Forward osmosis (FO), an alternative membrane process, has the potential to produce high quality water. FO is a technical term describing the natural phenomenon of osmosis: the transport of water molecules across a semi-permeable membrane (Lutchmiah, et al., 2014). An osmotic pressure gradient is the driving force. A draw solution, which is of higher concentration than the feed, will allow for the flow of water across the membrane into the draw solution, causing the feed water and its solutes to separate. Because RO makes use of hydraulic pressure to drive the separation, as opposed to osmotic pressure used in FO, significantly more energy is required for RO compared to FO. Free from energy input other than from the ambient environment, FO relies on water molecules passively diffusing by natural osmosis into the draw solution, whose volatile draw salt is then evaporated by low-grade heat (Figure 38). One such process is the ammonia-carbon dioxide FO process originally developed at Yale University (McCutcheon et al., 2005; McGinnis, 2009). Because ammonia and carbon dioxide readily dissociate into gases using heat, the draw solutes can effectively be recovered and reused in a closed loop system.

FO is still perceived as a “pre-treatment” process. To prompt FO-wastewater feasibility, the focus lies with new membrane developments, draw solutions to enhance wastewater treatment, energy recovery, and operating conditions.

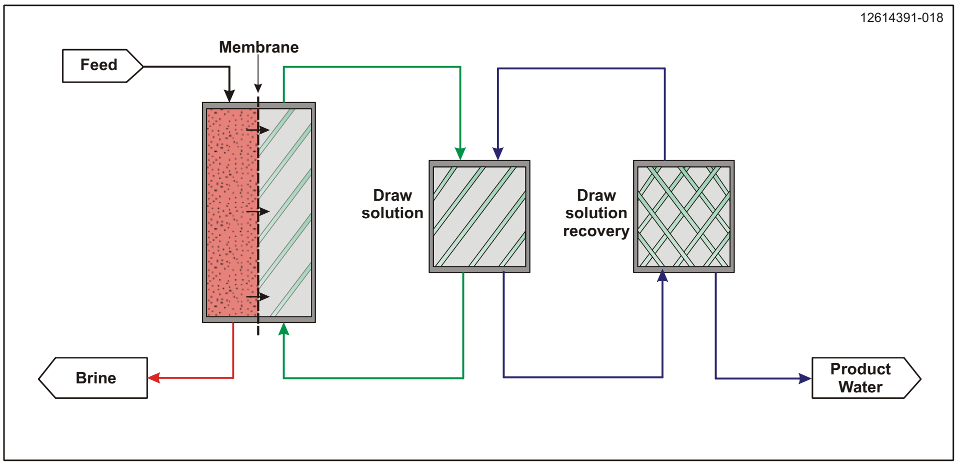


Figure 38: Forward osmosis desalination

6.8.2 Carbon nanotube desalination

Well-aligned carbon nanotubes can serve as robust pores in membranes for water desalination and decontamination applications (Elimelech and Phillip, 2011). An electric charge at a nanotube mouth repels positively charged salt ions which in turn withhold the ionically bonded partner anion. The hollow carbon nanotube structure provides frictionless transport of water molecules, and this makes it suitable for the development of high fluxing separation techniques. Appropriate pore diameters can constitute energy barriers at the channel entries, rejecting salt ions and permitting water through the nanotube hollows. The uncharged water molecules slip through on a resistance differential, greatly reducing the required pumping pressure (Figure 39). It is also possible to modify carbon nanotube pores to selectively sense and reject ions. Thus, carbon nanotube membranes can be used as 'gate keepers' for size-controlled separation of multiple pollutants.

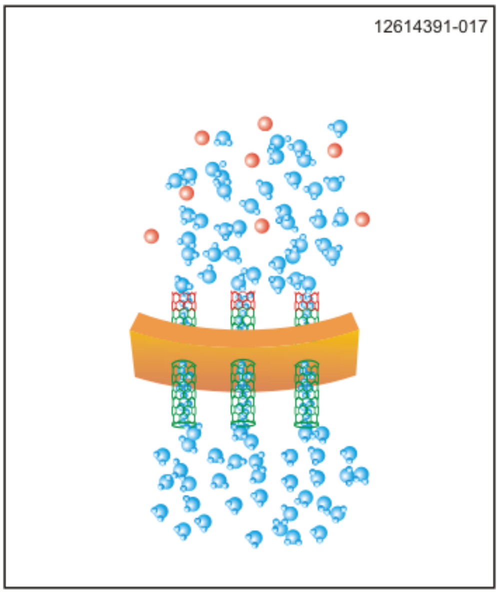


Figure 39: Illustration of the carbon nanotube desalination process

6.8.3 Biomimetic desalination using aquaporin proteins

Aquaporin is a protein found in most living cells. Its unique structure allows water molecules to penetrate the cell wall, while excluding other molecules based on size, shape and electrostatic charge (Figure 40). Scientists have synthesised this protein and are in the process of manufacturing membranes with similar characteristics. An aquaporin membrane will enable the desalination of high TDS waters at lower pressures than required by current RO membranes. The Aquaporin Inside™ membrane became commercially available in 2015.

6.8.4 Nano-electrochemical processes

A patented electrolytic process for treatment of MIW has been developed and used successfully for the removal of arsenic and cyanide since 2008 (Zeevy et al., 2015). Sulphate and metals are removed through the formation of crystalline metallic nanoparticles. The electrolysis takes place in the reactor on an electrode surface and within the flowing water. The reactors contain several individual electrolytic cells that combine modular cathodes and anodes. These are defined according to the type and concentration of the contaminants in the wastewater, and the pH.

This technology has been tested at pilot scale at Sibanye Gold Mine. Samples collected from the Western and Central Basins were treated successfully for removal of metals, including uranium and sulphate, to produce water of drinking quality.

This technology offers the following benefits:

- Pre-treatment may not be required (depending on the volume and quality of feed to be treated, and the desired product water quality);
- Little sludge is produced and the sludge may be recyclable (depending on its constituents);
- No brine is produced;
- Uranium removal to less than 5 ppb may be achieved (again, depending on the volume and quality of feed to be treated, and the desired product water quality).

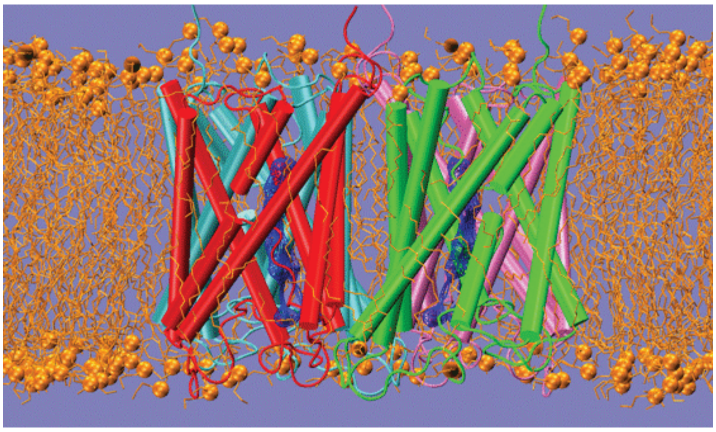


Figure 40: Illustration of membrane containing aquaporin

Figure 41: Pilot plant at Sibanye Gold

6.8.5 Sludge processing

Saleable products may be recovered from the sludge produced by several of the processes discussed in previous sections. During neutralisation with limestone and/or lime, a sludge rich in gypsum and metal hydroxides is created. Saleable products such as sulphur, $CaCO_3$ and metals can be recovered by regeneration.

The economic viability of several of the desalination processes is dependent on the recovery of process raw materials. Some examples are:

- Gypsum is produced as a by-product in the HiPRO® process and used in construction.
- In the barium sulphate precipitation process, $BaCO_3$ is regenerated from $BaSO_4$, or the $BaSO_4$ is sold as drilling mud. Other saleable products include sulphur and $CaCO_3$.
- In the SAVMIN™ process, $Al(OH)_3$, gypsum (which can be used for fertiliser, cement and wallboard production and as a filler for road construction) and $CaCO_3$ are produced as by-products.
- In the KNeW process, by-products, $NaNO_3$ and $(NH_4)_2SO_4$, may be sold to cover the cost of the raw materials, HNO_3 and NH_4OH.

Gypsum by-products may be thermally reduced to other saleable products such as sulphur and $CaCO_3$ (Maree and Theron, 2005; Nengovhela et al., 2007; Mbhele et al., 2009). Barium sulphate may also be converted to barium sulphide and sulphur in a similar process (Masukume et al., 2013). The chemical processing of barium sulphide into barium carbonate, for recycling within the process and elemental sulphur for sale, has been demonstrated on a pilot scale in batch mode.

CHAPTER 7: CONCLUSIONS

This review has shown that several water treatment options are available for the treatment of mine water. Many of these options have not been evaluated on mine water. Being risk averse, and with water treatment not being the core focus in the mining industry, the typical trend would be to replicate existing technologies. It is envisaged that a formal tool and risk assessment approach would assist the industry in selecting an appropriate technology, based on the site-specific needs in going forward.

This study showed that a combination of technologies needs to be considered in order to achieve maximum environmental protection at affordable cost. Affordability is a key factor since water treatment needs to be applied by all mine water users. The environment does not benefit if only a portion of the mine water is treated to a good quality and the balance is only neutralised or not treated at all. For this reason, water treatment technologies were divided into the following categories:

1. Neutralisation;
2. Desalination;
3. Evaporation;
4. Brine/sludge treatment.

It was concluded that neutralisation with $CaCO_3$/lime is recommended if there is a need to remove metals to below toxic concentrations as well as to achieve partial desalination due to gypsum crystallisation. Desalination needs to be applied if treated water is to be used for drinking or industrial purposes. Nano-filtration and RO are used for desalination in full-scale applications. Ion exchange is also a proven technology to consider. Chemical and biological desalination can be used for treatment of water low in monovalent ions. In the case of NaCl-rich waters chemical desalination needs to be combined with ion exchange or membrane processes for final “polishing”. Desalination using biological processes will find application where biological energy sources are available at low cost. Passive treatment systems can be used in applications where small volumes of water, in remote areas, which are not heavily polluted, need to be treated. Brine and sludge can be treated using freeze desalination and thermal processes.

Pumping of mine water has a huge influence on the cost of mine water treatment. Keeping water at deeper levels through pumping has the following effects:

(i) The quality of mine water deteriorates because of prolonged contact with pyrites-rich rock strata.

(ii) A larger volume needs to be pumped due to the lower back-pressure had mine water levels been higher. Further studies need to be carried out to determine the optimum depth at which underground mine water levels need to be kept through pumping. In the case of future mining, pumping is required. In the latter case the focus should be on how mine water needs to be treated to recover products such as sulphur (from sulphate), $CaCO_3$, magnetite and valuable metals.

The risk table shows that neutralisation with limestone and lime is the most cost-effective form of pre-treatment. This is due to low cost and partial desalination through gypsum crystallisation that has a long track record. More emphasis needs to be placed on the use of $CaCO_3$ so that it is not only used for neutralisation of acidity, but also for removal of Fe^{2+}, the main dissolved component in many MIWs. For desalination, the risk table shows that membrane treatment offers the lowest risk but in many cases the highest energy demand and operational cost. Since MIW amounts to less than 4% of the volume of surface water into which it is discharged, all MIW that is not treated using an active process should be concentrated through evaporation or used for irrigation, rather than be discharged untreated. This will avoid further salination of surface water.

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APPENDIX A – WATER QUALITY ANALYSES REQUIRED.

Ideally, one would recommend at least a year's worth of monthly water quality data. Analysing for the following constituents is recommended.

Physical and organoleptic parameters

Colour

Colour measurements on water are carried out on filtered samples. Colour can be an indication of contamination by natural minerals, such as ferric hydroxide, or organic substances such as humic acid or algae. This can be analysed for on the first sampling round and a second random sampling round.

Odour

Odour in water is often as the result of volatile organic compounds in the water. The Threshold Odour Number method was used to determine the odour. This can be analysed for on the first sampling round and a second random sampling round.

Total dissolved solids

Total Dissolved Solids (TDS) is an indication of the ions in the water. It serves as a useful value to confirm that the major contaminants in the water are being analysed for. The sum of the concentrations of individual anions and cations measured should be approximately equal to the measured TDS value. A significant difference can indicate that some anions or cations in the water are not being analysed for.

Conductivity

Conductivity is the ability of water to conduct an electric current. It is sensitive to variations in dissolved solids, mostly mineral salts. The conductivity levels correlate to the TDS readings. Conductivity can be measured on site and compared to the reading obtained from the laboratory.

pH, alkalinity and acidity

The pH value is an indication of the acid (H^+) / alkali (OH^-) balance of a solution. Acidity and Alkalinity are the base and acid neutralising capacities of the water. The pH value does not correlate to the acidity or alkalinity concentrations of the water. In the case of mine water, the acidity is linked to the metal concentrations (typically iron, manganese and aluminium) in the water. Alkalinity is typically linked to the concentration of carbonate, bicarbonate and hydroxide in the water. Water with a low acidity or alkalinity has a low buffering capacity and is susceptible to changes in pH.

Macro-determinants

Nitrogen compounds, Ammonia, Nitrate and Nitrite

Ammonia occurs naturally in water bodies, arising from the breakdown of nitrogenous organic and inorganic matter in soil and water. In mining, it can also be linked to explosives used. Substantial loss in ammonia is possible through volatilisation with an increase in pH above 9.

Organic nitrogen compounds in the water can lead to fouling on the membranes. The organic nitrogen compounds in the water should be taken into consideration in the selection of the membranes.

Phosphate

Phosphorus in the water can, together with the nitrogen compounds, lead to fouling of membranes through the stimulation of biological growth. Sources of phosphorous can include domestic waste water, weathering of phosphorous bearing rock and fertilisers.

Calcium

Calcium is a divalent ion, readily dissolved from rocks rich in calcium minerals. Calcium was monitored on a monthly basis.

Sodium

Sodium is a highly soluble monovalent ion. The monovalent ions will not be removed in the pre-treatment phase.

Chloride

Chloride, like sodium, is a monovalent ion and cannot be removed in pre-treatment processes.

Fluoride

High fluoride concentrations in the water combined with calcium ions can lead to calcium fluoride scaling on the membranes. Fluoride concentrations were well below the SANS 241 Class 1 Standard.

Magnesium

Magnesium can be successfully removed by the RO process or precipitated as magnesium hydroxide in the pre-treatment process.

Potassium

Potassium is a monovalent ion and relatively low concentrations of potassium were found in the samples monitored. Potassium found in wastewater generally arises from industrial waters and rocks containing potassium are relatively resilient to weathering.

Sulphate

Sulphate concentrations in AMD from coal mining operations are typically high. Sulphates can be removed in pre-treatment steps, biological processes and desalination processes.

Zinc

High zinc concentrations in the water can lead to fouling or scaling on the membranes.

Silica

High silica concentrations are undesirable for the RO process due to the risk of scaling associated with silica. The combination of lime and magnesium hydroxide in the pre-treatment step as well as the antiscalants used in the process should prevent scaling.

Micro-determinants

Metals

Metals, including aluminium, antimony, arsenic, cadmium, chromium, cobalt, copper, iron, manganese, nickel, selenium and vanadium can lead to fouling or scaling on membranes.

Cyanide

Cyanide concentrations were monitored due to the high toxicity to humans and the possibility of industrial wastewater contamination if these are found in the area.

Organic determinants

Dissolved organic carbon

The DOC concentrations were monitored to provide an indication of organic matter in the water being treated. High concentrations of organic matter can lead to algal growth in the clarifiers and on the membranes. The pre-treatment process must effectively reduce the DOC concentrations to acceptable levels.

Escherichia coli (*E*. *coli*)

E. coli concentrations are an indication of faecal contamination in the water. Very low *E. coli* concentrations are expected in the mine water.

Heterotrophic plate count.

The heterotrophic plate count is an indication of general bacteria in the water, although these bacteria are not necessarily harmful to humans.

SANS 241 Water Quality Standard

Analysis Type	Parameters	Units	SANS 241:2006 Class I
Physical & Organoleptic Requirements	Colour	mg Pt/ℓ	< 20
	Cond.	mS/m	< 150
	Diss. Solids	mg/ℓ	< 1000
	Odour	TON	< 5
	pH	-	5.0-9.5
	Taste	FTN	< 5
	Turbidity	NTU	< 1
Macro-determinants	NH_3	mg N/ℓ	< 1.0
	Ca^{2+}	mg Ca/ℓ	< 150
	Cl^-	mg Cl/ℓ	< 200
	F^-	mg F/ℓ	< 1.0
	Mg^{2+}	mg Mg/ℓ	< 70
	NO_3^-	mg N/ℓ	< 10
	K^+	mg K/ℓ	< 50
	Na^+	mg Na/ℓ	< 200
	SO_4^{2-}	mg SO_4/ℓ	< 400
	Zn^{2-}	mg Zn/ℓ	< 5.0
Micro-determinants	Al^{3+}	µg Al/ℓ	< 300
	Sb	µg Sb/ℓ	< 10
	As	µg As/ℓ	< 10
	Cd	µg Cd/ℓ	< 5
	Cr	µg Cr/ℓ	< 100
	Co	µg Co/ℓ	< 500
	Cu	µg Cu/ℓ	< 1000
	CN_{free}	µg CN/ℓ	-
	$CN_{recov.}$	µg CN/ℓ	< 50
	Fe	µg Fe/ℓ	< 200
	Pb	µg Pb/ℓ	< 20
	Mn	µg Mn/ℓ	< 100
	Hg	µg Hg/ℓ	< 1
	Ni	µg Ni/ℓ	< 150
	Se	µg Se/ℓ	< 20
	V	µg V/ℓ	< 200
Organic Determinants	DOC	mg C/ℓ	< 10
	THM	µg/ℓ	< 200
	Phenols	µg/ℓ	< 10

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