Series H: Hierarchy Guidelines







H4

BEST PRACTICE GUIDELINE

Water Treatment

Best Practice Guidelines for Water Resource Protection in the South African Mining Industry

DIRECTORATE: RESOURCE PROTECTION & WASTE

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This document is the fourth in a series of the following Hierarchy Best Practice Guideline documents:

BPG H1: Integrated Mine Water Management

BPG H2: Pollution Prevention and Minimization of Impacts

BPG H3: Water Reuse and Reclamation

BPG H4: Water Treatment

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Since 1999 a number of steering committee meetings and stakeholder workshops were held at various stages of the development and drafting of this series of Best Practice Guidelines for Water Resource Protection in the South African Mining Industry.

We are deeply indebted to the steering committee members, officials of the Department of Water Affairs and Forestry and stakeholders who participated in the meetings and stakeholder workshops held during the development of the series of Best Practice Guidelines for their inputs, comments and kind assistance.

The Department would like to acknowledge the authors of this document, as well as the specialists involved in the process of developing this Best Practice Guideline. Without their knowledge and expertise this guideline could not have been completed.

APPROVALS

This document is approved by the Department of Water Affairs and Forestry

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Date: 20/08/2007

PREFACE

Water is typically the prime environmental medium (besides air) that is affected by mining activities. Mining adversely affects water quality and poses a significant risk to South Africa's water resources. Mining operations can further substantially alter the hydrological and topographical characteristics of the mining areas and subsequently affect the surface runoff, soil moisture, evapo-transpiration and groundwater behaviour. Failure to manage impacts on water resources (surface and groundwater) in an acceptable manner throughout the life-of-mine and post-closure, on both a local and regional scale, will result in the mining industry finding it increasingly difficult to obtain community and government support for existing and future projects. Consequently, sound management practices to prevent or minimise water pollution are fundamental for mining operations to be sustainable.

Pro-active management of environmental impacts is required from the outset of mining activities. Internationally, principles of sustainable environmental management have developed rapidly in the past few years. Locally the Department of Water Affairs and Forestry (DWAF) and the mining industry have made major strides together in developing principles and approaches for the effective management of water within the industry. This has largely been achieved through the establishment of joint structures where problems have been discussed and addressed through co-operation.

The Bill of Rights in the Constitution of the Republic of South Africa, 1996 (Act 108 of 1996) enshrines the concept of sustainability; specifying rights regarding the environment, water, access to information and just administrative action. These rights and other requirements are further legislated through the National Water Act (NWA), 1998 (Act 36 of 1998). The latter is the primary statute providing the legal basis for water management in South Africa and has to ensure ecological integrity, economic growth and social equity when managing and using water. Use of water for mining and related activities is also regulated through regulations that were updated after the promulgation of the NWA (Government Notice No. GN704 dated 4 June 1999).

The NWA introduced the concept of Integrated Water Resource Management (IWRM), comprising all aspects of the water resource, including water quality, water quantity and the aquatic ecosystem quality (quality of the aquatic biota and in-stream and riparian habitat). The IWRM approach provides for both resource directed and source directed measures. Resource directed measures aim to protect and manage the receiving environment. Examples of resource directed actions are the formulation of resource quality objectives and the development of associated strategies to ensure ongoing attainment of these objectives; catchment management strategies and the establishment of catchment management agencies (CMAs) to implement these strategies.

On the other hand, source directed measures aim to control the impacts at source through the identification and implementation of pollution prevention, water reuse and water treatment mechanisms.

The integration of resource and source directed measures forms the basis of the *hierarchy of decision-taking* aimed at protecting the resource from waste impacts. This hierarchy is based on a precautionary approach and the following order of priority for mine water and waste management decisions and/or actions is applicable:

RESOURCE PROTECTION AND WASTE MANAGEMENT HIERARCHY

Step 1: Pollution Prevention

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Step 2: Minimisation of Impacts
Water reuse and reclamation
Water treatment

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Step 3: Discharge or disposal of waste and/or waste water
Site specific risk based approach
Polluter pays principle

The documentation describing **Water Resource Protection and Waste Management** in South Africa is being developed at a number of different levels, as described and illustrated in the schematic diagram on this page.

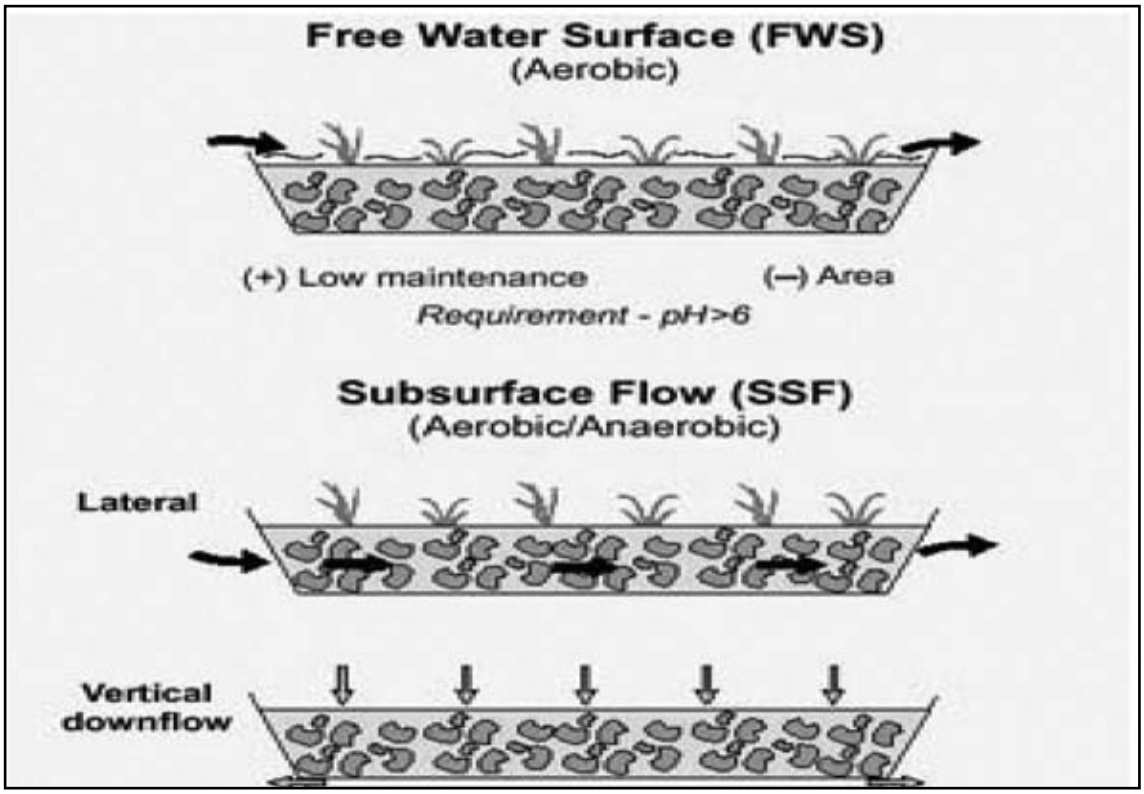
The overall Resource Protection and Waste Management Policy sets out the interpretation of policy and legal principles as well as functional and organisational arrangements for resource protection and waste management in South Africa.

Operational policies describe the rules applicable to different categories and aspects relating to waste discharge and disposal activities. Such activities from the mining sector are categorised and classified, based on their potential risks to the water environment.

Operational Guidelines contain the requirements for specific documents e.g. licence application reports.

Best Practice Guidelines (BPG's) define and document best practices for water and waste management.

Schematic Diagram of the Mining Sector Resource Protection and Waste Management Strategy



The DWAF has developed a series of Best Practice Guidelines (BPGs) for mines in line with International Principles and Approaches towards sustainability. The series of BPGs have been grouped as outlined below:

BEST PRACTICE GUIDELINES dealing with aspects of DWAF's water management HIERARCHY are prefaced with the letter H. The topics that are covered in these guidelines include:

- H1 Integrated Mine Water Management
- H2 Pollution Prevention and Minimisation of Impacts
- H3 Water Reuse and Reclamation
- H4 Water Treatment

BEST PRACTICE GUIDELINES dealing with GENERAL water management strategies, techniques and tools, which could be applied cross-sectoral and always prefaced by the letter G. The topics that are covered in these guidelines include:

- G1 Storm Water Management
- G2 Water and Salt Balances
- G3 Water Monitoring Systems
- G4 Impact Prediction

BEST PRACTICE GUIDELINES dealing with specific mining ACTIVITIES or ASPECTS and always prefaced by the letter A. These guidelines address the prevention and management of impacts from:

- A1 Small-scale Mining
- A2 Water Management for Mine Residue Deposits
- A3 Water Management in Hydrometallurgical Plants
- A4 Pollution Control Dams
- A5 Water Management for Surface Mines
- A6 Water Management for Underground Mines

The development of the guidelines is an inclusive consultative process that incorporates the input from a wide range of experts, including specialists within and outside the mining industry and government. The process of identifying which BPGs to prepare, who should participate in the preparation and consultative processes, and the approval of the BPGs was managed by a Project Steering Committee (PSC) with representation by key role-players.

The BPGs will perform the following functions within the hierarchy of decision making:

- Utilisation by the mining sector as input for compiling water use licence applications (and other legally required documents such as EMPs, EIAs, closure plans, etc.) and for drafting licence conditions.
- Serve as a uniform basis for negotiations through the licensing process prescribed by the NWA.
- Used specifically by DWAF personnel as a basis for negotiation with the mining industry, and likewise by the mining industry as a guideline as to what the DWAF considers as best practice in resource protection and waste management.
- Inform Interested and Affected Parties on good practice at mines.

The information contained in the BPGs will be transferred through a structured knowledge transfer process, which includes the following steps:

- Workshops in key mining regions open to all interested parties, including representatives from the mining industry, government and the public.
- Provision of material to mining industry training groups for inclusion into standard employee training programmes.
- Provision of material to tertiary education institutions for inclusion into existing training programmes.
- Provision of electronic BPGs on the DWAF Internet web page.

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1 INTRODUCTION AND OBJECTIVES

The implementation of integrated water and waste management (IWWM) at a mine may, in many instances require the incorporation of a certain degree of water treatment. Water treatment may be required to improve the quality of the water to such an extent that it can be reused by the mine or other users (***BPG H3: Water reuse and reclamation***). Water treatment may also be required as a final step to render water suitable for discharge in accordance with the conditions of a water use authorisation, catchment management objectives, reserve requirements and/or downstream user requirements.

The basis of IWWM at mines is the DWAF water quality management hierarchy of decision-making. This hierarchy is based on a precautionary principle and sets the following order of priority for mine water and waste management decisions and/or actions:

Pollution Prevention (BPG H2)

↓

Minimisation of Impacts (BPG H2)

↓

Water Reuse or Reclamation (BPG H3)

↓

Water Treatment (BPG H4)

↓

Discharge or Disposal of Waste

The treatment of water is thus included as the fourth step in the water management hierarchy set out by DWAF. It is also important to note that ***discharge/disposal should not be considered by the mine and will not be allowed by DWAF unless all prior steps in the water quality management hierarchy have been considered and applied.***

Water treatment is a consideration for exploration, operational and defunct/closed mines, although the water treatment technology of choice may be different (e.g. active treatment during operation versus passive treatment after closure). This Best Practice Guideline (BPG) only serves as an overview of possible water treatment options and does not aim to discuss all the various water treatment alternatives available at any point in time, in detail. New treatment technologies are continuously being developed and existing technologies are improved and this guideline is therefore not fully comprehensive and can therefore not replace the function of a water treatment specialist familiar with the latest technologies available on the market.

As stated previously, it is not the intention or objective of this BPG to provide a detailed discussion on water treatment methods here but rather to provide sufficient information to assist with the decision-making procedure for selecting an appropriate treatment method taking account of all the relevant factors that can influence such a decision.

Close inspection and evaluation of a mine's water and salt balance (***BPG G2: Water and salt balances***) will indicate that there is scope for water treatment wherever the following features are found:

- Where the implementation of pollution prevention, minimisation of impacts and water reuse/reclamation strategies do not result in zero discharge. Thus water containing waste is discharged/disposed and there is a need to further reduce the pollution load from the mine and minimise the mine's impact.
- Wherever significant water quality related problems (e.g. corrosion, scaling, biofouling, etc.) are experienced by mine water users, due to the reuse of process water.
- Wherever significant water quality related problems are experienced by downstream water users and the source(s) of the water quality deterioration can be ascribed to the mine.

It is important to emphasize that any water treatment option must take account of the changing water and salt balance (*BPG G2: Water and salt balances*) over the life cycle of the mine and that it must therefore be sustainable, flexible and capable of accommodating the relevant changes.

The objectives of this BPG are:

- To clearly describe the technical methodology that should be applied by a mine to identify the constituents of concern that may require mine water to be treated to enable sustainable reuse or discharge (in accordance with an approved water use licence, catchment management objectives etc.).
- To describe a methodology that, when applied, will enable the identification of suitable types of water treatment technology for the removal of constituents of concern and safe disposal of residues (brine and sludge management) thereafter.
- To enable the mine to prepare the relevant sections of an IWWM plan that deals with water treatment.

This document is of particular importance:

- Where a mine can impact on the water environment (discharge/disposal).
- To motivate for closure by stipulating post-closure water treatment methodology before discharge.
- In any event where government (DWAF) may have an interest in water treatment on a mine due to its responsibility for water resources and its protection. This will assist DWAF to track and ensure that a logical process/methodology was followed to select water treatment methods.

This document does not consider water treatment within the mine's processing operation, internal water treatment such as underground settlers, thickeners etc. though similar principles can be applied for these as well.

The deliverable resulting from the process/procedure suggested in this BPG can thus be incorporated into the IWWM plan and documents in which an IWWM plan is required (EIA/EMPR/Closure plan) but can also be used in a water use licence application. In a water use licence application, it can be used by the mine to motivate why a treatment plant is required and/or why a particular treatment method was selected. This will be in the following water use licence applications pertaining to Section 21 of the National Water Act (Act 36 of 1998):

- (e) Engaging in a controlled activity identified as such in section 37(1) or declared under section 38(1).
- (f) discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit.
- (g) disposing of waste in a matter which may detrimentally impact on a water resource.
- (h) disposing in any manner of water which contains waste from, or which has been heated in, any industrial or power generation process.

Where a long-term water discharge is predicted, it will be important to show that adequate financial provision has been made by appropriate means for water management/ treatment when motivating for closure of a mine.

Collection and treatment can be considered to be the last remaining option if neither the source nor the pathway can be sufficiently controlled to protect the receptor.

2 KEY CONSIDERATIONS OF WATER TREATMENT

Mine water contamination generally falls into the following categories in terms of effect on the environment:

- Acidity and low pH;
- Dissolved metals (Fe, Mn, Al, As, Cr, Cu, Co, Ni, Zn, Hg, Pb, etc);
- Radionuclides (U, Ra, Th, Po, etc);
- Turbidity/suspended solids;
- Salinity (Na, K, Ca, Mg, Cl and SO_4);
- Nutrients (Ammonia, Nitrate, Phosphate);
- Oxygen demand (organics);
- Aesthetics.

2.1 Treatment Processes

The processes available for removal of these abovementioned constituents can be divided into two broad categories:

- Active systems; and
- Passive systems.

The decision between active or passive treatment processes depends on a number of factors and these are detailed in Section 5.1.

2.2 Evaluation of Treatment

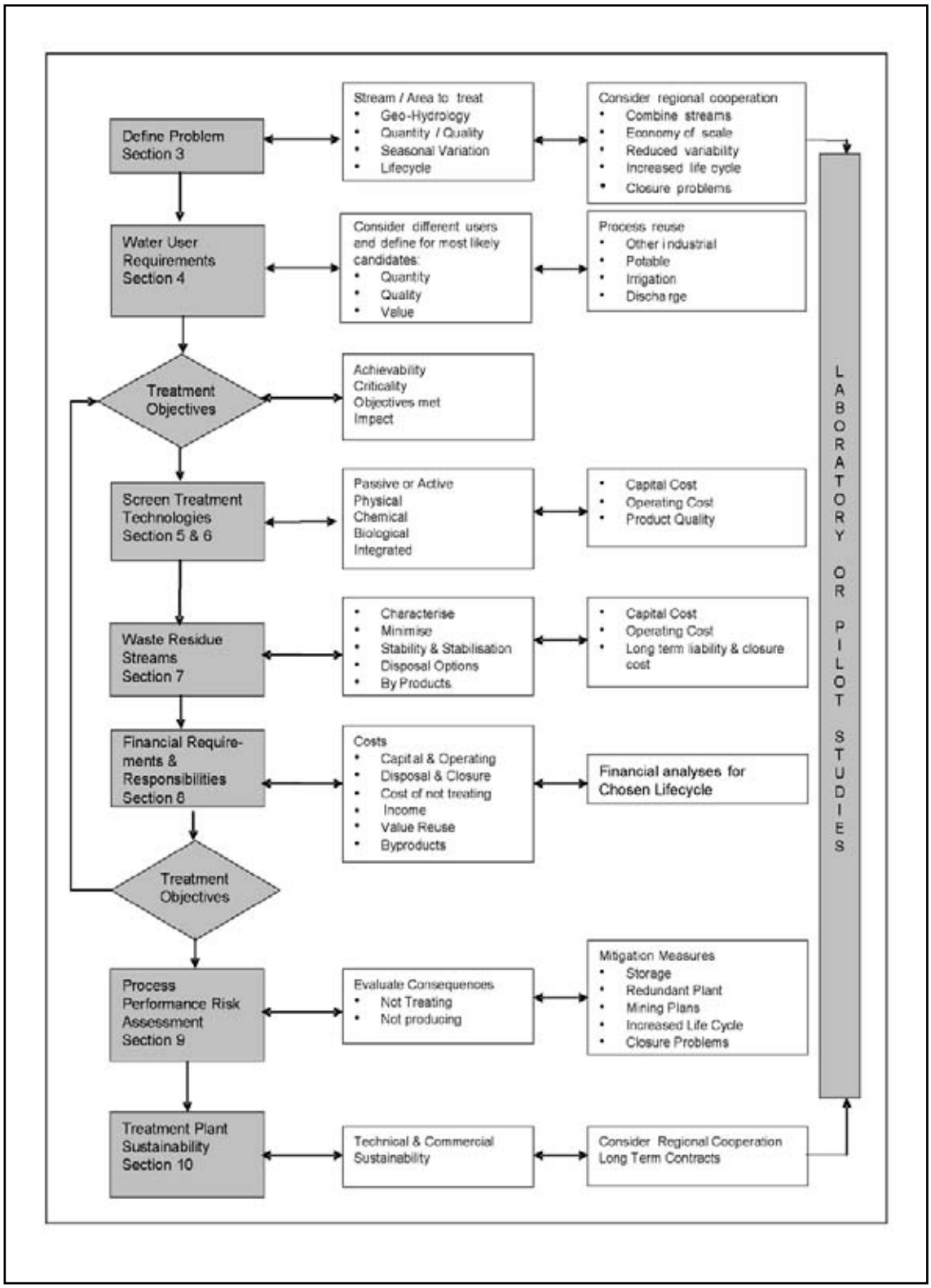
The end products of mine water treatment will be treated water, which may have a varying degree of remaining contamination, and some form of solid residue or sludge. The efficiency of a treatment process can be considered in terms of:

- the chemistry of the product water, whether it requires a further polishing stage or is suitable for reuse or perhaps discharge to a receiving water course;
- the nature of the sludge, its volume, toxicity/hazard potential, long-term stability, disposal requirements (Section 7); and
- whether any marketable products can be recovered from the treatment process to offset against costs, for example recoverable metals or potable water that can be sold.

A list of performance criteria to use in the evaluation and comparison of water treatment options for use is provided below.

- Applicability - raw water quality or key constituents of concern.
- Performance criteria in terms of whether objectives are achievable, volumes can be managed etc.
- Process efficiency and final water quality requirements.
- Plant reliability (achieving objectives) and life expectancy.
- Process principle.
- Critical design features and structure.
- Risk management.
- Water recovery and balance.
- Treatment and disposal of residues of process.
- Control systems.
- Previous successful implementation/examples (pilot scale or full scale).
- Environmental and social impact.
- Operating and investment/capital costs.
- Personnel requirements and training.
- Expansion possibilities.
- Legal requirements (licences, etc.).

Figure 2.1: Water treatment plant evaluation and selection process



2.3 CONSIDERATIONS

It is important that the selection of a water treatment process is done after careful, informed consideration of the abovementioned process criteria, as an incorrect process may have a significant negative environmental and economical impact. A water treatment selection process should follow a structured procedure as set out in Figure 2.1. This process is a logical process that has been applied in many applications and a recent and very pertinent case study is described in a technical paper that is included as Appendix E.

The following key considerations should be applied in the selection, design and implementation of water treatment options.

1 Define areas/streams earmarked for treatment in terms of water quantity and quality.

2 Define water user requirements - key constituents of concern (quality) for the affected water users of treated water.

3 Pre-screening: Identify potential water treatment technologies by assessing what the current situation is and what the desirable future scenario is.

4 Define water treatment technology requirements - critical parameters (flow patterns/volumes and constituents of concern) that may affect the performance of the potential water treatment technology in terms of their current status and anticipated future changes.

5 Define waste streams in terms of quantity and quality (e.g. brines and sludges), from the water treatment technology. Incorporate the safe disposal and management of these wastes into the overall water treatment and management strategy.

6 Define operational, maintenance and funding requirements as well as responsibilities for the water treatment technology and the waste management systems for the full design life of the technology.

7 Define the consequences of failure or reduced performance of the water treatment plant on the subsequent/downstream users of the treated water through a risk assessment. Identify appropriate measures to manage these consequences.

8 Define and consider sustainability of the water treatment plant and options over the mine's life cycle. It may be desirable to plan for different types of water treatment technologies at different stages in the mine's life.

9 Undertake appropriate laboratory and/or pilot studies where uncertainty exists with regard to the performance of the identified water treatment technology, its sensitivity to feed water or operational changes and the quantity and quality of its waste streams, to generate the required information.

To assist in the application, a number of components have been defined for each key consideration as presented below.

2.3.1 Areas/streams earmarked for treatment (Section 3)

- Define the problem by defining areas or streams identified for possible treatment.
- May include streams that cannot be reused on the mine property in terms of locality or water quality (*BPG H3: Water Reuse and Reclamation and BPG G2: Water and Salt Balances*).
- Assess streams earmarked for treatment in terms of water quality and quantity.
- Water quality and quantity records over a 5-year period are desirable (*BPG G3: Water monitoring*).
- The water and salt balance (*BPG G2: Water and salt balances*) will assist in highlighting areas/streams to be considered for treatment.
- Understand the impact of future developments on the mine in terms of water volume and quality
- Consider the implications when the mine changes from an operating to a closed mine

2.3.2 Water user requirements (Section 4)

- Define water quality related problems that are being (or will in future be) experienced by the affected water users within the mine or users downstream of the mine (including the aquatic environment), also considering applicable water resource quality objectives.
- Define constituents in the water responsible for the water quality problems experienced (constituents of concern).
- Ensure that the definition of constituents of concern is based on a reliable data record (see *BPG G3: Water monitoring*).
- It is important to also consider predicted future requirements of users (see Chapter 10 on sustainability).

- Based on an understanding of the user requirements and consideration and incorporation of appropriate safety factors, define the water quality objectives for the treated water.

2.3.3 Potential water treatment technologies (pre-screening) (Section 5)

- Consider all options, opportunities and constraints.
- Determine whether active or passive treatment processes are more appropriate based on the period within the mine life-cycle where the treatment is required.
- Determine most appropriate water treatment technologies available based on the constituents of concern (Chapter 6 and Appendix E).
- Select water treatment technologies for further investigation based on their proven reliability, etc.
- Most important considerations for treatment technology selection include wastewater characteristics (raw water), objectives (user requirements) and cost.

2.3.4 Water treatment technology requirements (Section 6)

- Establish current and future flow/volume profiles for the water to be treated (raw water) in terms of average flows/volumes, maximum and minimum flows/volumes and rate of change in flow/volume where significant variations can be expected.
- Establish current and future concentrations of key constituents of concern/interest from the perspective of the water treatment technology, i.e. which constituents could have a significant effect on the performance of the water treatment technology. These constituents could be different to those that are of concern to the water users (e.g. strontium may be a concern to a desalination plant that has an operating objective of reducing sulphate concentrations).
- Ensure that the definition of current constituents of concern is based on a reliable data record (see *BPG G3: Water monitoring*) that covers the expected range in variation of these constituents.
- Ensure that future predictions for the constituents of concern that affect the quality of the feed water are reliable over the same time period as the design life of the treatment plant and that the predictions have been made using accepted prediction techniques (BPG G4: Impact prediction).

2.3.5 Waste/residue streams (Section 7)

- Identify all potential waste streams associated with the water treatment technology (e.g. brines and sludges).
- Characterise waste streams in terms of quantity, environmental impacts and risks, etc. over the entire design life of the water treatment plant.
- Seasonality should be considered to prevent washout of for example precipitates in wetlands.
- Define any potential effects that may arise from the mixing of different waste streams.
- Identify legislation other than the National Water Act (NWA), regulatory measures and other requirements that are applicable to disposal and/or management of waste streams during the feasibility stage.
- Identify appropriate waste disposal and/or management options (including monitoring systems) for all the waste streams.

2.3.6 Financial requirements and responsibilities (Section 8)

- Define operating and maintenance procedures and responsibilities for the proposed water treatment and waste management options for all phases of the mine life cycle, including post-closure.
- Ensure that the capital, operating and maintenance costs are clearly defined for all the life cycle phases and that funding and management responsibilities are clearly defined, particularly for post-closure treatment and waste management requirements.

2.3.7 Process performance risk assessment (Section 9)

- Define possible situations that could result in significantly reduced efficiency or failure of the treatment plant with a resultant significant reduction in the quality of the product water (e.g. very high inflow rates not allowing sufficient retention time).
- Define the consequences to users of such process upsets (e.g. resulting poorer water quality may increase scaling or render water unsuitable for a particular use).
- Define appropriate measures that could be designed into the treatment plant, or implemented as and when needed, that will adequately manage the consequences of the process upsets.

2.3.8 Treatment plant sustainability (Section 10)

- Define the water treatment requirements over the various life cycle phases of the mine, incorporating predicted future changes as identified in terms of Consideration 2.
- Different types of treatment technology may be applicable at different stages of the mine's life cycle.
- Specifically define the post-closure water treatment requirements and define appropriate water treatment and waste management options to cater for the anticipated maintenance, operating and funding situation after mine closure.

2.3.9 Laboratory/pilot studies to address uncertainties (Section 11)

- Wherever there is significant uncertainty with regard to the product water or waste stream characteristics, implement appropriate laboratory scale and/or pilot scale studies to define the characteristics.
- Wherever there is significant uncertainty with regard to the ability of the proposed water treatment options to adequately deal with feed water changes (quantity and quality) and potential process upsets, implement appropriate laboratory scale and/or pilot scale studies to define the response of the water treatment options.
- Wherever pilot studies are undertaken, ensure that they are operated in a manner consistent with the anticipated full-scale plants.
- Bench or pilot-scale testing is commonly conducted in order to determine the ability of a particular process to cope with feed water and achieve treatment objectives. However, the efficiency of a full-scale plant is extremely difficult to predict, even after pilot testing, due to the highly variable quantity and quality of most mine effluents and management actions.

2.3.10 Regional treatment plants

- Evaluate the economy of scale benefits of regional water treatment options where effluents from a number of mines within a defined region are pumped to a central point for treatment.
- Evaluate the potential benefits of mixing various streams from various mines to make a combined stream that is more treatable than the individual streams
- Consider the benefits and/or pitfalls of a regional treatment plant in terms of shared funding responsibilities, surety of supply of product water, minimised environmental footprint and cost of environmental and regulatory permitting issues

The application of the above considerations is presented in detail in the following chapters (Sections 3 to 11) of this BPG and a very recent and relevant case study is presented in Appendix E.

3 AREAS/STREAMS EARMARKED FOR TREATMENT

The aim of the water treatment selection process is to select a treatment process that will address the identified problem adequately and the importance of defining the problem correctly can thus not be underestimated. The process to define the problem starts with the plant or mine audit and the following should be undertaken:

- Pollution prevention: Implement all possible pollution prevention strategies and measures (also see *BPG H2: Pollution Prevention and BPG G1: Storm Water Management*). This will include the separation of clean and dirty water systems.
- Minimisation of impacts: Where complete pollution prevention is not possible, ensure that all management measures are in place to minimise impacts on the surrounding environment, especially water resources.
- Water reuse and reclamation: Evaluate water reuse and reclamation strategies (see *BPG H3: Water reuse and reclamation*), which consider water sources, mine water uses, the water reticulation system and the possibility of linking the particular water sources and water uses effectively. During this process, areas or streams, which might require treatment in order to become a water source, would have been identified. Streams requiring treatment would thus include those water sources available but of an inferior quality to allow reuse, discharges etc. Streams requiring treatment may also include those that cannot be reused due to their location on the mine property and restrictions within the reticulation system.
- Contaminant loads: Determine water and contaminant load for the mine (refer to *BPG G2: Water and salt balance*). This will assist in determining areas/streams to be considered for treatment. It is important to define the water targeted for treatment in terms of water quantity and quality.
- Water characterisation: A detailed specification and characterization of the water to be treated (raw or feed water) is required in terms of quality (key constituents of concern) and quantity (flow/volume) data with statistics (minimum, maximum, average, rate of change/ variation). Monitoring (*BPG G3: Water Monitoring*) would assist with defining the water quantity and quality. Records over a five-year period are desirable (minimum of 1 year) to characterise water and use for future predictions (*BPG G4: Impact Prediction*). In the absence of reliable data, the most conservative data or assumptions available (worst-case scenario) should be used for treatment process identification. Long-term variation of the water in terms of quantity or quality should also be considered.
- Source characterisation: To obtain a conceptual understanding of the raw water quality and its key constituents of concern, a clear definition of the source of the contaminated water is required. Geochemical analysis and modelling can assist in this regard (see *BPG G4: Impact Prediction*). For example, water contaminated by pyrite-rich ore will require different treatment than water contaminated by radioactive ore. The source may also dictate the type and period of treatment required. For example, acid mine drainage from a closed mine will require a different treatment strategy and period of treatment than water discharged from an operational mine. Geochemical characterisation of the waste/source materials is required to determine pollution generating potential. Hydrological and geohydrological studies are required to determine the origin, quantity, extent and period for which the problem will exist into the future.
- Mine phases: The potential pollution risk of the waste/source material should be quantified throughout the mine life and different phases of mining (exploration and planning, commissioning, operation, decommission and closure, post-closure).

- Consultation with stakeholders: The problem should also be defined in consultation with all the relevant stakeholders. Related issues should be brought to the fore and the aim should be to address as many issues as possible with an integrated solution for the mine or even the catchment area or region. This will assist in optimising the money invested by for example preventing duplication and the implementation of a number of smaller similar treatment processes, each requiring its own infrastructure and personnel. The input and contribution of the relevant stakeholders at this early stage will also assist in gaining the acceptance and backing from the stakeholders in later phases of the process. As it is important throughout the water treatment selection process to keep the target end users in mind, stakeholder consultation will ensure that the target end users are involved in the process from an early stage.

4 WATER USER REQUIREMENTS

Certain water quality related problems such as scaling (due to the presence of for example high sulphate concentrations) may currently or at some point in the future be experienced by the users of the treated water. Water quality related problems is directly linked to the constituents of concern and differ depending on the user of the water, reference should be made to the Water Quality Guidelines as set for different users by DWAF. Different water users may experience different problems relating to the same water quality. It is important that water be treated to the specification applicable to the specific use it is targeted for.

Users of treated water may be quite diverse and their requirements could therefore also be. Possible users of treated water include:

- Water users at the mine - See *BPG H3: Water Reuse and Reclamation.* This may include direct reuse/reclamation (within the same unit process) or reuse in another unit process or plant on the mine property.
- Surrounding industries - The water may be obtained by the industry indirectly via downstream abstraction if the mine discharges the treated water into a stream or directly via the mine's reticulation system as part of a regional scheme.
- Agricultural users - The water may be used for irrigation and obtained by the farm indirectly via downstream abstraction if the mine discharges the treated water into a stream or directly via the mine's reticulation system as part of a regional scheme.
- Domestic or potable users - The water may be obtained by the user indirectly via downstream abstraction if the mine discharges the treated water into a stream or directly via the mine's reticulation system as part of a regional scheme.
- Aquatic ecosystem and environment - The water discharged by a mine after treatment reaches the aquatic ecosystem. The National Water Act, 1998 (Act 36 of 1998) puts high priority on the protection of this water user.

For water that is to be reused/reclaimed within the mine, a clear definition of the water quality requirements of the mine water use must be prepared. This will consider constituents that may interfere with the performance of mine processes or with product quality or yield. For water that is to be discharged to the natural water resource (e.g. watercourse), the available dilution (or assimilative capacity) of the resource must be understood in order to determine the resultant water quality at the downstream water user. The conditions stipulated in the mine's water use licence for discharges should therefore be adhered to as downstream user requirements and the capacity of the resource would have been considered in setting the discharge conditions. When discharging, consideration should also be given to the reserve/catchment water quality objectives, which take account of the downstream user requirements.

From the water quality problems that are experienced by mine water uses or downstream users, one can determine the constituents within the water responsible for these problems. The identification of constituents of interest/concern in waste streams will also indicate whether different waste streams can be combined. Once mine or downstream user requirements have clearly been defined, the water quality objectives for the treatment process can be defined through consideration and incorporation of appropriate safety factors (also refer to Sections 6 and 9). A detailed specification of water quality objectives/targets (minimum, maximum, average, 95th percentiles and other statistical data) required to be met by the treatment process is needed.

It is important that the constituents of interest/concern be determined based on a reliable data record over an extended period (BPG G3: Water Monitoring) and in consultation with the water users (mine and downstream) through consideration of the water quality related

problems experienced by the users. The treated water quality objectives will represent water that eliminates/ reduces the problems experienced by the water users to an acceptable level considering their requirements and specific use of the water as well as possible dilution available. Existing reliable data will allow for more accurate future predictions (BPG G4: Impact Prediction) considering users' future requirements (see Section 10)

5 POTENTIAL WATER TREATMENT TECHNOLOGIES (PRE-SCREENING)

The choice of an appropriate water treatment technology is very site-specific and requires the input of an appropriate water treatment specialist before making final decisions. The non-specialist can only identify and make some preliminary selections for an appropriate water treatment technology that would require further investigation or the opinion of a specialist.

For any water treatment problem, there are always a number of different treatment technologies that could be considered. Table 5.2 shows the various active (physico-chemical and biological) and passive water treatment alternatives that could be considered to determine the most appropriate technology or combination of technologies based on the constituents of interest/ concern given in the first column (also refer to Appendix D). Many of the water treatment options presented in Table 5.2 can be designed to achieve the required concentrations, but may not be economically feasible (see Section 10).

5.1 Active or Passive

The choice between active and passive water treatment technologies depends very much on the period in the mine's life-cycle. For example, at a remote, closed and abandoned mine, the choice is obviously passive treatment if the water flow rates are small enough, as the options are either passive treatment or no treatment. Although it is possible to combine active and passive treatment unit processes into an integrated water treatment plant, this is not generally done since it negates the major advantage of passive treatment, i.e. the ability to reduce operating costs by not requiring constant attention and supervision.

Both active and passive water treatment technologies are capable of addressing primary constituents of concern typically associated with mine waters. Whereas there is an active type of water treatment technology for the removal of any constituent, this is not the case with passive treatment. Active water treatment is also capable of producing a higher water quality with a high degree of surety. If the primary objective of water treatment is the removal of Total Dissolved Solids (TDS), electrical conductivity (EC) or conservative salts such as Na and Cl, then passive treatment may not be appropriate and active treatment options will need to be considered. Passive treatment technologies also have limitations in terms of the water flow rates that can be accommodated and would therefore not be considered ideal for water flows in excess of 5 Ml/day.

Examples of active treatment of contaminated mine water include chemical or biological processes such as the following:

- pH adjustment
- Metal precipitation
- Ion exchange
- Membrane processes (reverse osmosis and electrodialysis reversal)
- Biological based treatments (sulphate reduction/removal)
- Adsorption treatments
- Electrochemical treatment technologies
- Physical process technology (e.g. gravity settling, filtration, evaporation)

Examples of passive treatment of contaminated mine water include chemical or biological processes such as the following:

- pH adjustment (anoxic limestone drains (ALD), bioneutralisation, successive alkalinity producing systems (SAPS), sulphate reduction units)

- metals removal (ALD + oxidation pond; SAPS, sulphate reducing units, wetlands, oxidation cascades)
- sulphate removal (sulphate reducing units + sulphide oxidising bioreactors)

Table 5.1: Comparison Between Active and Passive Treatment Technology

Criteria	Active	Passive
Period in mine's life cycle	Exploration and operational phase - a workforce is required on site for implementation, control and maintenance. Application in post-closure phase generally only feasible for large volume flows.	Decommissioning, closure or post-closure phases as processes are largely self-sustaining.
Financial consideration	High capital investment and operational cost.	Medium capital cost and low operation and maintenance costs.
Power supply	Mechanical or electrical energy required.	No external power supplies. Use natural energy sources (solar energy and gravitational flow).
Supervision	High degree of operating supervision (continuous control and operator attention) and on-going maintenance.	No operators or constant supervision (minimum supervision and labour) although regular maintenance is required (e.g. every 2 weeks).
Flow rates	Can handle very high flow rates or water volumes depending on design (modules).	Optimum performance at lower flow rates of 0.1 - 2 Ml/day. Unlikely to be considered for flow rates > 5 Ml/day.
Input material	Generally require ongoing addition of chemicals, power supply, and equipment maintenance.	Natural, prolonged and self-sustaining treatment materials, although certain process technologies will require regular ongoing addition of chemicals in passive mode.
Treatment range	Can treat any constituent of concern.	Not applicable to all constituents of concern (i.e. TDS, EC, Na, Cl). Mainly applicable for acidity, metals and sulphate removal.
Product	Produce very high quality water. Process is more reliable in terms of its output due to control. Product is certain.	Produce water of lower quality than active systems and of variable quality dependant on input water quality.

5.2 Active Water Treatment Processes

Numerous active processes exist for the treatment of mine waste waters. The preferred process for the treatment of a specific effluent depends on the characteristics of the mine wastewater (effluent water quality and quantity), the treatment objectives (discharge criteria or target user requirements) and the total cost (see Chapter 10) associated with treatment. Appendix A provides some guidance on the selection of active treatment technologies.

5.2.1 Physico-Chemical Processes

Processes involving chemical and/or physical mechanisms for the removal of constituents from mine wastewater include pH adjustment, metal/chemical precipitation, chemical sulphate removal, ion exchange, reverse osmosis, air stripping, oxidation/reduction, electrodialysis, adsorption, thermal drying and sedimentation etc. Most of these treatment systems are fairly well established and have been proven as full-scale plants and detailed discussions will not be presented here (see Appendix C).

Table 5.2: Process Alternatives Matrix for Active and Passive Technologies

	Active Technology											Passive Technology					
	Physico-Chemical Processes						Biological Processes					Passive Processes					
Potential Technology	Solid/Liquid Separation[1]	Coagulation/ Flocculation	Evaporation[2]	Reverse Osmosis/ Electrodialysis[3]	Ion Exchange	Adsorption	Stripping	pH Adjustment	Precipitation/ Coprecipitation[4]	Chemical Oxidation	Chemical Reduction	Biological Oxidation	Anaerobic Degradation	Sulphate Removal[5]	Limestone Drains	Sulphate Reducing Units	Oxidation/ Settling Ponds
Constituent of concern																	
Acidity, pH			P	PC				P,S	I					P	P	P	S
Organics																	
BOD	S									P		P	P				P
cyanide					PC	PC	P	S		P		P	S	I		I	P
oil and grease	P	S							I	I		I	I	I		I	
phenol				PC		PC				P		P	I	I		I	I
chlorinated aliphatics				PC		PC				S	P	S					
Suspended Solids	P	P	I	I	I	I				S		S	I	I		I	P
Dissolved Solids																	
chloride			P	PC	PC												
sulphate	S	S	P	PC	PC			I	P				I	P		P	
Nutrients																	
nitrate/nitrite			I	PC	PC								P	I		I	
ammonia			I	PC	PC		P	I		P		P					P
phosphate	S	S	I	I	I				P			I					
Major Metals																	
aluminium	S	S	I	PC	PC			I	P			I		P	I	P	I
arsenic	S	S	I	PC	PC			I	P	PP		I		I		I	I
calcium	S	S	I	PC	PC			I	P			I				I	
chromium	S	S	I	PC	PC			I	P		PP	I		P	I	P	I
cobalt	S	S	I	PC	PC			I	P			I		P		P	I
copper	S	S	I	PC	PC			I	P			I		P	I	P	I
iron	S	S	I	PC	PC			I	P			I		P	I	P	P
lead	S	S	I	PC	PC			I	P			I		P	I	P	I
magnesium	S	S	I	PC	PC			I	P			I					
manganese	S	S	I	PC	PC			I	P			I				P	I
nickel	S	S	I	PC	PC			I	P			I		P		P	I
sodium/potassium			P	PC	PC												
cadmium	S	S	I	PC	PC			I	P			I		P	I	I	I
zinc	S	S	I	PC	PC			I	P			I		P		P	I
Trace Metals																	
mercury	S	S	I	PC	PC				P			I		P		P	I
molybdenum	S	S	I	PC	PC				P			I		I		P	I
tantalum	S	S	I	PC	PC			I	P			I		I		P	I
selenium	S	S	I	PC	PC				P		PP	I		I		P (?)	I
Radioactive Elements																	
lead-210	S	S	I	PC	PC			I	P			I		I	I	I	I
radium-226	S	S	I	PC	PC	P		I	P			I		I	I	I	I
thorium-230	S	S	I	PC	PC			I	P			I		I	I	I	I
uranium-238	S	S	I	PC	PC			I	P			I		I		I	I

[1] *includes sedimentation (ponds, clarifiers and thickeners), filtration and flotation.*

[2] *evaporation is not commonly used except for the control of dissolved salts (sodium chloride, sodium and calcium sulphate), all other dissolved contaminants are removed coincidentally.*

[3] *reverse osmosis, electrodialysis, ion exchange and adsorption are primarily concentrating processes that require secondary processes for the treatment of concentrates.*

[4] *include alkaline addition, carbon dioxide addition, co-precipitation reactions (e.g. $FeAs_2O_3$, $BaRaSO_4$) and sulphide precipitation*

[5] *sulphate removal covers a broad range of options using biological reactors, many of which are highly effective for metals removal*

Also see Appendix C.

Where:

P	Primary process either in use or potentially applicable for the removal of a contaminant (e.g. lime for neutralisation of acidic water).
S	Secondary process that would be used in combination with a primary process to remove a contaminant (e.g. co-precipitation of radium as a primary process followed by solid/liquid separation as a secondary step).
PC	Primary process that produces a concentrate stream that requires further processing (e.g. ion exchange to produce a saline concentrate stream followed by lime precipitation of gypsum).
I	A process in which some degree of contaminant removal may occur incidentally although the process is intended to remove another contaminant (e.g. pH adjustment for acidity control may result in the incidental reduction of sulphate through gypsum precipitation).
PP	Primary pre-treatment process that is an oxidation or reduction step prior to the removal of a contaminant (e.g. oxidation of As(III) to As(V) prior to iron arsenate precipitation).

pH ADJUSTMENT

Objective: To neutralise acidic (low pH) mine waste waters.

Process description:

The addition of a base reagent to acidic (low pH) mine wastewater for neutralisation.

Example:

The addition of lime ($Ca(OH)_2$), caustic soda (NaOH) or limestone ($CaCO_3$) to an acidic mine water will raise the pH to 7 or higher.

Example of industry application:

HDS (high density sludge) water treatment plant at Pamodzi Gold Grootvlei Proprietary Mines Limited

Waste:

Sludge residue that is voluminous and of variable stability and density. Type and volume of sludge dependant on type of neutralising agent used.

Benefits:

- Precipitation of various metals as pH is increased.
- Some degree of sulphate removal is possible with a calcium-based neutralising reagent (formation of gypsum).
- High water flows can be treated in a simple or complex process.
- It is a proven technology - the degree of neutralisation is good and can be controlled.

Constraints:

- The product water will often require further treatment to remove dissolved contaminants.
- Sludge residue is difficult to handle due to large volume as well as variable stability and density.

Other applications: Adjustment to reduce pH values is usually only required as a secondary (polishing) step to meet discharge standards after pH increase (neutralisation) with a strong neutralising agent for softening purposes or to remove recalcitrant metals such as manganese.

Other considerations: The choice/selection of reagent depends primarily on cost but may be influenced by other factors such as ease of use (operational control required), environmental impact (associated risks), site-specific requirements (chemistry of water to be treated, treatment objectives), and sludge production (quantity, toxicity, density/settleability).

METAL REMOVAL

Objective: To remove metals from metal-bearing mine waste waters.

Process description:

The addition of a base reagent to acidic, metal-bearing mine waste waters to remove metals through precipitation (due to the formation of insoluble metal compounds).

Example:

Manganese hydroxide ($Mn(OH)_2$) is insoluble and will precipitate with lime or caustic soda addition to water at pH 10.6.

Example of industry application:

HDS (high density sludge) water treatment plant at Pamodzi Gold Grootvlei Proprietary Mines Limited

Waste:

Metal-rich sludge residue that is of variable stability and density.

Benefits:

- Associated neutralisation of low pH mine water.
- High water flows can be treated in a simple or complex process.
- It is a proven technology – the degree of metal removal is good.
- Different metals can be precipitated at different pH in a highly controlled process thereby allowing metal recovery.
- The metal compound to precipitate can be determined based on the base reagent selection (hydroxide versus sulphide for example).

Constraints:

- The product water will often (depending on end user) require further treatment to remove dissolved contaminants.
- Process is very pH specific and temperature sensitive.
- For metal recovery, very accurate process control is required.
- The resulting sludge residue is of variable stability and density complicating its handling.

Other considerations: Also refer to pH adjustment. The process is often conducted in conjunction with aeration for oxidation (to change metal's valence).

CHEMICAL SULPHATE REMOVAL

Objective: To remove sulphate from sulphate-rich mine waters.

Process description:

Addition of chemicals to sulphate-rich mine waste waters to promote the chemical precipitation of sulphate from the water.

Example:

Addition of barium chloride/hydroxide/oxide followed by lime neutralisation.

Waste:

Sulphate-rich sludge with variable density.

Benefits:

- Sulphate concentrations in effluent are highly regulated in South Africa.
- Sulphate in mine water is a large problem in SA due to the formation of AMD.
- Recovery of valuable by-products is possible for example sulphuric acid (H_2SO_4), which can be reused or sold to recover some treatment cost.

Constraints:

- Sludge density is variable complicating its handling.
- Gypsum ($CaSO_4.2H_2O$) often resulting as a by-product is impure limiting its reuse possibilities.
- Process costs are often highly dependant on the ability to recover and recycle the barium metal

ION EXCHANGE (IX)

Objective: Purification of water or recovery of a valued component from solution.

Process description:

Ions from aqueous solution transfer to a solid support with the simultaneous transfer of an innocuous ion (i.e. H^+, and OH^-) from the solid to the solution and vice versa.

Example:

Water softening; concentration of gold cyanide complexes.

Example of industry application:

Commonly used in industry as pre-treatment of feed water for boilers

Waste:

Concentrated sludge or brines

Benefits:

- The process is reversible – transfer of ions (i.e. Cu^{2+}, Ni^{2+}, Ca^{2+}, NH_3^+, AsO_4^{3-}, SO_4^{2-}).
- Cation and anion exchangers available.
- Loaded resins can be regenerated (concentrated solution of counter ion).
- A number of natural materials exhibit ion exchange capabilities (zeolites, coal, algae, etc)
- Can be applied to be highly selective to yield a pure product and concentrated sludge.

Constraints:

- Natural ion exchangers are less efficient than synthetic ion exchangers that have higher capacities and can be designed to be highly selective.
- Costly if large volumes of water require treatment due to high regeneration cost and treatment of brine.
- Complex process.
- Resin replacement is required in the long-term due to physical degradation and irreversible fouling.
- Tend to be limited to moderate strength waste waters.

MEMBRANE PROCESSES - REVERSE OSMOSIS (RO)/NANOFILTRATION (NF)

Objective: To separate and remove molecules from solution.

Process description:

The separation and therefore removal of molecules/ solutes from water/solution by driving the solvent/water through a semi-permeable membrane.

Example:

Removal of salts through reverse osmosis (RO); desalination.

Example of industry application:

TRO membrane plant at Sasol Secunda U67, processing Clear Ash Effluent (CAE) and producing raw water quality permeate

Waste:

Highly concentrated brine.

Benefits:

- Very pure product quality is achieved.
- Nanofiltration can fractionate monovalent and divalent species.
- Low capital and operating cost relative to other desalination technologies.
- Mature technology with a wealth of reference applications, design software and competent suppliers.
- Spiral wound elements are most common and available as commodity items and with a wide variety of specific performance characteristics. An industry standard ensures that spares can be produced through a large number of suppliers at market prices.
- Support technology such as ultra filtration (UF) pre-treatment and antiscalants are widely available and rapidly evolving to meet the needs of RO applications.

Constraints:

- Susceptible to fouling by particulates, biogrowth and precipitation of sparingly soluble salts.
- Pre-treatment is almost always required and should be considered as a cost of the treatment technology.
- Scaling agents (such as iron salts, silica) can cause precipitation on the membrane (saturation conditions) and anti-scaling agents are therefore required to overcome this.
- Production of highly concentrated brine requires further treatment prior to disposal or specially constructed disposal facilities.
- Membrane processes perform best in a combined/ integrated system designed to overcome the above-mentioned constraints.

MEMBRANE PROCESSES - ELECTRODIALYSIS REVERSAL (EDR)

Objective: To separate and remove ionic species from solution.

Process description:

The separation and therefore removal of ionic species/ solutes from water/solution by electrically driving the ions through cation and anion exchange membranes. The membranes are configured in stacks of cell pairs which are alternately concentrating and diluting. These are manifolded together to form concentrating and diluting streams.

Example: Removal of salts through EDR; desalination.

Example of industry application:

EDR/SRO plant at U267 at Sasol Secunda, treating mine water.

Waste:

Highly concentrated brine.

Benefits:

- Product quality can be adjusted to suit the application by modulating the current input thereby optimising the energy consumption.
- Low capital and operating cost relative to evaporation but more costly than RO.
- Mature technology with a wealth of reference applications.
- EDR is relatively resistant to fouling and scaling through the periodic reversal of polarity. Thus the concentrate and dilute streams alternate, thereby cleaning the concentrate stream before scaling proceeds unchecked.

Constraints:

- Design software and competent suppliers is quite limited and this must now be considered a niche product.
- EDR systems are proprietary and there is no industry standard. Thus once purchased, there is only one supplier of spare parts.
- Maintenance of EDR stacks is quite high adding to the cost and reducing production time.
- Scaling agents (such as iron salts, silica) can cause precipitation on the membrane (saturation conditions) and anti-scaling agents are therefore required to overcome this.
- Production of highly concentrated brine requires further treatment prior to disposal or specially constructed disposal facilities.

- Membrane processes perform best in a combined/ integrated system designed to overcome the above-mentioned constraints.

AIR STRIPPING

Objective: To strip volatile compounds from liquid.

Process description:

The stripping of volatile compounds from a liquid stream by contacting the liquid with a gas stream.

Example:

Removal of ammonia (NH_3), cyanide (CN), hydrogen sulphide (H_2S) and other gaseous constituents.

Waste:

Minimal as stripped compound is air-borne, although where it is recovered from the waste air stream, a sludge or brine may be produced as a waste product.

Benefits:

- No chemical addition.
- Cheap technology requiring limited infrastructure and investment.

Constraints:

- Limited applicability.
- Can impact on air quality.
- Rate of mass transfer is dictated by interfacial surface area and partial pressure of volatile component in gas phase.

Other considerations: pH adjustment is often required prior to air stripping to convert ions in solution to a volatile compound.

OXIDATION AND REDUCTION

Objective: To change the valence of an element to enhance its precipitation properties.

Process description:

Oxidation (under oxygen-rich conditions) and/or reduction (under oxygen-poor conditions) are applied to change the valence of an element to enhance its precipitation properties.

Example:

Oxidise ferrous ion (Fe^{2+}) to ferric ion (Fe^{3+}) prior to neutralisation as ferric iron has a lower solubility and therefore precipitates at a lower pH (4.3) compared to ferrous iron. Electrolysis for recovering dissolved metal by passing a direct current through the solution causing pure metal to plate out on the cathode.

Waste:

Sludge requiring further treatment (filtration, addition of flocculant).

Benefits:

- Oxygen is a relatively cheap oxidising agent though many others are available (peroxide, chlorine).
- Improve the efficiency of other treatment processes such as metal removal.
- High-grade products can be produced for resale.

Constraints:

- Further treatment may be required, to be used in conjunction with other treatment processes.

SOFTENING

Objective: To remove hardness (calcium or magnesium) from solution to prevent scaling/corrosion.

Process description:

The addition of a chemical to precipitate and remove calcium/magnesium from solution to minimise scaling and corrosion of equipment and reticulation systems.

Example:

Soda ash (Na_2CO_3) or lime ($Ca(OH)_2$) can be added to remove calcium ions in the form of calcite/calcium carbonate ($CaCO_3$).

Waste:

Dense stable sludge.

Benefits:

- Reduced scaling and corrosion potential of water resulting in less operational interruptions and protection of equipment.
- Sludge produced is dense and stable in terms of leaching.
- Possible reduction of radium and magnesium levels possible due to co-precipitation.

Constraints:

- Limited applicability.

FILTRATION

Objective: To remove suspended solids from solution.

Process description:

Filtration is physical separation used as a pre-treatment, secondary or polishing step for the removal of fine suspended solids. May be effect in granular media filters (e.g. sand filter) or membrane filters (e.g. Nanofiltration).

Example:

Mechanical straining causes the retention of particles larger than the filter pore diameter. Smaller particles are carried into the filter bed and may be retained by an attachment mechanism to the filter medium (through electrostatic actions, polymeric bridging).

Example of industry application:

Commonly applied at mines, especially gold mines (e.g. Kloof), to remove suspended solids from water prior to it entering the mine service water or refrigeration circuits.

Waste:

Dilute backwash water containing suspended solids.

Benefits:

- Simple process.
- No addition of chemicals.
- Filter medium can be cleaned through backwashing (reversed flow).

Constraints:

- Backwashing or cleaning of filter medium is required to prevent excessive head loss through the filter due to clogging. Backwashing may be required regularly depending on solid loading on filter.
- Filters require replacement in the long-term to ensure continued efficiency.
- Affected by coagulants, chemical characteristics of water and filter medium.

FLOTATION

Objective: To remove suspended material that generally settles slowly.

Process description:

The physical separation and removal of suspended material that settles slowly by bubbling air through the solution and allowing particulates to float to the surface on air bubbles, where it is skimmed off.

Example:

Fine bubbles of air are introduced to which particulate matter attach and float to the surface due to the buoyant force. The particles are collected at the surface and removed by skimming.

Waste:

Minimal sludge.

Benefits:

- Simple cheap process with aeration under atmospheric conditions.
- No addition of chemicals.
- Process can be enhanced by the addition of flocculants.

Constraints:

- Not applicable for all types of contaminants.
- The addition of flocculants may be necessary to enhance the process.

Other considerations: Air bubbles can be introduced by aeration under atmospheric conditions, aeration with liquid under pressure or aeration followed by vacuum pressure.

ADSORPTION

Objective: To collect or accumulate molecules at a surface/interface where it can be removed.

Process description:

Constituents are attracted to the surface of the adsorbing substance and held there by weak reversible forces such as van der Waals forces, electrostatic forces and hydrogen bonding.

Example:

Adsorbent materials include granular activated carbon (GAC), activated alumina and many hydroxide flocs.

Waste:

Sludge.

Benefits:

- Reversible process due to the use of reversible driving forces in the process.
- Some absorbing substances such as GAC can be regenerated and reused.
- Simple process that is partially selective.

Constraints:

- Some absorbing substances such as activated alumina require disposal after use.
- Long contact times are often required.
- Accumulation of hazardous substances in the system can result.

THERMAL EVAPORATION PROCESSES

Objective: To purify water or recover water from brine solutions

Process description:

Mechanical or thermal evaporation for the purification of water (condensate) and the production of a solid salt waste.

Example:

The production of a high quality condensate for reuse and solid salt waste for disposal in a mechanical vapour recompression process.

Example of industry application:

Evaporator/crystalliser at U265 for brine treatment from EDR/SRO plant (U267) at Sasol Secunda.

Waste:

Solid salt waste and condensate.

Benefits:

- Large variety of process configurations: single or multi-stage, natural or forced circulation, mechanical vapour recompression, falling film, multi-stage flash and fluidised bed evaporators.
- Improved waste management as residue volumes are reduced due to lower moisture content.

Constraints:

- High capital and energy cost. Use of waste heat or an inexpensive fuel source can be considered to reduce energy cost.
- If condensation is not associated with evaporation, the process is considered a method of water disposal and a water use licence is required in terms of the NWA.

SEDIMENT REMOVAL

Objective: To remove coarser-sized particles from sediment-laden runoff.

Process description:

Sediment basins are used to settle and remove coarser-sized particles from sediment-laden runoff.

Example:

Sand-sized particles (> 0.1mm diameter) are settled in a sediment basin and therefore removed from water.

Example of industry application:

All underground gold mines use settlers to remove suspended solids from underground water

Waste:

Sludge containing suspended solids

Benefits:

- Common technology widely used in all types of water treatment plants and in metallurgical processes.
- Low and high rate settling systems are available for different applications
- Can readily remove suspended solids to below 5 - 20 mg/l, making the settled water amenable for further purification in filtration systems.
- Often used in conjunction with coagulants or flocculants to enhance removal of colloidal suspended solids

Constraints:

- Sediment-laden inflows consist of a mix of particle sizes (particle size distribution curve) all of which require different retention times.
- Sufficiently long retention times are required to remove significant quantities of silt-sized particles (0.01 - 0.05mm).
- Sediment basins have to be large for desired removal efficiency and therefore take up large surface areas – can use high rate settlers where space is at a premium.

5.2.2 Active Biological Processes

The biological component can either use the metabolic processes of micro-organisms or use living or non-living biomass for their absorbent properties.

SULPHATE REMOVAL

Objective: To remove sulphate from sulphate-rich mine water.

Process description:

Sulphate-reducing bacteria (SRB) are used in a bioreactor to convert sulphate to sulphide and/or sulphur in a reduction process.

Example:

Pacques Thiopaq process; BIOSURE, CSIROSURE.

Example of industry application:

BIOSURE water treatment plant at Pamodzi Gold Grootvlei Proprietary Mines Limited

Waste:

Hydrogen sulphide into air (air pollution) and sulphur/ biomass sludge.

Benefits:

- No addition of chemical precipitants as the dynamics of the process relies on natural living organisms (SRB) – carbon sources and electron donors are added as the energy source for the SRB.
- The reduction of sulphate is a natural process that occurs in conjunction with the oxidation of sugars by the SRB to obtain energy.
- Simple sugars or complex materials can be used/ oxidised by the SRB to obtain energy. Complex materials require a phased approach to allow breakdown.
- Hydrogen sulphide (H_2S) produced can be captured and brought into contact with metal ions causing metal sulphide precipitation.

Constraints:

- Anaerobic conditions are required for sulphate reduction phase and bacteria are sensitive living organisms.
- SRB (organisms) assimilate a small amount of reduced sulphur.
- Hydrogen sulphide (H_2S) produced as metabolic end product and released into the external environment can cause air pollution and be a health risk.

METAL REMOVAL

Objective: To remove metals from metal-bearing solutions.

Process description:

Removal of metal ions from solution through bio-sorption by some microbial and plant materials.

Example:

BIOFIX.

Waste:

Depends on process used – could be minimal as metals accumulate in plants or biomass.

Benefits:

- No addition of chemicals as the dynamics of the process relies on the absorption capacity of natural living organisms and non-living material.
- Biosorbents such as waste-activated sludge can be obtained at minimal cost.

Constraints:

- High metal loadings on the biosorbent.
- pH has a major influence on the biosorption reaction as hydrogen ions effectively compete with heavy metals for attachment to microbial cell surfaces.
- Not always cost-effective due to low biosorptive capacity of sludge, large volumes and mass of sludge requiring transport, and distance requiring transportation.
- Treatment is merely transfer from one phase (water) to another (biomass).
- Possibility of remobilisation if conditions change.

Other considerations: Dead microbial biomass appears to offer a number of advantages over live biomass. Though live microbial biomass can accumulate more metal per unit weight, the processes involved are generally slower and live biomass is more demanding in terms of environmental conditions. The use of dead biomass offers increased opportunities for metal recovery, since metals bound to the cell wall may be desorbed using electrolyte solutions from which the metal can be recovered by electrolysis.

5.3 Passive Biological Treatment Processes

Using natural systems for polluted mine water treatment, has been investigated for more than 25 years. Systems use a variety of plants, substrates and flow configurations. As many passive treatment unit operation design criteria are based on contaminant loads, an understanding of the “hydrograph” of a discharge is essential, as flow is often the primary determinant of the load (see Section

3 on the characterisation of the stream/area targeted for treatment). The reality is that passive treatment is often the only alternative to no action where closed, abandoned mines are concerned.

5.3.1 pH Adjustment

Objective: To neutralise acidic (low pH) water by generating alkalinity.

Process description:

Generate alkalinity to neutralise acidic water by passing this water through limestone drains or sulphate reduction systems.

Example:

Anoxic limestone drains (ALD) and anaerobic sulphate reducing units (SRU) to treat acid mine drainage (AMD).

Example of industry application: Widely applied in North America and Europe, especially for closed or abandoned mines

Waste:

Minimal and retained within system.

Benefits:

- Simple construction and operation.
- Limited supervision, intervention and maintenance.
- Removal of other constituents in addition to acidity, such as iron, manganese and aluminium.

Constraints:

- Cannot handle large flows (limited throughput) and have specific requirements in terms of the feed water for ALDs.
- Efficiency may reduce over time.
- Inflows may require pre-treatment (for example removal of ferric iron and aluminium).

5.3.2 Metal Removal

Objective: To remove metals from metal-bearing mine waters.

Process description:

Removal of metals through bioaccumulation by plants and biomass and precipitation as sulphides (in sulphide reducing systems) or hydroxides (in sulphate reducing systems, limestone drains or aerobic wetlands).

Example:

Wetlands, oxidation cascades, oxidation and settling ponds and anaerobic sulphate reducing units (SRU)

Example of industry application: Widely applied in North America and Europe, especially for closed or abandoned mines

Waste:

Minimal as metals accumulate in plants and biomass as sulphides/hydroxides – although long-term disposal of biomass does need to be addressed.

Benefits:

- Simple construction and operation.
- Limited supervision, intervention and maintenance.
- Reduce flow velocity which reduces erosion potential.
- Wetlands act as physical filtration barrier.
- Very effective, particularly for iron and aluminium removal

Constraints:

- The extent to which metals accumulate in plants may be related to the plant's physiological need for the metal. Metals such as Fe (respiration), Cu and Mn (enzyme activation) and Zn (protein synthesis) have important roles to play in plant biology. Other metals may not be required by the plants and will therefore not be removed from the water.
- Cannot handle large flows (limited throughput) and have specific requirements in terms of the feed water.
- Uptake or encrustation may be the major process for metal removal in wetlands.
- Accumulation in sediments may present a later risk and require special decommissioning - uncertainty regarding the long-term fate of the precipitated constituents.
- The dying of plants may cause remobilisation of the metals.
- Large space (surface area) requirements.
- Birds, wildlife and fish could be exposed to elevated metal levels in wetland plants ingested.
- Manganese is most difficult to remove.

5.3.3 Sulphate Removal

Objective: To remove sulphate from sulphate-rich mine waters.

Process description:

Sulphate is reduced to sulphide by sulphate reducing bacteria (SRB) under anaerobic conditions and then oxidised to elemental sulphur for removal in a separate reactor.

Example:

Sulphate reducing units (SRU).

Example of industry application: None as yet, as this technology has been developed in South Africa and still needs to be applied at full-scale.

Waste:

Accumulation of some metal sulphides in system. Sulphur removed in associated sulphide oxidising reactor also requires removal and disposal

Benefits:

- Simple construction and operation.
- Limited supervision, intervention and maintenance.
- Cost effective as it requires minimal equipment (no pumps) and uses natural driving forces such as gravitational flow and sunlight energy (heat) – no external mechanical and/or electrical power requirements.
- Bacteria can use a variety of organic lignocellulose materials as carbon sources - spent mushroom compost, different manures, wood compounds, and other waste organic material.
- Sulphate (SO_4^{2-}) is reduced to sulphide (S^{2-}) and produce hydrogen sulphide (H_2S or HS^-) or metal sulphide precipitates. Provided sufficient sulphate is available, the process is not sensitive to elevated metal concentrations.
- The bacterial reduction of nitrate (NO_3^-) and nitrite (NO_2^-) can be included in the process.
- Large amounts of alkalinity are produced in the process – between 1 – 1.5 mg/l for each mg/l sulphate reduced and most metals, other than manganese, are very effectively removed.
- The technology for high-rate sulphate removal and subsequent sulphide oxidation to sulphur has essentially been developed through a long-term research programme in South Africa and is soon to be demonstrated at full-scale on a mine.

Constraints:

- Cannot handle large flows (limited throughput); optimum performance < 5Ml/day.
- Accumulation of metals in substrate may present a later risk and require special decommissioning - uncertainty regarding the long-term fate of the precipitated constituents.
- Bacteria are temperature sensitive.
- Unstable under aerobic conditions - maintain anaerobic conditions to prevent precipitates from oxidation and remobilisation.
- The resulting water quality cannot be guaranteed and the quality that can be achieved is limited.
- To achieve sulphate removal, a secondary passive system is required to convert hydrogen sulphide to elemental sulphur (S) which can then be removed from the water through a solid/liquid separation process.

5.4 Combined Processes and Technologies

Most waste streams associated with mining contain more than one constituent of concern (contaminant). The selection of a combination of processes (integrated process) for the removal of multiple constituents depends on the constituents targeted for removal, the desired effluent quality (target user requirements) and economic factors (cost). Some water treatment plants can therefore consist of multiple steps or a treatment train employing any number of treatment processes.

If confident data cannot be provided, then the treatment process identification should be based on the most conservative data or assumptions available (worst-case scenario). This is particularly important where advanced technologies such as reverse osmosis (RO) or electro-dialysis reversal (EDR) are considered as these have very definite pre-treatment requirements, depending on the feed water quality, which may add substantially to the overall cost. For any unique or novel combination of water treatment processes, it is also necessary to consider pilot testing (Section 11) to clarify uncertainties associated with the interface between the different water treatment technologies.

5.5 Emerging Technologies

Many new technologies are continuously being developed. It is therefore important to research and consider new technologies coming onto the market and consult with a specialist in this regard. It should however, be noted that there are risks associated with new and emerging technologies. Before implementing any new or emerging technology, the mine should go through a process to evaluate the applicability, practicality and sustainability of such a technology.

5.6 Screening Assessment

When reviewing and considering water treatment technology alternatives, it is imperative to evaluate the potential options in a consistent manner to ensure that one is comparing “apples with apples”. To do this, it is necessary to prepare a very thorough and detailed description of the intended duty of the treatment plant and to ensure that all the options being considered are capable of meeting this duty. The aspects of the duty and the technology that need to be evaluated incorporate technical, financial, waste production and sustainability issues as highlighted in Section 2.3.1 to 2.3.10 and Chapters 3 to 11.

6 WATER TREATMENT TECHNOLOGY REQUIREMENTS

Variations in feed water quantity and quality should be considered for the design life of the water treatment plant as well as for the life of the mine or phase of mining. Predictions on future water quantity and quality of the feed water should be made using accepted prediction techniques (see *BPG G4: Impact prediction*).

Current and future flow/volume profiles for the water to be treated should be based on a reliable data record (see *BPG G3: Water monitoring*). This includes statistical data to determine ranges (average, minimum, maximum) as well as rate of change where significant variation is expected. The same applies to the key constituents of interest/concern from the water treatment technology's perspective, which might be different from the constituents of concern from the treated water user's perspective. The key constituents on interest/concern from the water treatment technology perspective would be constituents that may affect the performance of the treatment plant in terms of reliability, efficiency, achieving its objectives, maintenance required, etc.

Some treatment processes are sensitive to large fluctuations in the water quantity and quality of the inflow and would therefore not be considered appropriate for the treatment of water with such variability. The variability of water quantity and quality of the inflow to water treatment processes is considered a critical parameter for consideration when making a decision on the water treatment process to be implemented.

The management of inflow variation (flow and load) is essential to prevent reduced efficiency/ performance or failure of the treatment plant (Section 9). Management of the inflow and treatment process will ensure that the quantity and quality of the outflow from the treatment plant is kept consistent and does not have major consequences for the users of water from the treatment plant. Variations will occur between seasons, with processing changes and over the life cycle of the mine and these changes must be explicitly considered in the process design.

Flow rate/volume variation:

Treatment technologies are generally intolerant of significant variations in feed flow rate since the design is based on and sized for a specific contact time to achieve certain objectives. Contaminant load, of which flow is often the primary determinant, is also considered for design criteria and understanding of the "hydrograph" is therefore essential.

These variations in flow rate can cause the process performance to be compromised (Section 9) These variations can however, be addressed by designing and installing flow equalisation dams or stabilising tanks, as part of the treatment plant but prior to actual treatment. These dams or tanks can accommodate varying inflow while ensuring a near constant outflow to the treatment plant. Problems with this approach may be encountered in instances where the inflow water may have large sediment loads that could settle out causing capacity reduction in the dam/tank, or where chemical or biological reactions in the flow equalisation dams may lead to water quality changes or formation of precipitates.

In active treatment plants, due to the presence of plant operators, significant changes in flow rate can be identified rapidly. In such cases it would be possible, if the treatment plant design has made provision for it, to bring additional measures into operation to deal with the changed flow (addition of modular process units).

If the changes in flow are gradual, biological treatment systems have the ability to adapt and accommodate this without affecting performance by changing their reaction kinetics. Active

physical systems generally do not have this ability. Passive biological systems are limited in terms of the maximum flow rate it can handle (< 5Ml/day) and perform optimally at lower flow rates.

It is also important to consider how the flow rates might change not only between seasons but also over the life cycle of the mine (sustainability of the technology, Section 10).

Quality Variation:

Due to the presence of plant operators, process instrumentation and process control systems, active treatment plants generally are more equipped to deal with variations in water quality by adjusting reaction and retention times, amount of reagents added, number of modular units brought into operation, etc.

Passive treatment plants can accommodate variation in feed water quality, provided this variation does not occur too rapidly and is not too significant (<25%). The degree of tolerance to feed water quality variation differs for each passive treatment process and for each contaminant. For example, reaction rates of biological processes that occur in an anaerobic sulphate-reducing unit (SRU) can change with changes in temperature (temperature-sensitive). However, these same units are quite tolerant of very large changes in metal concentrations (provided adequate sulphate is available) without affecting their ability to effectively precipitate metals as metal sulphides.

Depending on flow rates/volumes to be treated, the reticulation system, the constituents of interest/concern etc, it may be economical and feasible to mix mine waste streams and treat them together on the mine or within the region (different industries). Alternatively, sufficiently large storage capacity can be provided to equalise the variations.

The importance of long-term changes in water quality can not be over-emphasised as water quality may deteriorate or improve over time and it is essential to know this before deciding on the water treatment technology.

Land availability:

Passive treatment systems require more land than active treatment systems. It is however, only the aerobic wetland type of passive treatment system that has large space requirements since anaerobic systems can be constructed in a fairly compact manner. As passive treatment systems do not use external mechanical and/or electrical power such as pumps, the land must also support the use of gravity flow, distribution and control (correct gradient or earthworks).

The land area required by active systems should consider and include the land required for residue disposal. Before making decisions the likely land requirements of different options should be estimated and considered.

7 WASTE/RESIDUE STREAMS

7.1 Characteristics

Once all potential waste streams (e.g. brines and sludges) associated with the water treatment technology have been identified, the waste streams should be characterised in terms of quantity, quality, environmental impacts, risks and cost of management over the design life of the treatment plant. In order to minimise the amount of hazardous waste, with associated disposal problems, produced, a phased treatment approach should be adopted. The phased approach should aim to segregate the most hazardous constituents (small concentrated stream) from the bulk of the waste stream in the early phases.

Legislation other than the National Water Act (NWA) (e.g. Environmental Conservation Act, National Environmental Management Act, Hazardous Substances Act, Nuclear Energy Act), regulatory measures (DWAF Minimum Requirements) and other requirements (SABS Code, licences, registrations, hazard classifications, etc) that have a bearing on the disposal and/or management of waste streams from water treatment processes should be considered during the feasibility stage (cost-benefit and risk assessment) and licences should be applied for before implementation.

The characteristics of some waste streams are:

- Active systems based on lime dosing generate large amounts of metal-contaminated sludge, which need to be safely disposed of over the long term.
- Active systems based on desalination (such as reverse osmosis) produce highly saline and toxic brine, which need to be disposed of or evaporated to a solid for final disposal.
- Active systems such as GYPCIX produce large amounts of gypsum which require disposal if long-term markets cannot be guaranteed.
- Aerobic passive systems such as wetlands produce small amounts of sludge as no chemicals are added. However, the long-term fate of this sludge is uncertain and if the passive system is not designed to be isolated from extreme hydrological events, then a risk exists that these precipitated constituents may be liberated or mobilised (washout).
- Anaerobic passive systems produce even less sludge than aerobic systems and, due to their design are less likely to remobilise precipitates with hydrological fluctuations. However, these precipitates are unstable under aerobic conditions (will oxidise and remobilise) and continued anaerobic conditions need to be assured.
- For all passive treatment systems there is currently uncertainty regarding the long-term fate of the precipitated constituents. It is possible that in 25 years time, the depleted passive treatment plant may need to be cleaned up with the accumulated precipitates being disposed of in an acceptable manner.

7.2 Disposal

It is not the intention to provide a detailed discussion on disposal methods here but rather to provide sufficient information to assist with the decision-making procedure for selecting an appropriate water treatment method taking account of the resulting residues to be disposed of. It is therefore important when considering the different water treatment technologies available to at that stage also identify appropriate waste disposal and/or management options (including monitoring) for all the waste streams.

Costs associated with the disposal of residues/sludges include disposal cost (based on volume and nature) and transportation cost (distance to transport to disposal site). Risks associated with the disposal of water treatment sludges relate to sludge stability, disposal site design

and location, the constituents in the sludge and their hazardousness, possible groundwater pollution, pollution of surface runoff as well as valuable land surface area taken up by surface disposal.

Contact of disposed sludge with water (ground and surface) should be prevented or where prevention is not possible be minimised (also see *BPG G1: Storm water management and BPG G4: Impact prediction*). Thus, the disposal site should be above the groundwater table, underlain by an impermeably layer (synthetic liner) or layer of low permeability (unfractured bedrock or clay) and contoured and capped following closure. DWAF Minimum Requirements provide details on requirements for waste disposal in terms of classification, site selection, leachate generation and capturing, lining, monitoring etc.

Further, also consider the potential effects that may arise from mixing different waste streams.

The following are possible disposal options for waste/ residue:

- Settling ponds: For low strength streams with small sludge volumes. Consider additional volume required in design capacity. Discuss ultimate destiny and liability with authorities.
- Tailings/slimes dam: For treated water where sludge is allowed to settle and the treated water is decanted for reuse/discharge or sludge from a settling pond or clarifier/thickener. Consider pumping cost, additional material reducing tailings dam's operating life and resolubilisation possibility with co-disposal.
- Dumps: For more solid type waste (dewatered). Consider surface area required, leachability (remobilisation of constituents), and possible groundwater pollution.
- Off-site: Smaller quantities and hazardous waste types should be disposed to an authorised waste disposal site in the area. Disposal cost depends on volume of sludge to be removed and transported, the distance to be transported and disposal cost (tipping fees, depending on volume and toxicity).
- Deep mines: This disposal method is not widely implemented but can be considered for large volumes of waste with low environmental risk and would be subject to the appropriate regulatory approval process. Benefits include potential reduced risk of subsidence due to filling of mine voids with solids; potential neutralisation of mine water by excess alkaline materials in the sludge; reduction in surface land space occupied by permanent storage of residues; and potential isolation of sludges from the near surface environment exposed to rainfall infiltration and leaching. Feasibility will depend on sludge characteristics, geology, water flow paths and site-specific conditions.

7.3 Reduction of Quantity

The volume of waste/sludge requiring disposal can be a major issue if storage capacity is limited and the sludge volume is large. The volume or quantity of sludge is also a major cost factor when considering management options. Sludge volume reduction options include:

- High density sludge lime neutralisation system, which produces a denser sludge (5 - 10 times) than conventional treatment systems.
- Mechanical dewatering can increase the sludge density and reduce the volume.
- Using a non-calcium neutralising agent (sodium or magnesium based) reduces the mass and volume of sludge produced but poses other problems.
- Smelting of sludge yields valuable metal recovery. Feasible when metal concentration is high (economical); the sludge does not contain free water; and the concentrations of certain constituents (arsenic, cadmium and bismuth) are below specified limits.

7.4 Sludge Stabilisation

Most sludge stabilisation methods increase the physical stability of the sludge but also increase the weight and volume of the material to be disposed. These include:

- Fixation: Addition of chemicals (cement and lime based additives) to harden/solidify the sludge after placement in a permanent disposal location. Advantages: Cement-mixing equipment is inexpensive; unit cost decreases for dense sludges (require less cement); effective for immobilisation of radioactive wastes and heavy metals. Disadvantages: Organic material, silt, clay, lignite, salts of magnesium, tin, zinc and copper may hinder the curing process.
- Encapsulation: Materials used include polymers, polyurethane, asphalt, concrete and polyethylene. Advantage: It limits contact between sludge and water (reduce leaching possibility).

- Vitrification: Stabilising waste in a glassy matrix. Disadvantage: Often creates secondary waste streams (off-gasses and slags).
- Phosphate-based additives: Include natural and apatite mineral based phosphates. Disadvantage: Nominally effective to stabilise a limited range of metals in contaminated sludges.
- Envirobond™: A man-made phosphate chain that treats metal contaminated sludges (cadmium, lead, chromium, arsenic, aluminium and barium) to yield sludges with insoluble phosphate metal complexes that can be disposed of in non-hazardous landfill sites. Advantage: Reduce hazardousness.

7.5 Sludge Stability

Lime neutralisation sludges are stable when chemical conditions remain near those under which the sludge was formed. Metal hydroxide sludges dissolve under acidic conditions (remobilising precipitants). Sludges with excess lime (neutralising capacity) are more stable and less likely to remobilise metals. Ferric iron serves as a co-precipitant for other elements (arsenic and molybdenum) and decreases leachability.

Barium radium sulphate produced by barium sulphate precipitation is unstable under reducing conditions ($BaSO_4$ reduces to BaS, releasing radium).

Some elements such as arsenic and molybdenum are less stable in sludges. Arsenic is typically precipitated as $FeAsO_4$ (ferric arsenate), which is unstable and slowly decomposes to iron hydroxide and arsenate ion. The stability of this precipitate is dependent upon the Fe:As ratio and other cation levels in the sludge (e.g. calcium). At near neutral pH levels, and Fe:As ratios of 5 or more, these precipitates do not leach significant levels of arsenic. Molybdenum is typically precipitated as an iron molybdate complex, which is also unstable. At pH levels above 5.0, the complex degrades rapidly, releasing molybdenum into solution. Under mildly acidic conditions, molybdenum leaching rates are not expected to be significant.

The following factors should be considered in establishing sludge stability:

- Changes in pH (acidic/alkaline) and temperature.
- The mixing of waste streams to increase stability.
- Change in oxidising/reducing conditions.
- Change in chemical, biological or environmental conditions.
- Exposure to water (rain) and leachability.
- Stability of chemical compounds and precipitates (decomposition or remobilisation).

7.6 Product Recovery

As water treatment technologies are often expensive requiring large capital and operational cost, recovering some of the cost is an attractive option. The waste stream from one process may, in fact, be a feedstock for another process. The concentrated brines and sludges produced in water treatment plants may, after appropriate investigation, be found to provide opportunities for the recovery off valuable by-products that will offset operating costs and reduce risk and liability. By-products recovered can be used in the following ways:

- If the product has a market value, it can be sold to recover some of the water treatment cost.
- If the product has some internal value or use, it can be reused in the mine process. This also has an indirect cost-benefit in that the mine saves on the purchase of raw materials from outside.
- Recovery of by-products can also significantly reduce the volume of waste to be disposed of, with resulting cost savings and reduction in long-term risks and liabilities

7.7 Screening Assessment

Refer to Section 5.6.

8 FINANCIAL REQUIREMENTS AND RESPONSIBILITIES

Cost factors are site-specific and are always an integral and key component of the decision-making procedure. Cost factors associated with water treatment include but are not limited to:

- Land cost - for the water treatment plant (cost associated with obtaining surface area or sacrificing valuable mining land to place plant infrastructure).
- Capital cost - design and building cost for the water treatment plant (depends on the size and complexity of the plant).
- Operational cost - labour, chemicals used, mechanical, physical, energy, etc.
- Maintenance cost – maintenance of plant and equipment (replacement or repair of pipes, pumps).
- Monitoring cost - monitoring of plant performance, impact monitoring, etc.
- Waste management/disposal cost for treatment residues - land used for waste disposal, lining and leachate/drainage system for waste disposal site, off-site transport and disposal, further treatment, operational cost for waste disposal facility, legal compliance cost, maintenance and monitoring of waste disposal facility. Also provide for future sites or expansions to existing sites, thereby considering the life of the water treatment plant.
- Legal cost - compliance with all the necessary applicable legislation/requirements, preparation of necessary documentation for submission to authorities, specialist studies required, liabilities, etc.
- Discharge cost - waste discharge charge system, liabilities, impact on downstream users, water supply to downstream users, etc.
- Income from sale of water

These cost elements should be considered and planned for, for all the different stages/phases of the mine life-cycle (operational, decommissioning and closure, post-closure). Management should allocate and ensure sufficient resources (financial/funding, personnel) and responsibilities for all tasks during all phases of mining.

The cost evaluation should be undertaken over a standard period, such as 20 or 25 years, and all costs should be considered in terms of appropriate financial considerations (e.g. Net Present Value [NPV]) using agreed rates of return. Capital replacement cost should also be considered. The replacement period to use in cost calculations is driven by:

- Company policy/practice
- Water treatment plant replacement period (how long the plant will last)
- Period over which treatment is required
- Tax implications

The precise plant design is very dependant on the feed water quality and the treated water quality objectives and therefore it is not considered feasible to provide standard cost factors, which can be used. An additional consideration is that direct conversion from cost estimates undertaken in other countries, using currency exchange rates, is not valid and cost factors relevant to the intended location of the plant must be used. The input of appropriate specialists will be required to undertake the cost estimation exercise.

Flow rate/volume is considered a critical parameter for water treatment technology but the water treatment technology decision should also be based on a risk and cost benefit assessment (technical, economical, social and environmental feasibility).

Different approaches/models can be used for the funding of water treatment and the following can be considered:

- Partnerships (industry-education-government institutions)
- Sell water resulting from treatment process
- Sell valuable by-products recovered
- Water utilities

9 PROCESS PERFORMANCE RISK ASSESSMENT

Section 6 identifies the parameters of particular importance to the water treatment process as the inflow rate/volume and the raw water quality. Variations in flow rate and quality of the inflow can cause process performance efficiency to reduce or even fail if not managed properly. If these factors are not managed properly they can have detrimental consequences such as:

- infrastructure damage (scaling, corrosion, pipe raptures, overflows, flooding, etc),
- loss of human lives (operators or downstream),
- water of unsuitable quality for discharge or particular use (due to insufficient retention times, etc),
- further treatment requirements (due to unsuitable quality), and
- other downstream impacts on water users (water availability, etc).

Variations in feed flow rate/volume can be managed in both passive and active systems by designing and installing appropriate management measures as part of the water treatment plant or prior to the treatment process or as an optional diversion when required. Flow equalisation ponds can for example accommodate varying inflow while ensuring a near constant outflow from the dam to the water treatment plant (also see Section 6).

Due to the presence of plant operators and constant supervision, together with process instrumentation and control systems, active water treatment plants generally have a better capacity to deal with variations in raw water quality. This can be managed by adjusting reaction times, amount of reagents added, number of modular units brought into operation, etc. Active systems can therefore ensure near 100% compliance through the provision of extra capacity or emergency storage facilities or by modifying process conditions to deal with the changes in feed conditions.

Due to the fact that passive water treatment systems make use of natural processes for the removal of constituents, there is always a risk that for limited periods of time, treatment objectives may be exceeded. Appropriate design of the passive water treatment systems can ensure that this is minimised and compliance of the order of 95% could reasonably safely be assured.

The water treatment technology decided upon should be based on the degree and surety of removal of constituents required. Pre-treatment may also be required depending on the treatment technology selected and the objectives to be met. Reduced process performance may cause the objectives to not be achieved (reduced outflow water quality) and therefore impact on the environment or downstream users with resulting consequences if appropriate management measures are not in place. The following factors should be considered:

- Degree and surety of outflow required.
- Water user requirements (Section 4) – acceptable range; consistency.
- Process technology's ability or capacity to handle and deal with variations.
- Process technology's tolerance to changes in feed.
- Expected inflow variance in terms of quantity and quality.
- Possible consequences of reduced process performance.
- Flexibility of process technology (adjustment of reaction times; modular units added).

10 TREATMENT PLANT SUSTAINABILITY

It is important to consider for how long water treatment is required (expected duration) and during which phase of the mine's life-cycle it is required. A particular water treatment technology is seldom applicable over the entire life-cycle of the mine and therefore it becomes important to determine when it is required: during the operational phases of the mine or after closure. Water treatment requirements differ over the various mine life-cycle phases and therefore the water treatment technology required may differ. Predictions on future requirements will identify future changes required in terms of the treatment technology.

The major advantage of passive treatment over active treatment is that the operating cost is lower (no plant operator required, limited maintenance, no external mechanical/electrical requirements), especially at low flow rates. Therefore, the longer the anticipated need for treatment to continue after mine closure, the greater the advantage of passive treatment over active treatment. An additional advantage of passive treatment in the post-closure phase is that there are no components of the plant that have salvage value and hence the incentive for theft is reduced.

It is necessary to already define post-closure water treatment requirements during the planning and operational phase of the mine in order to plan for anticipated maintenance, operating and financial requirements after mine closure.

Appropriate geochemical, geohydrological and hydrological modelling will provide a prediction of the long-term water quality and quantity that can be expected for each possible water pollution source (see *BPG G4: Impact Prediction*). Interrogation of this prediction will indicate which water treatment technologies are favoured. The appropriate type of water management and treatment is very dependant on the period in the life of the mine. For example, water quality and quantity during the operational phase of the mine and the decommissioning phase will differ significantly. It is therefore important to determine or obtain an estimate of future water quantity and quality before deciding on a treatment technology. The water volumes may decrease as mining and processing is ceased and the water quality may improve, resulting in no treatment required. However, a few years later the underground mine may start decanting, increasing mine water volumes and the water quality may be poor due to its contact with oxygen and pyrite and therefore require treatment.

11 LABORATORY/PILOT PLANT STUDIES

Laboratory or pilot scale studies are required where a decision on the water treatment technology to be used or treatment plant design cannot be finalised because of uncertainties and are also important in terms of emerging technologies (Section 5.5). Laboratory or pilot scale studies should therefore be undertaken where significant uncertainty exists with regards to the following:

- Product water characteristics (downstream user requirements; discharge/treatment objectives).
- Waste/residue characteristics (hazardousness, disposal requirement, further treatment, Section 7).
- Ability of the proposed water treatment option to adequately deal with or respond to feed water changes or variability (quantity and quality) or potential process upsets (Section 9).
- Operability (Section 6) and integration of processes/technologies.

All laboratory or pilot plants should be operated in a manner consistent with the anticipated full-scale plants.

The application of anaerobic passive treatment technology is preceded by site-specific pilot plant studies aimed at generating design data appropriate to that particular application. Sufficient experience however, is available to design passive aerobic systems such as aerobic wetlands and anoxic limestone drains without pilot plant studies.

Passive treatment can be considered proven technology for the removal of acidity and most heavy metals and sufficient understanding and experience is available to confidently design appropriate treatment plants. This is not yet the case with regard to high rate sulphate removal or the removal of radionuclides. Whereas there is information which indicates high removal of uranium, there is insufficient information available on the behaviour of radium, thorium and other radionuclides and this will need to be demonstrated through appropriate pilot plant studies.

Desalination processes often require pilot plant studies in order to optimise the pre-treatment configuration that is generally required to protect the membranes and to test the configurations that are proposed to attain the extremely high water recovery values that plants are currently being designed for.

Previous successful implementations of water treatment plants and examples should be used when laboratory or pilot plant studies are undertaken to investigate specific issues with regard to a particular treatment technology.

Where the selected treatment plant incorporates the integration of a variety of unit processes, with the performance of a preceding process potentially affecting the performance of the subsequent process, it is especially important to ensure that appropriate pilot plant studies of the complete integrated process are undertaken. It is essential to resolve any process conflicts or upsets prior to the final design of the integrated plant.

12 ABBREVIATIONS AND TERMINOLOGY

Active process:	In this document refers to a process that employs mechanical and/or electrical energy. Also refer to passive process
Adsorption:	Accumulation of a substance on a surface or interface
Aerobic:	An environment exposed to oxygen from air; oxygen rich environment or process; oxidising conditions. (Also refer to anaerobic.)
AMD:	Acid mine drainage
Anaerobic:	An environment deficient in oxygen; reducing conditions
Anion:	Faraday's term for an ion carrying a negative charge. (Also refer to cation.)
Brine:	Concentrated salt solution
Cation:	Faraday's term for an ion carrying a positive charge
Desalination:	Process whereby salts are removed from a solution, include a wide range of technologies that have this ability
DWAF:	Department of Water Affairs and Forestry
ECA:	Environmental Conservation Act, 1989 (Act 73 of 1989)
EDR:	Electro-dialyses reversal
Hydrograph:	A graph showing and describing the variation of water flow/quantity over time
Ion:	Electrically charged particle released by dissociation of an electrolyte
IWWM:	Integrated water and waste management
IX:	Ion exchange
Monovalent:	Atom with a valence of one
NEMA:	National Environmental Management Act, 1998 (Act 107 of 1998)
NF:	Nano filtration
NWA:	National Water Act, 1998 (Act 36 of 1998)
Oxidation:	Reaction in the presence of oxygen or an oxidising substance. Also refer to reduction
Passive process:	Process requiring limited supervision, intervention and maintenance as it makes use of natural driving forces such as gravitational flow and sunlight energy (heat)
Reduction:	Reaction in the absence of oxygen or in the presence of a reducing substance
RO:	Reverse osmosis
SRB:	Sulphate reducing bacteria
SRO:	Seeded reverse osmosis
SRU:	Sulphate reducing units
Thermal:	Elevated temperatures involved as heat is added
TRO:	Tubular reverse osmosis
Water reuse:	The use of water in the same or another process without treatment
Water reclamation:	The use of water within the operation after treatment has been applied in order to enable the water to be used

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APPENDIX A

SELECTION OF ACTIVE TREATMENT TECHNOLOGY

If a decision has been made to evaluate and consider active treatment technology options, then the decision procedure shown below can be used to assist in defining the appropriate combination of active technologies for an integrated active treatment system. This logic diagram is designed with key decision points based on TDS, recalcitrant metals such as arsenic, dissolved metals, sulphate and residual metal and radionuclide concentrations.

TDS removal by reverse osmosis (RO), electrodialysis reversal (EDR) or ion exchange (IX) produces a concentrated brine stream that must be disposed of in an appropriate manner or treated further by thermal processes. Thermal evaporation would be used only for treating streams containing high levels of dissolved salts such as calcium sulphate, sodium sulphate and sodium chloride. Thermal treatment systems produce effluents that are acceptable for discharge and a solid residue, which must be disposed of properly.

Recalcitrant metals include arsenic, molybdenum, antimony, chromium and selenium. These metals are not precipitated by conventional neutralisation processes and must be removed using alternative methods. Chemical precipitation may be preceded by an oxidation or reduction step, if necessary. The resulting sludges must be disposed of in specially designed facilities or sent to hazardous waste disposal sites.

The most effective and proven method for radium removal is by barium precipitation. The sludge from this process must be placed in an engineered impoundment.

A number of options are available for the treatment of metals and acidity including chemical precipitation using a base (i.e. lime), sulphide precipitation by chemical addition (i.e. Na_2S) or by using active biological sulphate reduction and possibly passive treatment. The selection between these alternatives would be based on economics (cost), phase of mine and treatability (quantity and quality of wastewater stream to be treated versus objectives) studies.

Several options exist for the removal of sulphate including chemical precipitation with barium or calcium aluminate, IX using GYP-CIX, RO, EDR, active biological sulphate reduction or passive sulphate reduction. Again, the choice between options would be based on cost, phase of mine and treatability.

A final polishing stage using specialty precipitants (such as flocculants) may be necessary to remove residual concentrations of metals and radionuclides, depending on the efficiency of removal by preceding treatment steps.

Once the constituents requiring treatment have been identified, a long list of treatment options can be generated. Using the process principles and descriptions given in Chapter 6, as well as experience from other sites around the world, some of the processes identified may be deleted from the list to create a short list of treatment options. Experience from other sites may indicate that certain process alternatives are simply not feasible due to cost, process complexity or an inability to reach product water standards.

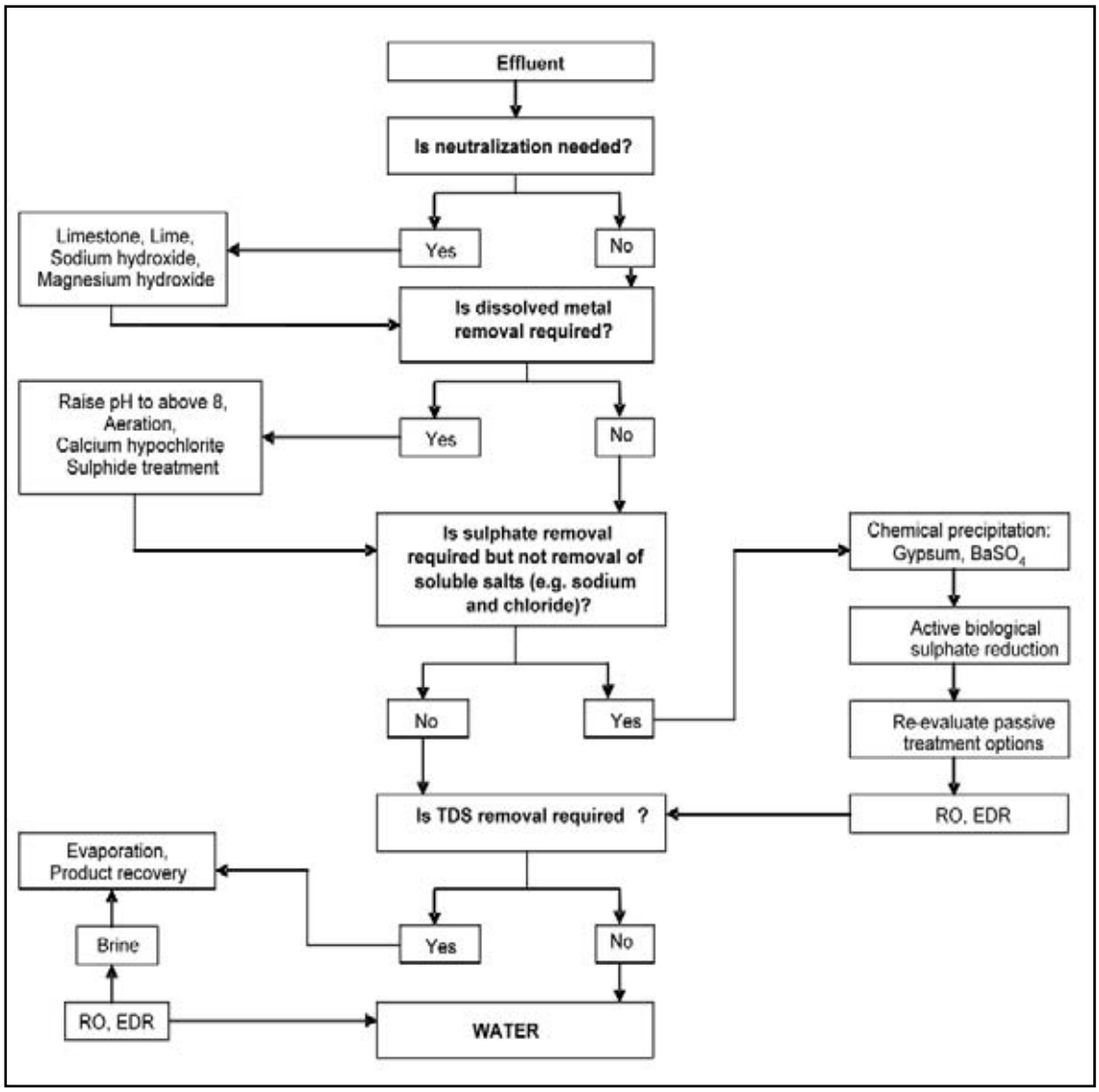
Treatability studies can be designed and initiated based on water characteristics and the short list of identified treatment alternatives. These studies are necessary to determine the potential treated water quality, reagent demand and residue production that may exist for a particular treatment alternative. Results of the treatment studies would be used in a cost benefit analysis to come to a final decision on the optimal treatment configuration.

The process described above for the selection of treatment technologies is subject to a number of limitations and caveats, which would include;

- presence of interfering constituents (e.g. sodium for sulphate precipitation, carbonate for uranium precipitation, oil and grease for adsorption processes, etc.)
- requirement for laboratory treatability studies to define actual limits achievable and specific design requirements (e.g. overflow rate for solid-liquid separation, reactor residence time for arsenic precipitation, etc.)
- other factors, such as scaling and resin fouling that can only be assessed through detailed testing.

Example of selection procedure for Active Treatment Systems

Different flowcharts could be prepared for different contaminants.



APPENDIX B

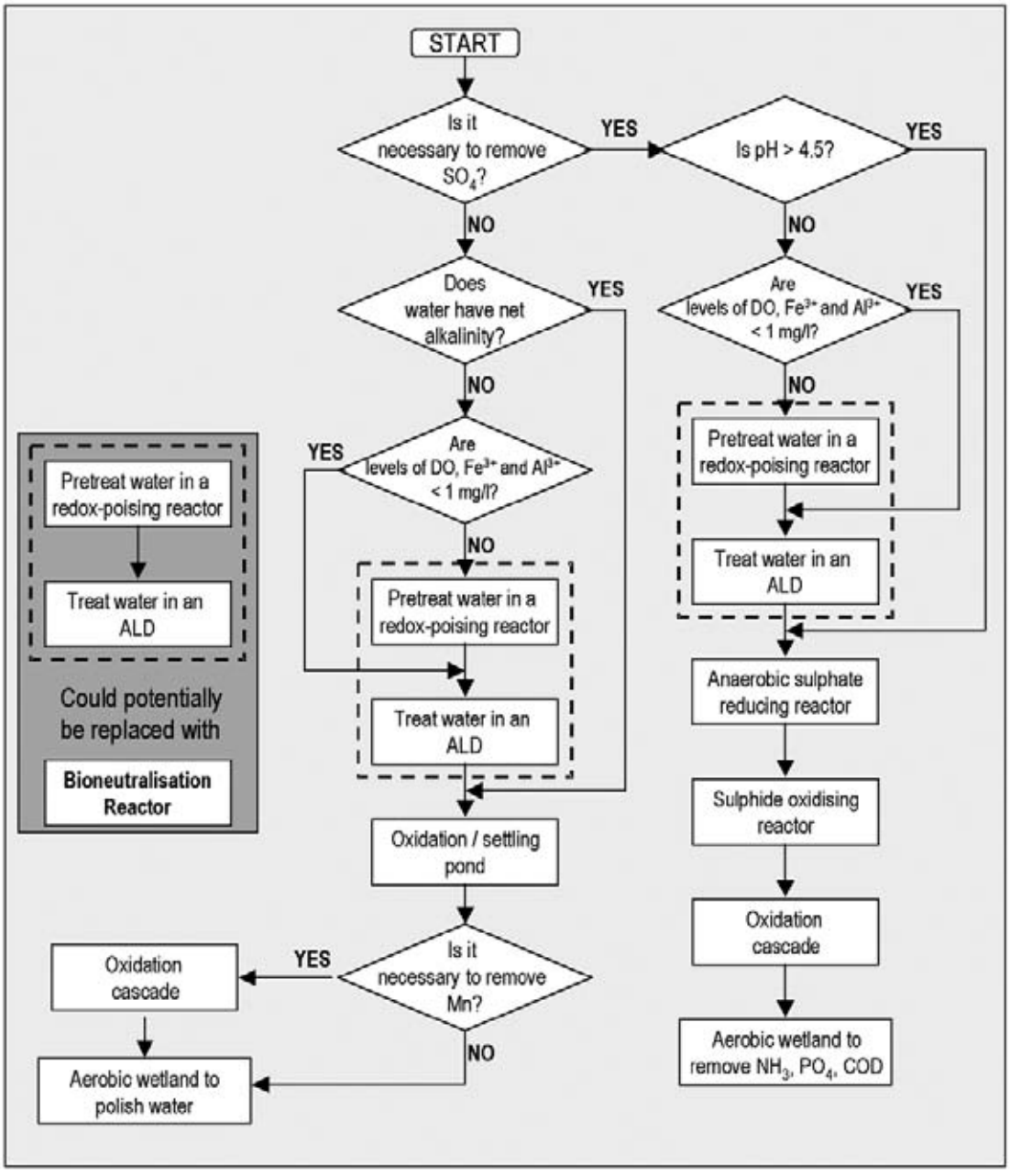
SELECTION OF PASSIVE TREATMENT TECHNOLOGY

If a decision has been made to evaluate and consider passive treatment technology options, then the decision procedure shown below can be used to assist in defining the appropriate combination of passive technologies for an integrated passive treatment system. The decision procedure also clearly indicates whether an aerobic (oxygen-rich) or anaerobic (oxygen-deficient) treatment technology is most appropriate.

Key questions that need to be answered in this selection process are:

- Is it necessary to remove sulphate? If it is necessary to remove sulphate then anaerobic systems are essential. These systems will simultaneously remove acidity, heavy metals and radionuclides.
- Does the water have net alkalinity? The assessment of net alkalinity is undertaken by comparing measured alkalinity with calculated acidity. This evaluation is important, as the removal of metals in aerobic systems is dependent on the presence of sufficient alkalinity. If there is insufficient alkalinity then the water will need to undergo treatment to add alkalinity before metals can be removed. In anaerobic systems, metals will precipitate as hydroxides if sufficient alkalinity and hydroxide anions are available.
- Are dissolved oxygen (DO) levels, Fe^{3+} and Al^{3+} <1 mg/l? If an aerobic treatment configuration is desired and the water has insufficient alkalinity, then pre-treatment in an Anoxic Limestone Drain (ALD) will be required. An ALD is only feasible if dissolved oxygen, ferric iron and aluminium are each below 1 mg/l, thereby preventing the ALD from incurring serious fouling.
- Is pH above 4? Water with higher pH values and high metal concentrations can precipitate metals under oxidizing conditions in a pond. For pH values below 4 it is important to keep conditions anaerobic to achieve objectives.

Selection Procedure for Passive Treatment Technology



APPENDIX C

WATER TREATMENT PROCESSES

ACTIVE WATER TREATMENT PROCESSES

PHYSICO-CHEMICAL PROCESSES

1 pH Adjustment

Chemicals/reagents used for neutralisation of acid mine drainage:

Chemical name	Chemical formula/ active ingredient	Neutralising Capacity *	Relative Cost**	Comments
Calcium oxide (quicklime, caustic lime)	CaO	1.0	1.0	Very reactive
Calcium carbonate (limestone)	$CaCO_3$	1.79	0.3	In passive systems it is most successful under anaerobic situations as reactivity can be reduced by precipitates armouring particles (reduce reactive surface), which may require physical scouring (fluidisation). Self-controlled (over-dosing not a problem) since it will not dissolve above pH 8.3. Active systems can be operated under anaerobic or aerobic conditions as the possibility of armouring can be overcome in an active system
Calcium magnesium carbonate (dolomite)	(Ca, Mg) CO_3			Similar to limestone though less reactive.
Calcium hydroxide (hydrated lime)	$Ca(OH)_2$	1.33	1.6	Requires extensive mixing. Low density sludge (1-5%) and therefore bulky for disposal.
Sodium hydroxide (caustic soda)	NaOH	1.43	8.8	Very costly but readily available and highly soluble. Available in solid form or in solution. Careful and accurate control required and possible – prevent high pH. Hazardous, corrosive nature requires special handling, storage, dosing etc (worker protection). Less sludge produced than for lime. Metal hydroxide precipitation. Sodium sulphate (soluble) in effluent.
Sodium carbonate (soda ash)	Na_2CO_3	1.89	3.5	Usually in briquette form. Used for remote locations. Less hazardous than sodium hydroxide and less sludge than lime. Over-dosing not a problem. Adds buffering capacity and reduce scaling.
Potassium hydroxide	KOH			Similar to sodium hydroxide.
Magnesium oxide (magna lime)	MgO	0.72	3.4	Similar to calcium oxide. Result in highly soluble Epsom salts. 20-30% of sludge generated with lime neutralisation. Due to low solubility, a plug flow or parallel batch reactor system is required. Reaction time is 5-15 minutes.

Chemical name	Chemical formula/ active ingredient	Neutralising Capacity *	Relative Cost**	Comments
Magnesium hydroxide	$Mg(OH)_2$	1.04	4.9	Similar to calcium hydroxide.
Ammonia	NH_3 or NH_4OH			Reactive and soluble. Supplied as aqueous ammonia. Effective for manganese removal. Strict control required due to possible harmful effects with handling and on the environment.
Calcium peroxide (trapzene)	CaO_2			Neutraliser and oxidant. Supplied as a powder or as briquettes.
WASTE PRODUCTS: Concerns with respect to variation in availability and content. A waste product from one industry being used in treatment at another has liabilities, legalities, leaching etc associated with it which requires investigation, consultation with DWAF.				
Kiln dust	$CaO.Ca(OH)_2$			Waste product of cement industry. Contains lime.
Coal-use residues (fly ash)	$CaO.CaCO_3$			Many coal-use residues contain lime or carbonate. Neutralisation potential varies between sources. Application as alkaline backfill material, soil amendment, cover material, amelioration of AMD by layering/blending with acid generating wastes, etc. Unlikely in an active system due to high level of inert material and possibility of Mg, SO_4 & metal leaching

* *Relative to CaO*

** *Relative to CaO, corrected for differences in neutralising capacity*

Drawbacks: high establishment and ongoing costs (a maintenance intensive system); sludge requires separate disposal.

Factors influencing selection of calcium or sodium compound for AMD treatment (Skousen 1996):

Factor	Calcium	Sodium
Solubility	Slow	Fast
Application	Requires mixing	Diffuses well
Hardness	High	Low
High total suspended solids or clay particles	Helps settle clay	Disperses clay particles and keeps clay in suspension
Chemical cost	Lower	Higher
Installation and maintenance costs	High	Low

Carbon dioxide (CO_2) is another commonly used reagent for pH adjustment. Addition of carbon dioxide is usually performed after neutralisation with a strong neutralising agent in order to reduce the pH to meet discharge requirements. Carbon dioxide reacts reversibly with water to form carbonic acid, which deprotonates (loses its hydrogen cation) causing the pH to decrease (due to the H^+ in solution). CO_2 is cheap but requires special handling (compressed gas).

The High Density Sludge (HDS) process is the most common adaptation that has been adopted by the mining industry for neutralisation and precipitation. This process is very similar to the conventional system with a portion of the sludge being recycled and mixed with the lime slurry prior to mixing with the acidic drainage. Underflow sludge from the clarifier is recycled at a ratio of up to 50% of the influent flow and provides a surface for crystal growth of precipitates formed during neutralisation. The sludge particles thus become more granular and dense (sludge density of 20-30%) than in a conventional neutralisation system. Examples of commercial HDS processes include: Comonco, TetraHDS, Geco Staged neutralisation, Unipure, Keeco-Silica Micro Encapsulation Technology, Aquafix, Hazleton Iron Removal System, Modular Environment Technologies-the HARDTAC process, Virotec Bauxsol process, Mintek Savmin process, Hydrometrics CESR process.

2 Metal Precipitation

Metal hydroxide precipitation: Metal hydroxide solubility is a direct function of the solution pH and generally minimum solubility occurs between pH 8 and 11 (see table below). The basis of this treatment is the addition of a base reagent (e.g. lime, caustic soda) to raise the pH of the water to the point where insoluble metal hydroxides form.

Metal ion to precipitate as hydroxide	Minimum pH for complete precipitation
Sn^{2+}	4.2
Fe^{3+}	4.3
Al^{3+}	5.2
Pb^{2+}	6.3
Cu^{2+}	7.2
Zn^{2+}	8.4
Ni^{2+}	9.3
Fe^{2+}	9.5
Cd^{2+}	9.7
Mn^{2+}	10.6

Ferric hydroxide precipitates will also adsorb other metals (e.g. Cu, Ni, Co, etc.) from solution allowing them to be removed below their solubility limits. Ferric hydroxide is much less soluble than ferrous hydroxide and as a result the effluent stream is often sparged with oxygen, prior to neutralisation in order to oxidise ferrous ion to ferric and assist in precipitation of iron.

Metal sulphide precipitation: Metal sulphides tend to have much lower solubilities than metal hydroxides, often orders of magnitude lower. This implies that metal sulphide precipitation can be achieved with water with much lower metal concentrations than with metal hydroxide precipitation (lime neutralisation).

Metal sulphides in order of increasing solubility:

HgS<CuS<CdS ≅ PbS<ZnS<CoS<NiS<FeS<MnS.

Sulphide can be added in the form of a solid reagent or generated by the biological reduction of sulphate (discussed under biological processes). Reagents used for metal sulphide precipitation include sodium sulphide (Na_2S), sodium hydrosulphide (NaHS), and calcium sulphide (CaS). Drawbacks: Toxic hydrogen sulphide (H_2S) gas production (pH < 8); Downstream oxidation of residual sulphide reagent (formation of sulphur); High cost of sulphide reagents; Disposal of sulphide sludge (reducing environment to prevent re-oxidation); Ineffective for calcium, magnesium, uranium and radium. Sulphide product can be sold or recycled to a smelter for metal recovery.

Others:

- Ferric chloride (dry solid) or ferric sulphate (commercial - Ferrifloc) for the removal of arsenic and molybdenum (< 2 mg/l) as well as a flocculant/coagulant to improve settling of suspended solids. Ferric ion will react with/remove arsenic (< 0.5 mg/l with Fe:As $\geq$ 4:1 for precipitate stability), molybdenum and antimony to form insoluble compounds. Equipment should be able to handle corrosive character. Most acid mine waters contain sufficient iron for precipitation of these elements if all ferrous ion present is oxidised to ferric ion;
- Barium chloride for radium (best available technology to < 0.1 Bq/l) and sulphate removal. Barium sulphate co-precipitate with radium due to its low solubility. Retention times of > 30 minutes for crystallisation. Fine crystalline precipitate requires coagulant to promote settling. Tertiary removal (single/dual medium filtration) is required to remove radium (ANSTO, 1994);
- Lime or soda ash for calcium and hardness removal.
- Commercial products – Examples are GoPur 3000 and AMERSEP (stable sludge). Due to cost these are mainly used in polishing stages. Addition of these can reduce the leachability of metals from the treated sludge.
- Insoluble starch xanthate (ISX). High reagent costs and the dosage rate is between 7 and 20 times the metal concentration to be treated.

When present in sufficiently high concentrations, dissolved metals in acid waters may represent an economic resource. Recovery of metal through solvent extraction and electro-winning or other extraction technologies may be commercially viable. Solvent extraction, leaching and electro-winning technologies generally result in a wastewater, which may be more acid than conventional acid drainage, containing essentially the same constituents minus the metal targeted for recovery and neutralisation will be required.

Modifications:

Aeration or oxidation: The valence state of the metal greatly affects the solubility of the hydroxide (Fe^{3+} has a valence status of 3, it can thus share 3 electrons with another charged atom). As shown in the following order:

$Fe(OH)_3 = MnO_2 > Al(OH)_3 >> Fe(OH)_2 > Mn(OH)_2$

Insoluble → Soluble

Since $Fe(OH)_3$ and MnO_2 are insoluble, whereas $Fe(OH)_2$ and $Mn(OH)_2$ are soluble, the best route to achieve a stable precipitate is to oxidise the iron and manganese prior to precipitation, co-precipitation and adsorption of other metals, superior settling properties). Oxidation can be achieved by a passive, physical means, i.e. cascading the mine water (depending on area and head availability) or if this doesn't introduce sufficient oxygen by chemical oxidation through the addition of oxidants, catalysts, inline pre-aeration, or using micro organisms in a bioreactor (IWA, 2001).

Flocculants: Sludge formed by alkaline addition is generally low density, with a solids content of as little as 2%. It is therefore very bulky for disposal purposes. The precipitated hydroxides also tend to have a small particle size and thus need substantial amounts of time to settle out in the settlement tanks or tailings dam. Settling can be improved by the use of chemicals to aid the coagulation and flocculation processes, which in turn improve the settling efficiency. Flocculants, usually polyelectrolytes, may be added to the neutralised feed prior to liquid-solid separation.

3 Sulphate Removal

Barium compounds:

- Barium chloride
- Barium hydroxide
- Barium oxide
- Barium carbonate - Pulles, et al. (1995). A barium carbonate/lime slurry is added to an effluent stream containing sulphate. Sulphate and calcium are removed from solution via the following reaction:

$$BaCO_3 + Ca^{2+} + SO_4^{2-} \rightarrow BaSO_4(s) + CaCO_3(s)$$

The solids produced are thermally treated at 1 150ºC to produce barium sulphide and carbon dioxide. Barium sulphide is then reacted with water and carbon dioxide to produce barium carbonate and hydrogen sulphide. The barium carbonate is recycled to the treatment system, and the hydrogen sulphide can be converted into elemental sulphur.

For barium salt addition, typical requirements for sulphate removal are the addition of 2.2 kg barium salt ($BaCl_2$) per kg SO_4. Costs can be increased by more than three times over lime treatment, if one removes sulphate by chemical precipitation.

Calcium aluminate:

Calcium aluminate addition is marketed in the U.S. under the trade name Walhalla Process. The Walhalla process achieves dissolved salt reduction by precipitating sulphate as a hydrous calcium aluminium sulphate solid known as ettringite ($[Ca_3Al(OH)_6.12H_2O]_2(SO_4)_3.2H_2O$).

The Walhalla process may be preceded by lime addition to pH 11.5 for heavy metal and sulphate precipitation/ removal, depending on the level of sulphate (> 4 000 mg/l) and dissolved metals in the influent stream. Calcium aluminate addition can easily remove sulphate (SO_4 < 100 mg/l) from a gypsum-saturated stream but is limited in the presence of sodium (Na > 1 000 mg/l requires presence of equivalent amount of chloride) due to the solubility of sodium sulphate.

The Walhalla process claims to reduce fluoride, phosphate and boron to less than 1 mg/l, arsenic, selenium and cadmium to less than 0.005 mg/l and reduce chloride by 20% and nitrate by 30%. Other constituents present in the aqueous phase are incorporated into the crystal structure during the precipitation of ettringite and are thereby removed from solution. The solid waste produced is not susceptible to leaching and can be re-used in premanufactured (prefab) concrete products.

The addition of calcium aluminate is more effective in removing sulphate to lower levels than for example gypsum precipitation through lime addition. It is less costly than RO and the chemical used is not as hazardous as for example barium chloride. Calcium aluminate can remove sulphate to as low as < 5 mg/l it is claimed, and simultaneously remove metals.

4 Ion Exchange

Ion exchange (IX) is the reversible process of transferring undesirable ions (i.e. Cu^{2+}, Ni^{2+}, Ca^{2+}, NH_3^+, AsO_4^{3-}, SO_4^{2-}) from an aqueous solution to a solid support with the simultaneous transfer of innocuous ions (i.e. H^+, and OH^-) from the solid to the solution. This process is widely used in a variety of industries for the purification of water (e.g. residential water softening) or the recovery of a valued component from solution (e.g. concentration of gold cyanide complexes).

Ion exchange resins consist of an insoluble support that has active functional groups attached to it. The functional groups are ionogenic (capable of dissociation) and are electrostatically balanced with mobile ions of the opposite charge. Cation exchangers are used to replace metals, and other cations in solution with H^+ or Na^+; anion exchangers substitute sulphate, phosphate, etc. with OH^- or Cl^-. Loaded resins are regenerated with acid or caustic concentrated solution of counter ion), depending on the type of resin, to produce a concentrated brine containing the ions removed from solution and mostly requires treatment prior to disposal.

A number of natural materials exhibit ion exchange capabilities: zeolites (a class of aluminosilicate minerals), coal, metallic oxides and some types of algae and bacteria. Hundreds of synthetic ion exchange resins have been developed and they tend to be more efficient than natural ion exchangers, have higher capacities and can be designed to be highly selective. The properties of a particular resin are largely defined by the functional groups attached to it.

In general, ion exchange is not economically feasible for treating large volumes of concentrated wastewater due to the high cost of regeneration agents and the need to treat a concentrated regeneration brine. Resin replacement will be required due to physical degradation of the resin and irreversible fouling by scaling, organics and some metals (e.g. cobalt).

Ion exchange may have applications as a secondary treatment step to selectively remove specific constituents such as heavy metals, ammonia, radionuclides or calcium sulphate. Ion exchange tends to be limited to moderate strength waste waters (TDS less than 350 mg/l).

Commercial examples:

- Desel: removes sulphate (< 2 000 mg/l) in exchange for bicarbonate.
- Sirotherm (CSIRO): removes TDS (< 2000 mg/l) and uses hot water as a regenerant and not a chemical.
- CHEMEFFCO GYP-CIX process - desalination of scaling calcium sulphates and other salts and metals.
- Insoluble starch xanthate (ISX) - cereal grain-based ion exchange medium that exchanges sodium and magnesium for heavy metal cations. Used for plating wastes but not treatment of mine waters.
- KAD technology - remove metals using kaolin amorphous derivative
- Dynaphore Inc-FORAGER Sponge - open celled cellulose sponge containing a polymer with selective affinity for dissolved heavy metals in both cationic and anionic states.
- Octolig MRP - removes metals by chelation on immobilized ligands.

Capital and operating costs could be 20 to 40% more than for lime treatment since ion exchange unit/circuit is added (rest is similar). Ion exchange becomes economical when lower sulphate levels are required and to achieve these levels.

The presence of base metals (zinc, copper) gives rise to the possibility that costs may be offset against the value of the metal recovered. The valuable metals from the mine water would then be stripped before conventional treatment. Metals can be eluted from the ion exchange medium in a much more concentrated form. Due to high cost (and high flow rates), the cost for producing the metal becomes greater than the potential value or the profit so small that initial costs for installing the technology would not be repaid for many years. Furthermore, in the case of post-closure mine water treatment, the metal reclaimed and the associated economic gain would tend to decrease over the life of the plant due to the gradual improvement of mine water quality that is frequently observed.

5 Membrane Processes

All separation processes using membranes separate the feed stream into a permeate (the desalinated water) and a concentrate (the stream in which the salts are concentrated). Membrane processes can be distinguished based on the driving force for removal and the type of molecules rejected by the membrane (Particulates, Divalent Ions, Monovalent ions). Reverse osmosis (RO) removes all ionic species, although acidic and basic dissolved gasses are quite poorly rejected, depending on the pH. (Nanofiltration (NF) is used to separate larger molecules such as sugars and divalent salts; ultrafiltration (UF) can retain proteins and colloids in the 0.001 to 0.1μm range; and microfiltration (MF) is used for sterilisation and removal of suspended material ranging in size from 0.1 to 10 μm.)

Reverse Osmosis

Osmosis is defined as the spontaneous movement of water through a semi-permeable membrane from a dilute solution to a more concentrated one. The

movement of water through the membrane causes an increase in pressure in the concentrated solution. Upon equilibrium, the pressure difference between the dilute and concentrated solutions is called the osmotic pressure. A pressure difference across the membrane in excess of the osmotic pressure of the concentrated solution drives water through the membrane from the concentrated solution to the dilute solution. This is called Reverse Osmosis.

The basic components of a RO system are the semi-permeable membrane, membrane support, pressure vessel and a high-pressure pump.

Four configurations exist: plate and frame, tubular, hollow fibre and spiral wound. Plate and frame units are not commonly used but consist of annular disk membranes and support plates, which are stacked inside a pressure vessel. Hollow fibre units contain hundreds of thousands of small (approximately 80 µm o.d.) fibres, which result in a large surface area per unit volume and therefore can treat high volume streams. The hollow fibre system however, is extremely susceptible to fouling and difficult to clean. Tubular and spiral wound units are the most commonly used due to ease of cleaning and comparative resistance to fouling. Spiral wound systems tend to have larger membrane surface areas per unit volume than tubular units and therefore can treat higher volumes of effluent with a smaller circuit. Tubular units are the least susceptible to fouling resulting in lower pre-treatment requirements.

Operating pressures range from 0.5 - 5 MPa for brackish water desalination and 5 - 10 MPa for seawater desalination. Important variables for RO are feed flow rate, concentration and type of dissolved species, operating pressure, temperature and pH. Water recovery is generally 80 - 90% and salt rejection approximately $\geq$ 80% depending on the system design and requirements.

RO systems are susceptible to fouling by particulates, gas bubbles and other fouling constituents and therefore the feed water must be pre-treated. Fine particulates and colloidal silica are usually removed by microfiltration.

Scaling agents (i.e. iron salts, silica, calcium/barium/strontium sulphate and calcium carbonate/fluoride) can cause precipitation on the membrane when saturation conditions are met at the membrane surface. Calcium removal by ion exchange or soda softening and the addition of anti-scaling agents can help to alleviate some of these scaling problems.

Calcium sulphate scaling (characteristic of many mine waste waters) thus represents a major challenge to the use of RO in treating mine waters saturated in this compound. This has been overcome by the Keyplan High Recovery Precipitating Reverse Osmosis (HiPRO®) process which is being implemented by Anglo Coal at the Emalahleni Water Reclamation Plant (Gunther, et al 2006). Here a plant is being constructed to recover 20Ml/day of fresh water from acidic mine waters saturated in Calcium Sulphate. This is achieved through the use of Ultrafiltration pre-treatment and the use of antiscalants allowing 300% $CaSO_4$ saturation levels to be maintained in the RO plant. Subsequent re-treatment of the brine and precipitation of gypsum allows a water recovery of 99% to be achieved. This reduces problems and costs of disposal of the highly concentrated brine traditionally associated with RO systems.

Gypsum seed: The incorporation of gypsum (calcium sulphate) seed crystals in the feed stream to promote the precipitation of calcium sulphate on the seed rather than on the membrane. Pilot-scale tubular RO operation (Juby, 1992) using seed crystals achieved salt rejection of 80-90% and 85-95% water recovery. High energy consumption, high gypsum recirculation rate and poor mass balance control of gypsum seed and brine was experienced.

SPARRO - Slurry Precipitation and Recycle Reverse Osmosis (patent 1988): Pilot plant produced 0.85 l/s of potable water. Initial pre-treatment required pH adjustment to 10 (NaOH), oxidation ($KMnO_4$), clarification (polymer flocculant), filtration (dual medium) and final pH adjustment (H_2SO_4) 5/6. Membrane degradation was experienced and attributed to bacterial attack on the cellulose acetate membranes and subsequently chlorination was added as a pre-treatment step. Neutralisation (NaOH), oxidation ($KMnO_4$) and flocculation were also discontinued due to cost considerations. The pilot plant was operated for ± 6000 hours with an average water recovery of 95%. Membrane flux rates decreased during operation (550-300 l/m^2/d), possibly due to compaction or fouling of the membranes.

Electrodialysis reversal (EDR)

EDR uses alternating anion and cation selective membranes. A direct current is applied across a stack of ion selective membranes, which causes ions to

move toward the corresponding electrode (anions move toward anode passing through anion permeable membranes and become trapped in the channel between membranes because it cannot move through cation selective membranes). The anode and cathode, as well as the brine and product channels, are periodically reversed, facilitating cleaning (self-cleaning) and reducing the potential for scaling of the membranes and pre-treatment requirements (filtration may be required to remove fine particles). To minimise fouling, remove gypsum (lime softening), iron and manganese (aeration and precipitation). Despite higher energy consumption with EDR, pre-treatment can be reduced (membranes are less susceptible to fouling) and it allows broader temperature and pH ranges. Product water quality is controlled simply by varying the current applied across the membranes.

6 Air Stripping

Volatile compounds can be stripped from a liquid stream by contacting the liquid with a gas stream. Air stripping is an effective method for the removal of ammonia, cyanide, hydrogen sulphide and other gaseous constituents.

The fundamental basis of air stripping is the partitioning of a volatile compound into the gas and liquid phase, until an equilibrium condition is reached. Henry's Law describes the equilibrium concentration in the gas and liquid phase. The rate of mass transfer is dictated by the interfacial surface area (size of gas bubbles) and the partial pressure of the volatile component in the gas phase. The mass transfer rate increases with a larger interfacial surface area and when the partial pressure of the volatile compound is far from its equilibrium concentration.

For ammonia removal, the pH of the effluent must be raised to $\geq$ 10.5 to convert ammonium ions into volatile ammonia. Operational problems with air stripping of ammonia include calcium carbonate scaling and increased solubility of ammonia at lower temperatures which requires higher air flow rates.

7 Oxidation/Reduction

Oxidation or reduction involves a change in the valency of an element to enhance its precipitation properties. Ferrous ion (Fe^{2+} with a valence of 2) is often oxidised to the ferric ion (Fe^{3+} with a valence of 3) prior to neutralisation, as the lower solubility of ferric ion enhances the precipitation and removal of the iron. Oxidation may also be achieved by addition of peroxide, chlorine, sulphur dioxide or other chemical oxidants, but oxygen is mostly used due to its lower cost. Selenium and chromium are less soluble in a reduced state and iron filings or sulphur dioxide are commonly used as reductants. Another example is the biological reduction of sulphate to sulphide, which has the benefit of removing sulphate from the effluent (through reduction) and simultaneously precipitating metal sulphides.

Electrolysis is an oxidation/reduction process that can be used for recovering dissolved metals by passing a direct current through the solution causing pure metal to plate out on the cathode. Off-the-shelf systems include the Extended Surface Electrolysis process (Dupont), Fluidised Bed Electrolysis (Akzo-Zout) and Eco-cell (Ecological Engineering). Electrolysis is excellent for recovering a high-grade metal product for resale but has a number of drawbacks such as high energy costs; sulphate and other anions are not removed; and the process is only suitable for streams containing more than 2 g/l of metal.

8 Softening

Soda ash (Na_2CO_3) or lime ($Ca(OH)_2$) can be added to remove calcium ions in the form of calcite/calcium carbonate (CaCO3). The following equations describe the softening reactions:

soda softening:

$$Ca^{2+} + Na_2CO_3(s) \rightarrow 2Na^{+} + CaCO_3(s)$$

lime softening:

$$Ca^{2+} + 2HCO_3^{-} + 2Ca(OH)_2(s) \rightarrow 2CaCO_3(s) + 2H_2O$$

The sludge produced is dense and stable with respect to leaching. Softening is only effective for removing calcium and carbonate hardness from solution, although some reduction of radium and magnesium levels may occur due to its co-precipitation with calcite.

9 Filtration

Filtration is a physical separation process generally used as a secondary or polishing step for the removal of fine suspended material. An example is the use of sand filters after radium removal with barium chloride because fine precipitates of barium sulphate are difficult to settle out and must be filtered in order to meet discharge requirements for total radium. Filtration may also be used

as a pre-treatment to remove suspended solids prior to other treatment processes such as reverse osmosis or activated carbon adsorption.

Filtration removes solids by two mechanisms. Mechanical straining retains particles larger than the filter pore diameter. Smaller particles are carried into the filter bed and may be retained by an attachment mechanism to the filter medium. Mechanisms of attachment to the filter medium include electrostatic interactions, polymeric bridging and adsorption, all of which will be affected by the presence of coagulants and the chemical characteristics of the water and the filter medium.

Granular media commonly used in wastewater filters include sand, anthracite and garnet. These media are used singly or in combination as dual or multimedia filters. Granular filters can be operated in down flow or up flow configuration, although down flow is more common. Backwashing or cleaning of the medium is required to prevent excessive head loss through the filter bed due to clogging. During backwashing the filter medium is fluidised by flow reversal to remove filtered material. Sparging with air provides extra turbulence. Backwashing frequency depends on solids loading on the filter.

The design of a granular media filter depends on the characteristics of the wastewater stream to be treated and important variables include the flow rate, suspended solids concentration (frequency of backwashing) and the particle size distribution of the suspended material.

Properly designed and operated filters should be capable of reducing the total suspended solid concentration to less than 5-10 mg/l.

10 Flotation

Physical separation of suspended material that does settle slowly can also be achieved by flotation. Fine bubbles of air are introduced and particulate matter attaches to the bubbles and floats to the surface due to the buoyant force of the combined particulate and air bubbles. The particles are collected at the surface and are removed by skimming.

Air bubbles can be introduced in three ways: by aeration under atmospheric conditions; injection of air while the liquid is under pressure followed by release of pressure; or, aeration followed by the application of a vacuum pressure.

The degree of removal can be enhanced by the addition of chemicals such as flocculants that lead to entrapment of bubbles in the flocs or surface-active compounds that augment the interfacial adsorption of the solids on the bubbles.

Factors to be considered in the design include the concentration of suspended material, the quantity of air used, the particle rise velocity and the solids loading rate.

11 Adsorption

Adsorption is defined as the inter-phase accumulation of a substance on a surface or interface. Only adsorption from the liquid phase to the solid phase was considered here. Constituents are attracted to the surface of the adsorbing substance (substance providing the surface or interface for adsorption of constituents) and held there by weak reversible forces such as van der Waals forces, electrostatic forces and hydrogen bonding. Adsorbent materials include activated carbon (regeneration possible for reuse), activated alumina (requires disposal after use) and many hydroxide flocs (e.g. $Fe(OH)_3$ also requires disposal after use).

Granular activated carbon (GAC) can be used to adsorb selected metals such as nickel, copper, lead, zinc and cadmium from acid mine drainage (Kilborn 1991). GAC can also remove radon (up to 95%) but has several drawbacks such as long contact times, accumulation of ^{210}Pb, ^{210}Po and ^{214}Bi in the system and regeneration or proper disposal of the spent GAC. GAC has limited application for the treatment of mine waters except for the removal and recovery of cyanide and gold cyanide complexes.

12 Thermal Evaporation Processes

Mechanical or thermal evaporation has been successfully employed for the purification of water and the production of a solid salt waste. Process configurations include single and multi-stage, natural recirculation, forced circulation, mechanical vapour recompression, falling film, multi-stage flash and fluidised bed evaporators. High quality effluents suitable for discharge/recycling are produced but capital and energy costs are high.

Thermal evaporation can be an economically viable process, particularly if waste heat or an inexpensive fuel source is available. Energy consumption varies with design, wastewater flow rate and concentration of dissolved salts.

In arid climates where pan evaporation exceeds precipitation, evaporation ponds (solar evaporation) can be used to concentrate liquid effluents. Evaporation ponds (large surface area with shallow depths) are considered a method of disposal due to the "loss" of a valuable resource (water) rather than treatment.

In cold climates where ambient temperatures can be utilised, freeze-thaw desalination based on water's natural freeze-thaw cycles has been developed (Delta Engineering, 1989). It relies on the simple fact that clean water freezes before salty water. Extensive research in South Africa found freeze desalination to be unfeasible since temperatures will have to be physically reduced, adding to the cost (World Water and Environmental Engineering, May 1999).

13 Sediment Removal

Sediment basins are an effective way to remove coarser-sized particles from sediment-laden runoff, i.e. sand-sized particles (0.1 mm diameter or larger). Sediment basins have to be large (surface area) to remove significant quantities of silt-sized particles (0.01-0.05 mm). For a medium-sized silt (0.02 mm diameter), a surface area of 1 000 km^2 per m^3/s of inflow is required to achieve a removal efficiency of 30%.

The ability of a sediment basin to remove sediment (removal efficiency) depends on the discharge through the basin and the particle size distribution of the inflowing sediment. Sediment inflows consist of a mix of particle sizes, as defined by the particle size distribution curve.

Biological Water Treatment Processes

1 Sulphate Removal

Sulphate-reducing bacteria (SRB) are used in a bioreactor (controlled biological manner) to treat contaminated mine water. SRB are a diverse group of anaerobic, heterotrophic micro-organisms. SRB oxidise simple sugars (represented by CH_2O) while simultaneously reducing sulphate according to the following reaction:

$$SO_4^{2-} + 2CH_2O \xrightarrow{SRB} H_2S + 2HCO_3^-$$

The organism assimilates a small amount of reduced sulphur, but virtually all is released into the external environment (hydrogen sulphide gas). If this metabolic end product comes into contact with metal ions, precipitation of metal sulphide occurs.

Pacques Thiopaq Process (Janssen 1997) comprises two biological treatment steps in separate reactors. First, sulphate is anaerobically converted/reduced to sulphide by sulphate-reducing bacteria, after which sulphide is converted to elemental sulphur by sulphur-oxidising bacteria with associated alkalinity production. Heavy metals in the mine water will precipitate as metal sulphides in the first reactor (recovery possible through manipulation of pH). Sulphur cake (separated by tilted plate separator) of up to 60% dry solids (after dewatering) and 95% purity is produced in the second reactor (possibly marketable for sulphuric acid production). Suspended solids are removed and then the effluent is polished in two or more polishing steps. Performance requirements include a temperature of 25-30°C, pH adjustment to 7. Depending on sulphate loads, different electron donors are used for the process - hydrogen gas (large), ethanol or an organic waste stream (small). Due to bacterial growth, settled excess biomass must be periodically removed (± 15 kg dry biomass produced/ton sulphate reduced).

The micro-organisms in the Upflow Anaerobic Sludge Blanket (UASB) reactor reduces the sulphate content of the incoming water to produce sulphide, which can combine with dissolved metals to induce metal sulphide precipitation. Polymeric flocculants and nutrients are added to the influent with a mixture of organic acids (reducing agent). The effluent from the reactor contains residual dissolved sulphide (not consumed by metal precipitation), which is then oxidised to elemental sulphur by air in a submerged fixed film biological reactor. Sand filtration is included for final liquid effluent polishing.

The Rhodes BIOSURE Process uses sewage sludge as the carbon source. The availability of carbon for biological sulphate reduction depends on the hydrolysis (breakdown to usable form) and solubilisation of the sewage sludge, which has been accomplished in the Falling Sludge Bed Reactor (FSBR). Full scale application is proceeding at Erwat, treating Grootvlei Mine water.

The NTBC Biosulphide process, is an integrated chemical–biological process designed to treat metal-contaminated, sulphate-rich mine water. The process can be divided into two stages: a chemical circuit for treatment, and a biological circuit in which reagents (dissolved and gaseous sulphide and alkalinity) are generated for use in the chemical circuit. Thus each

circuit can operate at maximum efficiency independent of the other. Thus smaller and less expensive reactors are required than for bioreactors.

CSIR-O-SURE Process is a one stage process in which the sulphate is biologically reduced to produce sulphide and alkalinity, which results in an increase of the pH of the AMD. The reactor system comprises a completely mixed system, with a clarifier and a recycle from the clarifier to the reactor to retain the sludge. Ethanol, to which a small amount of sugar is added, is used as the carbon and energy source. The sulphide produced can be treated with CO_2 gas, so that the sulphide gas thus produced can be fed through a $Fe(OH)_3$ solution to produce Fe^{++} and sulphur. The Fe^{++} can be oxidised to Fe^{+++} such that sulphur can be produced continuously. The sulphur produced is in a pure form and can be sold to industry.

CSIR Biomass Process is a one stage process in which the fermentation of biomass products, such as grass, and the biological sulphate reduction occur in one reactor. The biomass degradation, using rumen fluid containing the degradative microorganisms, produces Volatile fatty Acids (VFA) and other intermediates, which form the substrate for the biological sulphate removal process. Continuous sulphate removal to values <200 mg/l were achieved, when a small amount of grass was added daily and when the reactor was operated at 37 °C and at a pH between 6.6-6.9, to accommodate the rumen fluid microorganisms. The sulphide produced can be removed following the method as mentioned under the SCIR-o-sure Process.

Lawrence Consulting Ltd process is based on Pacques' process but is less capital intensive and uses a novel partial extraction burner to generate the hydrogen used as an electron donor (advantage over hydrogen generated by steam reforming used in Pacques process).

Hydrometrics process using a passive bioreactor with a substrate containing organic carbon at a mine with a small flow of acid mine drainage.

Waste stabilisation ponding process entails retaining large volumes of wastewater within earthworks ponds. The addition of an organic carbon source allows algal growth (Rose et al, 1998) on the surface and SRB at depth. Algae perform a function in metal immobilisation and also provide a renewable and sustainable biomass/ carbon source for the SRB.

Acidophilic bacteria: Generally SRB reactors contain neutraphilic bacteria and thus care is required to prevent exposure to low pH mine waters. Johnssen (2000) investigated two types of fixed bed reactors (separate and in tandem) where one contained acidophilic iron-reducing bacteria and fungi and the other contained acidophilic and neutraphilic SRB. Sulphate reduction was observed in mine water at pH 3 although the rates were lower than reported for circum-neutral pH systems.

Positive: high removal of metals, possible recovery of saleable metal sulphide concentrates and sulphur. Negative: H_2S gas emissions, sludge disposal issues.

2 Metal Removal

Biosorption by some microbial and plant materials has proved to be effective at removing metal ions from solution resulting in high metal loadings on the biosorbent. Metal ion biosorption by dead microbial biomass would appear to offer a number of advantages over the use of live biomass. Biosorption involves rapid physico-chemical reactions between metal cations in solution and binding sites on the microbial cell wall. Live microbial biomass can accumulate more metal per unit weight but the processes involved are generally slower and live biomass is more demanding in terms of environmental conditions. The use of dead biomass offers increased opportunities for metal recovery, since metals bound to the cell wall may be desorbed using electrolyte solutions from which the metal can be recovered by electrolysis (Butter et al., 1998).

Waste-activated sludge as a biosorbent can be obtained at a minimal cost. Sludges from a domestic origin were found to be more effective in biosorbing metals than sludges from an industrial origin (Bux et al, 1997). It was found that higher initial soluble metal concentrations resulted in faster kinetics. pH has a major influence on the biosorption reaction since hydrogen ions are capable of effectively competing with heavy metals for attachment to microbial cell surfaces and optimum pH was found to be 4 – 6. A fully mixed process design is required as well as the addition of polyelectrolytes to reduce solids content in treated effluent. The process is less cost-effective because of relatively low biosorptive capacity of sludge; large volumes and mass of sludge requiring transport; distance of transport between points.

Biosorption processes mostly only transfer metal ions from water to the biomass or transfer the pollution problem from one phase to another. Ultimate disposal is still a problem and a process to recover the metal by elution and electrolysis has been evaluated (Butter et al., 1998).

BIO-FIX is a biosorbent bead (U.S. Bureau of Mines), which is composed of sterilised sphagnum peat moss immobilised in a polysulfone matrix. The cation exchange capacity of BIO-FIX beads was measured to be 4.5 to 5 meq/g of dry bead and the beads were found to be effective at adsorbing metals over a pH range of 3 - 8. Calcium and magnesium are readily adsorbed by the beads but are eluted in favour of heavy metals as adsorption continues. Beads display excellent physical and chemical stability and operating costs can be compared to that of lime neutralisation.

Scott and Karanjkar (1998) investigated the applicability of developing selected bacterial biofilms over granular activated carbon (GAC) in order to promote metal biosorption. Since GAC is mostly used for removing organic constituents, the objective has been to provide the foundation for remediation processes that can provide metal biosorption concurrently with the removal of non-metal constituents. Nickel removal by biofilm-GAC could range from 10-60%, depending on the species of the biofilm. As the pH falls < 4–5, the biosorption capacity of biofilm-GAC falls for divalent metals.

Many heavy metals (Cu, As, Ni, etc.) adsorb onto iron and aluminium hydroxide precipitates, formed during neutralisation. Some remobilisation of metals is likely to occur if the pH conditions in the sludge change.

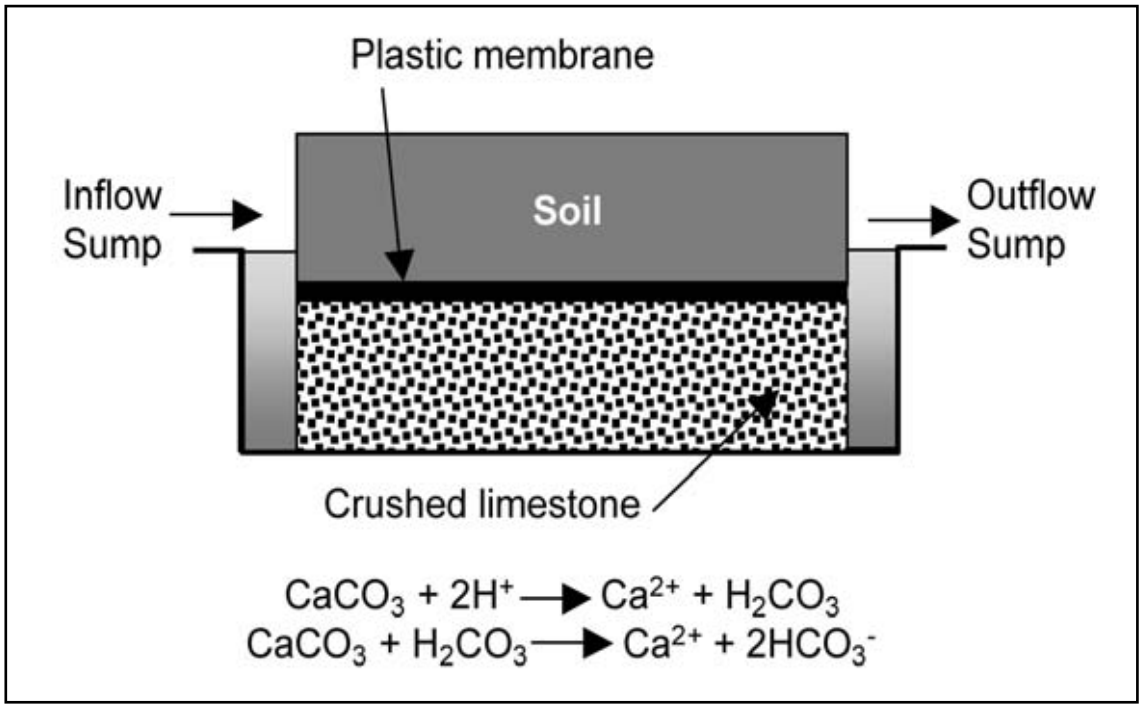
Passive Biological Water Treatment Processes

Passive Water Treatment Tool Road Map	
Principle	Passive technologies are defined here as those processes: 1 that do not require the input of external energy sources and are capable of operating with the use of gravitational, solar and biological energy only; 2 that do not require constant operational or supervisory labour input but only intermittent maintenance and monitoring attention; and 3 where solid residues are retained within the process units and gaseous residues are vented to the atmosphere.
Process types	In terms of treatment systems, a distinction can be drawn on the basis of whether the systems are aerobic or anaerobic and which constituents are removed, i.e.: 1 pH adjustment (removal of acidity/addition of alkalinity): a) anoxic chemical addition - Anoxic Limestone Drain (ALD) b) anaerobic biological action - Sulphate Reducing Units (SRU) or Bioneutralisation 2 Metal and radionuclide precipitation: a) aerobic systems with removal as metal hydroxides, metal co-precipitates and/or plant uptake - aerobic surface flow wetlands b) anaerobic systems with removal as metal sulphides - Sulphate Reducing Units (SRU) 3 Sulphate removal/reduction: a) anaerobic sulphate reduction - Sulphate Reducing Units (SRU) followed by sulphide oxidation in a Sulphide Oxidising Bioreactor
Efficiency	Results as to the success of constructed passive treatment facilities are conflicting. Due to the fact that the technology is young and still developing, many of the earlier systems may have been designed incorrectly. Current research is aimed at investigating the biological and chemical mechanisms of constituent removal to redefine the design and operational procedures of passive treatment systems. Long-term data on the longevity of these systems is limited. Wetland technology has been implemented for the last 15 years, but an understanding of how they work and the development of sizing criteria are very recent. Anoxic limestone drains have only been used to treat mine water in the last 10-15 years. Other reduction and alkalinity-producing systems have only been implemented in the last 10 years. Passive reactors designed specifically to remove sulphates are a new and emerging technology, primarily developed in South Africa. Since passive treatment technology is relatively new, no systems have been in existence long enough to determine if the design lives of 20 to 40 years are realistic. Typical reasons for failure of passive treatment systems include: • Improper/insufficient mine drainage characterisation (obtain sufficient reliable data – BPG G3: Water monitoring). • Inappropriate selection of passive treatment unit operations. • Under sizing of the systems (consider hydrograph and seasonal variation) • Hydraulic short-circuiting

1 pH Adjustment

Anoxic Limestone Drain (ALD) - Acid mine drainage (AMD) is passed through a constructed channel of coarse limestone gravel. The limestone bed is submerged and capped with a plastic liner to prevent the ingress of oxygen (maintain anoxic conditions) and subsequent precipitation of metal hydroxides in the drain (armouring of limestone particles reduce efficiency). The capping also serves to trap CO_2, thereby increasing the CO_2 partial pressure and the solubility of carbonate compounds. A soil or clay layer on top of the liner further prevents the ingress of oxygen and should consider topography and storm water runoff.

Cross section through an anoxic limestone drain



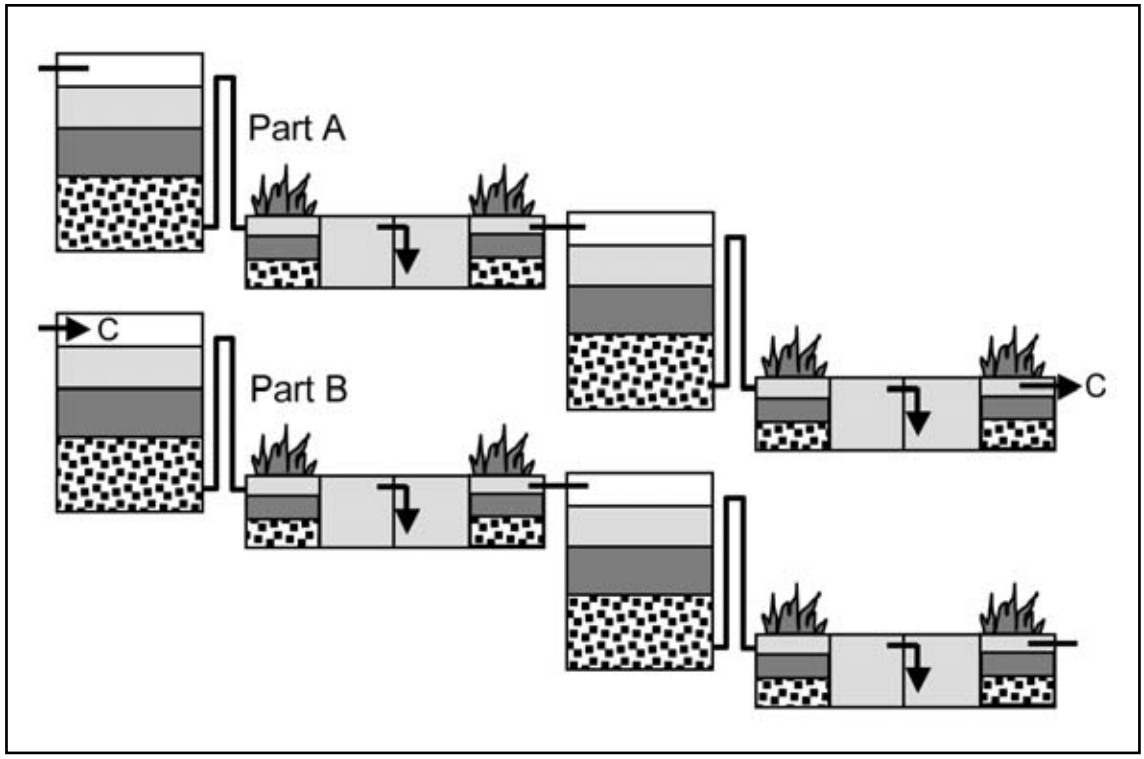
Subsequent aeration and ponding of the discharge from the ALD results in precipitation of metal hydroxides and a clear decant (supernatant).

ALDs are generally considered to have a relatively short effective life since alkaline materials in the drain (limestone) will be consumed, requiring ongoing maintenance (supplementing). Efficiency reduces over time and intervention can thus be anticipated and planned through monitoring. Water containing significant concentrations of dissolved oxygen, ferric iron and aluminium is not directly (without pre-treatment) suited to ALD treatment due to problems of limestone fouling and bed plugging.

Successive Alkalinity-Producing Systems (SAPS) are designed to avoid some of the problems experienced with ALDs. It is a hybrid of compost wetlands and ALDs. SAPS require less surface area than compost wetlands and are more effective in adding alkalinity in the winter than ALD. An oxidation/settling pond or aerobic wetland is also required after treatment.

Sizing criteria can be based on acidity loading or on a minimum retention time. The higher head pressure will allow for the treatment of water with problem metals such as aluminium, which can be removed in the compost layer (situated above the limestone layer). The water thus gravitates downwards and passes through the compost layer, which also generates alkalinity by sulphate reduction, thereby precipitating the aluminium. The limestone below the compost bed is then used to increase the pH (from pH 4-5) to pH 6-7 and to provide residual alkalinity to the effluent.

SAPS - Mt Lyell Remediation system



Open Limestone Drain functions in a similar chemical manner as an ALD but no attempt is made to create an anoxic environment. The system design thus allows for limestone armouring and therefore operates at 20% efficiency of ALD and are built approximately 5 times larger. A gradient in the design allows metal hydroxides, which form in the systems, to flush through. Long-term performance data is lacking. Construction and operating costs are relatively similar to that of an ALD.

Sulphate Reducing Units (SRU) utilize lignocellulose material to reduce sulphate and produce alkalinity in the process. The most significant research and development of this technology has taken place in South Africa and reactors can be designed to reduce sulphate and produce alkalinity at a rate of over 300 g alkalinity (as $CaCO_3$) per m^3 of reactor per day (Pulles et al, 2004).

Bioneutralization: Research is well advanced to develop novel bioneutralisation technology that can raise the pH of acidic mine waters from below 3 to around 7 and this work is also reported in Pulles, 2004. Pilot scale units have been operating for around 3 years, but this technology is still very much in the developmental phase.

2 Metal Removal

Plants and biomass have the potential to remove metals through bioaccumulation (De Wet et al, 1990 and Jeffers et al, 1994). Metal removal rates by plants are generally low compared to abiotic precipitation processes and the fundamental role of plants in wetland systems is to stimulate microbial activity as well as to provide a physical filtration barrier and flow velocity reduction. The extent to which metals are accumulated may be related to the plant's physiological need for the metal. Metals such as Fe (respiration), Cu and Mn (enzyme activation) and Zn (protein synthesis) have important roles to play in plant biology (De Wet et al, 1990). It is not clear as to whether uptake or encrustation is the major process for biotic removal of metals. In some cases, such as the sulphate reduction processes, the metal removal may be incidental.

Wetlands are used as cost effective and aesthetically attractive components of mine water management and treatment and can range from a marsh or pond created in a natural setting to formed structures requiring earth moving and erection of permeable bunds and impermeable

containment barriers. Design should consider hydrology, alkalinity, depth, area hydraulics, substrate, vegetative and microbial species and numbers.

Constructed wetlands can be designed to remove fine suspended solids, polish nutrient-rich water (from sewage plants), strip nitrate (explosives) from pit water, remove heavy metals or process reagents (cyanide, xanthates) and neutralise the acidity in AMD.

Major functional niches that a wetland system can be designed to fill are:

- a 'stand-alone' treatment system.
- intermediate treatment prior to flood irrigation or land disposal.
- polishing water from some form of chemical pre-treatment.
- providing emergency backup to a chemical treatment plant.

In addition to a series of linked ponds containing plants, process units include pre-neutralisation systems (active and passive chemical), aeration zones, at least one of four different types of 'wetland' cell designs and algal-filters.

AMD may have to be pre-treated (neutralised) with lime or magnesia to a target pH of about 6. The neutralising chemical is added to the effluent prior to a turbulent cascade or riffle system to oxygenate the treated stream. If the initial concentration of dissolved iron is high, it may be necessary to construct a sedimentation pond between the riffle zone and the wetland to avoid excessive delivery of metal hydroxide sludge to the wetland itself which will lead to premature loss of capacity, smothering of benthic algae and submerged plants.

There are four potential types of wetland treatment cells:

- Free water surface (FWS) – Aerobic system with predominantly surface flow. Shallow water depths and extensive growths of emergent aquatic plants.
- Subsurface flow (SSF) – Aerobic/Anaerobic system with lateral water flow through a bed of sand or gravel, planted with emergent aquatic plants. Experimental or small pilot-scale stage.
- Subsurface flow – system with vertical upwards or downwards water flow through a permeable sub-stratum, which does not contain plants.
- Lagoons – sedimentation basins/ponds several metres deep with floating plants in the middle of the basin and rooted emergent plants around the periphery. With sufficient organic matter in the bottom sediments, microbial respiration can lead to anaerobic conditions, which favour the immobilisation of many metals as insoluble sulphides.

Drawbacks:

- The amount of non-degradable constituents held in the sediments of a wetland will increase with time and can therefore possibly be classified as a 'contaminated site' which requires special decommissioning (removal and disposal of sediment or sediment left in-situ and covered - benign rock and soil). This risk is significantly reduced for post-decommissioning phases due to small volumes (lower loading).
- Birds and other wildlife could be exposed to elevated levels of metals in wetland plants and/or in animals (fish) ingested as food. The elements most likely to bioaccumulate or biomagnify are cadmium, mercury and selenium.
- Impact on downstream users due to remobilisation of metals. Remobilisation is affected by flow regime, water balance, changes in the nature of the source water and biological activity.

Oxidation/Settling Ponds are used within the aerobic section of passive treatment plants and are designed to precipitate metal hydroxides. The formation and precipitation of iron hydroxides consumes dissolved oxygen and generates acidity. If the water treated does not have a net alkalinity, then iron hydroxide precipitation will decrease the water's pH to where precipitation stops. In such situations, additional alkalinity will have to be added (ALD). With high iron removal rates required and where the incoming water has a low pH (< 4) and there is also a need to remove uranium and aluminium, it would be better to rely on anaerobic systems to remove the metals.

The removal of heavy metals in a Sulphate Reducing Unit (SRU) requires the mine water to flow through a body of organic material under anaerobic conditions. Sulphate reducing bacteria use the carbon in the organic material to produce hydrogen sulphide gas and bicarbonate. The resulting hydrogen sulphide then reacts with the metals within the mine water precipitating out metal sulphides. Among heavy metals, copper is usually the first to precipitate, followed closely by zinc. Due to the relatively high solubility of manganese, manganese sulphide will only form when the concentrations of the other metals are very low (<1 mg/l) (Christensen et al.,

1996). Produced alkalinity can also result in metals being removed as hydroxides or carbonates.

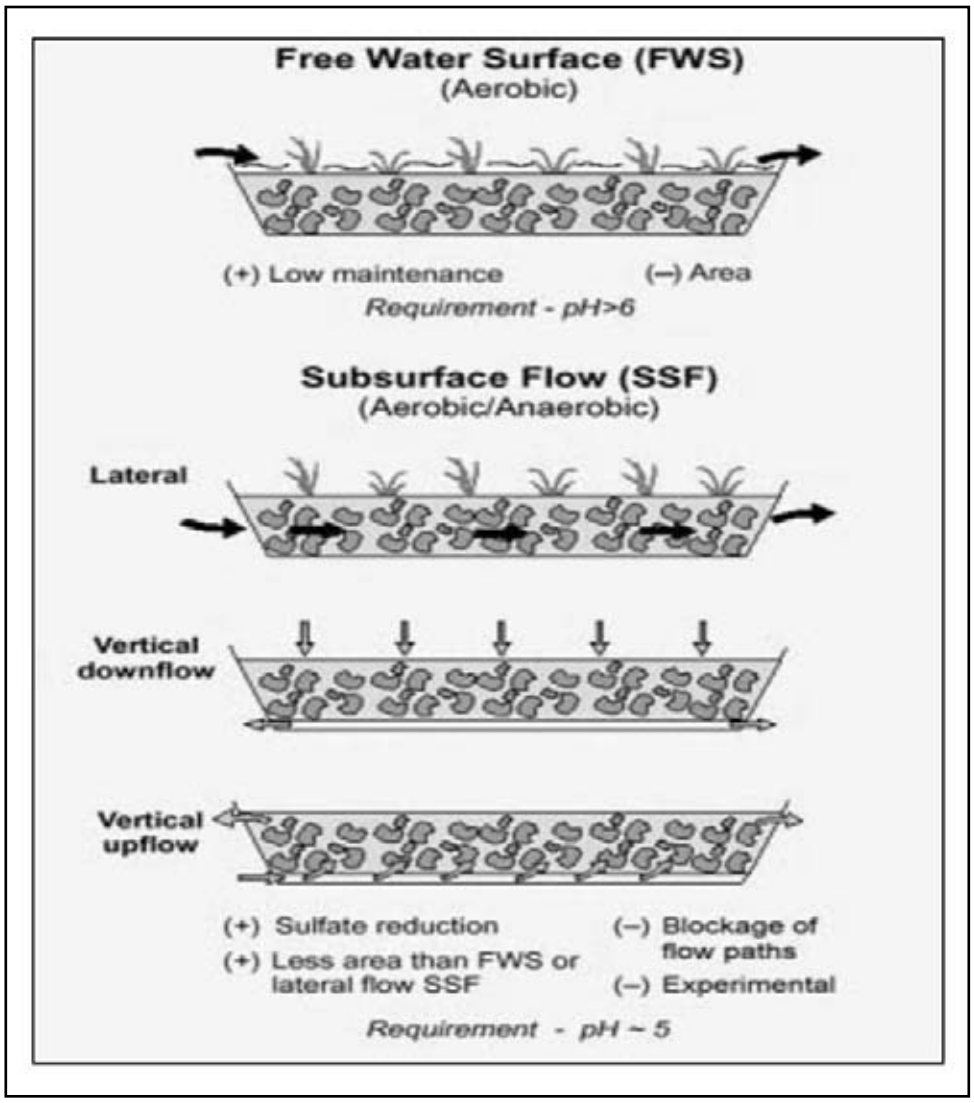
Oxidation cascades have been used for the enhanced removal of manganese – a metal that is difficult to remove in most other passive treatment systems. These units are essentially shallow rock filters at relatively steep gradients, that promote aeration and oxidation of the water while providing growth surfaces for algae and bacteria that can remove manganese

3 Sulphate Removal

Water flows by gravitation through organic lignocellulose material under anaerobic conditions. Sulphate reducing bacteria use the carbon in the organic material to reduce sulphate to sulphide and produce hydrogen sulphide (precipitate metal sulphides) and bicarbonate.

A major research programme has been undertaken in South Africa to develop passive sulphate reduction

Schematic diagrams of four different types of constructed wetland cells. (Jones DR and Chapman BM, 1995)



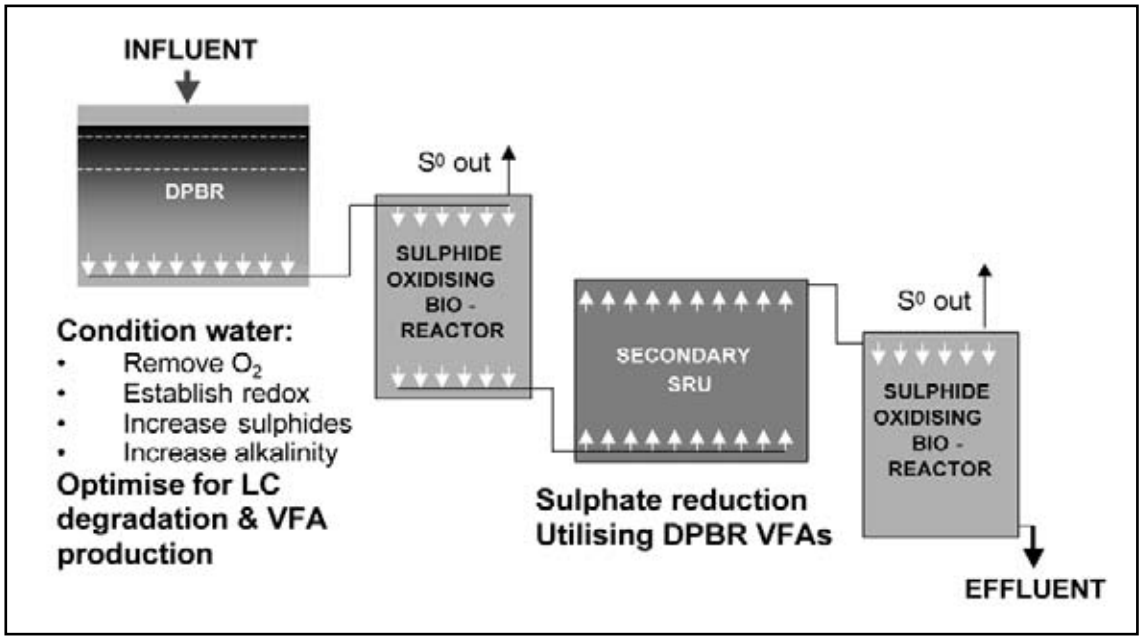
technology and the outcome of the research is the development and patenting of a new integrated and managed passive treatment process, known as the IMPI Process (Pulles, 2004). The essence of the IMPI process is the subdivision of the overall treatment process into individual units, each designed and optimized to perform a key function. This integrated process is shown in the figure below.

The purpose and essential features of the 4 different stages can be summarised as follows:

Reactor 1: Degrading Packed Bed Reactor (DPBR): This reactor is packed with multiple layers of specially selected carbon sources (electron donors) and also receives regular inputs of readily available carbon. The primary functions of this unit are to rapidly condition the influent by removing dissolved oxygen, establishing the desired redox conditions and producing elevated levels of sulphides and alkalinity in the first portion of the reactor. The remainder of the reactor is devoted to the optimized hydrolysis of lignocellulose material and the production of volatile fatty acids (VFA). The effluent from this reactor will contain reduced levels of metals and sulphate and elevated levels of sulphides, alkalinity, VFAs and nutrients.

Reactor 2: Primary Sulphide Oxidising Bioreactor (PSOB): This reactor contains very little or no carbon source and has the primary function of oxidizing sulphides to elemental sulphur for removal from the reactor while minimizing changes to the VFAs, nutrients and redox conditions.

Schematic of the IMPI process



Reactor 3: Secondary Sulphate Reducing Reactor (SSRR): This reactor contains a specially selected single carbon source rather than a multiple layer, multi-carbon source. The primary function of this reactor is to utilize the VFAs produced in the DPBR and to remove additional sulphate down to the design level. The effluent from this reactor would contain reduced levels of metals, sulphate, VFAs and nutrients and elevated levels of sulphides, and alkalinity.

Reactor 4: Secondary Sulphide Oxidising Bioreactor (SSOB): This reactor contains very little carbon source and has the primary function of oxidizing sulphides to elemental sulphur for removal from the reactor.

If required, a final aerobic polishing stage could be added, primarily to remove residual levels of VFAs and nutrients. The individual units could be combined in a tapered –up or tapered-down configuration, i.e. one DPBR to many SSRRs or vice-versa, depending on the design duty of the reactors.

Combined Active Water Treatment Processes

Removal of dissolved metals, arsenic, uranium and radium through the oxidation (use air to provide As(V)) and precipitation of arsenic (add ferric sulphate or ferric chloride), precipitation of radium (by barium chloride), lime precipitation of metals and uranium (HDS process) and a final polishing stage for the removal of residual uranium (by a speciality precipitant if necessary) prior to discharge. A standard flocculant addition and solid-liquid separation unit for sludge removal follows each separation process. A sand filter may be added prior to final discharge for the control of suspended solids and suspended metals.

Removal of dissolved metals and acidity with the HDS lime neutralisation process often results in an effluent supersaturated with gypsum (significant concentration of sulphate). Downstream removal of sulphate is thus required and can be achieved by a number of active treatment processes including chemical precipitation using barium chloride or calcium aluminate (i.e. the Walhalla Process), ion exchange (i.e. the GYP-CIX process) or by active biological sulphate reduction. Ion exchange produces a spent regenerant stream and therefore requires another treatment stage. The effluent from biological sulphate reduction may need air sparging prior to discharge to remove sulphide and increase dissolved oxygen.

High Total Dissolved Solids (TDS) streams containing large concentrations of chloride, sulphate, sodium, calcium and other ions can only be treated by concentration and evaporation. The concentration stage may consist of RO, EDR or IX (not usually due to high cost of large amounts of regenerant chemicals required). Effluents from RO and EDR are generally suitable for reuse or discharge and the concentrated brine produced would be evaporated to dryness (thermal treatment process). The dry salt product of thermal evaporation must be disposed of in an engineered and lined storage site.

Metal and ammonia removal: Conventional precipitation techniques such as lime neutralisation will be used for metal removal. Ammonia may be stripped (recovery) upstream of such a conventional process or biological polishing (nitrification) and freezing may be applied after conventional lime treatment.

Metal removal and biological treatment: Biological treatment has been proposed as a primary treatment for cyanide, thiosalts, ammonia, and organic substances. A preceding metal removal stage is required to ensure toxicity effects from metals do not affect biological activity.

Combined Passive Water Treatment Processes

Various combinations are possible as discussed below.

1 Anoxic limestone drain + oxidation pond + aerobic wetland to remove acidity, iron and manganese

The ALD raises the pH and alkalinity of the water to enable the precipitation of metal hydroxides in the next unit process. No dissolved oxygen, aluminium or ferric iron in the feed water is allowed if there is no pre-treatment. The oxidation pond allows formation and precipitation of metal hydroxides (primarily iron hydroxide). Water entering the pond is aerated while the rest of the pond is still. Prevent hydraulic short-circuiting and allow sufficient retention time for settlement. The aerobic wetland (shallow FWS) will typically remove the manganese and remaining iron together, as well as suspended solids.

2 Anoxic cell + anoxic limestone drain + aerobic wetland + anaerobic cell + rock filter to remove acidity, various heavy metals and perhaps some sulphate

The anoxic cell (bed of organic material under anaerobic conditions) removes problem metals (aluminium, ferric iron) and dissolved oxygen by subjecting the water to strongly reducing conditions. The ALD raises the pH and alkalinity of the water to enable the precipitation of metal hydroxides in the next unit process. The aerobic wetland (shallow FWS) will typically remove the iron and suspended solids, together with manganese (if the Fe: Mn ratio is right). The anaerobic cell (also referred to as a SRU) can be designed in a horizontal or vertical flow configuration, may be deep or shallow and may contain various different types of organic material. Through anaerobic digestion and sulphate reduction, sulphates are reduced to sulphides, which, in turn, precipitate heavy metals as metal sulphides. Alkalinity is also produced. The

rock filter removes, by aerobic algal means, manganese, which may have been carried through. It also oxidises the surplus organic loading added to the water in the anaerobic cell.

3 Anaerobic cell + aerobic wetland

The anaerobic cell (also referred to as a SRU) can be designed in a horizontal or vertical flow configuration, may be deep or shallow and may contain various different types of organic material. Through anaerobic digestion and sulphate reduction, sulphates are reduced to sulphides, which, in turn, precipitate heavy metals as metal sulphides. Alkalinity is also produced. The aerobic wetland is designed to remove any surplus organic loading added to the water during its passage through the anaerobic cell.

Combined Active And Passive Water Treatment Processes

The most common combined active and passive water treatment systems are those that incorporate a wetland to polish the discharge from an active water treatment plant.

APPENDIX D

OVERVIEW OF UNIT PROCESSES AND OPERATIONS USED IN EFFLUENT TREATMENT

Appendix D1: Overview of unit processes and operations used in effluent treatment

Process	Description	Application
Solid/liquid separation		
Coagulation	Addition of chemicals to destabilize suspended and colloidal matter	Promote particle destabilization to improve flocculation and solids separation
Flocculation	Particle aggregation	Particle agglomeration upstream of liquid/solid separation processes
Filtration	Particle removal by porous medium	Removal of particles larger than about 3 μm. But, sub-micron particles may be removed depending on the chemical pre-treatment
Sedimentation	Gravity sedimentation of particulate matter, chemical floc, and precipitates from suspension by gravity settling	Settleable solids removal
Biological treatment		
Aerobic biological treatment	Biological metabolism of waste solids by bacteria in an aeration basin	Removal of organic matter from solution by synthesis into microbial cells
Oxidation Pond	Ponds with 2 to 3 feet of water depth for aerated lagoons and sunlight penetration	Reduction of suspended solids, BOD, faecal bacteria, parasites, and ammonia
Disinfection	The inactivation of pathogenic organisms using oxidizing chemicals, ultraviolet light, caustic chemicals, heat, or physical separation processes	Protection of public health Coagulation enhancement
Advanced treatment		
Activated Carbon	Process by which constituents are physically adsorbed onto the carbon surface	Removal of hydrophobic organic compounds
Air Stripping	Wastewater is distributed over a packing through which forced air is drawn to extract ammonia from the water droplets under high pH	Used to remove ammonia nitrogen and some volatile organics
Ion Exchange	Exchange of ions between an exchange resin and water using a flow through reactor	Softening and removal of selected ionic constituents; Effective for removal of cations such as calcium, magnesium, iron and anions such as nitrate
Lime treatment	The use of lime to precipitate cations (metals) from solution	Used to stabilise lime-treated water, to reduce its scale forming potential, and disinfection
Reverse Osmosis	Pressure membrane to separate ions from solution based on reversing osmotic pressure differentials	Removal of dissolved salts from solution as well as pathogens

Appendix D2: Active Treatment Options for Water Quality Constituents

Water Quality Constituents	Active Treatment Options
Algae: Blue-green Green Euglena Diatoms	Coagulation, flocculation and/or sedimentation
Arsenic	• After being oxidised to pentavalent form, coagulation and flocculation processes followed by settlement and filtration. Coagulant – aluminium sulphate, ferric salts and lime (hazardous sludge)
Cadmium	• Add lime or iron salts to raise pH to 8.5 – 11.5. Precipitate insoluble cadmium salts. Settlement and filtration. • Ion exchange column with appropriate resin
Calcium	• Precipitation as calcium carbonate by addition of sodium carbonate • Cation exchange softening • Demineralisation in mixed bed ion exchange columns – yield low salinity water
Chloride	• Electrolysis – chlorine gas liberated at anode • Anion exchange resin beds • Desalination techniques (reverse osmosis or electrodialysis)
Chromium	Reduction with ferrous sulphate or reaction with oxidisable organic matter to reduce to trivalent state • Precipitation and flocculation with lime and alum or ferric salts – settlement and filtration • Reverse osmosis • Ion exchange
Colour	• Filtration through slow sand filter (metabolising organic material in water) • Coagulation, flocculation, clarification flotation or settlement) and filtration • Activated carbon filtration • Ozone – strong oxidising agent
Copper	• Flocculation with alum and ferric salts at pH 6-7 • Raise pH, precipitate insoluble copper carbonate and hydroxide complexes with lime treatment, followed by settlement and filtration
Dissolved organic carbon	• Filtration through a slow sand filter • Coagulation, flocculation, clarification (settlement or flotation) and filtration • Activated carbon filtration • Oxidation by strong oxidising agents such as hydrogen peroxide, ozone or peroxone
Fluoride	• Adsorption in bed of activated alumina • Ion exchange columns • Membrane processes – reverse osmosis and electrodialysis
Indicator organisms	• Partial removal by sedimentation, absorption, coagulation and flocculation • Chlorine disinfection

Water Quality Constituents	Active Treatment Options
Iron	• Aeration (mechanical or cascades) • Addition of lime (raise pH) – oxidation (by air) – settlement • Chemical oxidation – chlorine, peroxide, ozone or other strong oxidants
Lead	• Coagulation with alum, ferric salts or lime followed by settlement and filtration
Magnesium	• Lime softening followed by recarbonation • Precipitation (sodium hydroxide) – pre-treatment • Cation exchange columns – replace with sodium – caution! • Demineralisation in mixed bed ion exchange
Manganese	Oxidation and then filtration. Manganese oxidised at pH >9 by oxygen in water. Otherwise use strong oxidising agents such as: • Chlorine • Hydrogen peroxide • Potassium permanganate • Ozone
Mercury	• Precipitation • Co-precipitate with aluminium hydroxide by addition of alum • Co-precipitation with ferric hydroxide by addition of iron salts • Adsorption, using powered or granular activated carbon • Ion exchange using appropriate resins • Disposal of hazardous precipitates
Nitrate	• Slow sand filtration • Biological reduction – denitrification – caution – carbon • Ion exchange column • Reverse osmosis
Odour	• Aeration – blowing air counter current to water flow through stripping tower • Coagulation, flocculation, settlement and filtration – preliminary • Adsorption – powered activated carbon dosed upstream of filter • Adsorption – filter charged with granular activated carbon – steam stripping or regeneration periodically
pH	• Addition of acid or alkali to adjust for treatment processes – caution in handling • Alkaline – sodium carbonate, sodium hydroxide and lime • Acids – carbon dioxide, hydrochloric acid, sulphuric acid • Buffering reagents
Phenols	• Oxidation – ozone (NOT CHLORINE) • Adsorption – filtration through granular activated carbon column
Potassium	• Demineralisation in a mixed-bed ion exchange column • Membrane processes – reverse osmosis or electrodialysis • Distillation
Settleable matter	• Reduce flow to allow settlement of material to bottom of clarifier • Gravity settlement • Sedimentation assisted by coagulation and/or flocculation prior to settlement • Filtration – rapid gravity sand filters or pressure sand filters – coagulants and/or polyelectrolytes

Water Quality Constituents	Active Treatment Options
Sodium	• Demineralisation in a mixed-bed ion exchange column • Membrane processes – reverse osmosis or electrodialysis • Distillation
Sulphate	• Ion exchange in an anion exchange column • Desalination • Demineralisation in mixed bed ion exchange columns • Membrane treatment (reverse osmosis or electrodialysis) • Distillation
Total Dissolved Solids (TDS)	• Demineralisation in mixed bed ion exchange columns • Membrane treatment (reverse osmosis or electrodialysis) • Distillation
Total Hardness	• Base exchange softening – replace with sodium in ion exchange columns • Demineralisation in mixed bed ion exchange columns • Addition of lime followed by recarbonation
Turbidity	• Settleable fraction – gradually settle • Coagulation and Flocculation of smaller particles and colloidal fraction • Silica sand filters • Membrane processes – microfiltration or ultrafiltration
Zinc	• Raise pH with lime to pH 9.5 – 10.0, precipitate insoluble zinc hydroxide, settlement, filtration. Caution – disposal of sludge

APPENDIX E

A SUSTAINABLE MINE WATER TREATMENT INITIATIVE TO PROVIDE POTABLE WATER FOR A SOUTH AFRICAN CITY - A PUBLIC-PRIVATE PARTNERSHIP

Paper by P Günther[1], W Mey[2] and A M van Niekerk[3] presented at
Water in Mining Conference, Brisbane, Australia 14-16 November 2006

ABSTRACT

Coal mining has an impact on the water management of the water scarce Upper Olifants River Catchment. A prefeasibility study was carried out by Anglo Coal and Ingwe Collieries Limited to establish the water supply and demand in the catchment. A geohydrological model was used for the coalfields to determine the stored water and excess water available. Two distinct collective and treatment systems were proposed for the Witbank and Middelburg municipalities to treat excess water from the Anglo Coal and Ingwe Collieries Limited. The Emalahleni Water Reclamation Project for Witbank was initiated first. Water management and treatment experience gained at Anglo Coal was the cornerstone to develop the collection, treatment and distribution system. A full enquiry was issued to Keyplan, Veolia, Bateman Africa and IST Technik to construct, commission, operate and maintain a 20 ML/day desalination plant to treat acidic, saline mine waters to a South African National Standard (SANS) 0241 Class 0 potable water. After the technical and financial adjudication, Keyplan were awarded the contract. An integrated regulatory process was adopted through consultation with all the relevant regional and head office staff of the Department of Minerals and Energy, Department of Water Affairs and Forestry and the Mpumalanga Department of Land Affairs via an authority's steering committee. A rock engineering evaluation was done to select both the plant and waste disposal sites as all possible sites are undermined. Various contracts are required with the individual mines for water supply, the Emalahleni Local Municipality for the delivery of potable water and for the disposal of wastes.

BACKGROUND

The background of this project reflects the work done by the coal mines on water management whilst taking cognisance of the water management needs in the Upper Olifants River Catchment. As a result of water stored in underground workings sterilising coal mining reserves and the obligation to address environmental liabilities, Anglo Coal and Ingwe Collieries Limited have decided to build a 20 ML/day desalination plant to treat excess mine water. The plant will produce potable water and sell the water onto the Emalahleni Local Municipality in a sustainable public-private partnership project as indicated by van Niekerk and Günther (2004). The evolution of water treatment technologies, pioneered and developed at Anglo Coal, has been key to the confidence of technology selection for the 20 ML/day Emalahleni Water Reclamation Project.

Upper Olifants River Catchment

The Upper Olifants River Catchment stretches across the City of Witbank and Town of Middelburg with extensive coal mining operations (both existing and historic – over the past 100 years) covering a large portion of this area. Coal mining in the catchment has a significant effect on the hydrological cycle and it is essential that the coal mine's water management systems dovetail with the water management of the catchment.

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This catchment is a water scarce area with an average of only 700 mm of rain falling on an annual basis, with an average evaporation rate of 1400 mm per annum. Supply of water to communities and downstream users are prime objectives for this catchment. The water demand growth over the past six years has averaged 3,5 per cent per annum in the Witbank and Middelburg areas. The Emalahleni Local Municipality, which incorporates Witbank and surrounding areas, is already over-abstracting from the Witbank dam by about 11 ML/day and is set to reach 20 ML/day by 2015. The Steve Tshwete Local Municipality, which incorporates Middelburg and surrounding areas, is reaching the abstraction capacity from the Middelburg dam and is set to exceed its permit conditions from 2008 onwards. With future mining developments earmarked for the short to medium term in the Middle Olifants and Steelpoort catchments, which are downstream of the Upper Olifants Catchment, the water that is available requires crucial management. Figure 1 shows where the Upper Olifants River Catchment and the locality of the Witbank City and Middelburg Town, fit into the Mpumalanga Province in the Republic of South Africa.

Prof F D Hodgson was commissioned to generate a comprehensive geohydrological mine water model for Anglo Coal. Hodgson (2003) stated that this model generates volumes of stored water in the underground workings, as well as predicting the water make in each discrete compartment or hydraulic unit. The model is dynamic, with water level data being used to update the model, as well as the model being able to accept updates in the mining plans. Figure 2 shows the water stored in the No 2 coal seam workings as generated by the model.

The solid blue shapes indicate the stored water, with the colours representing the floor contours. The elevations rise from the lowest, depicted as light blue, to green to orange to red at the highest point.

Figure 3 is the graphical output of the model detailing the total and net amount of excess water in m^3/day over the next 40 years. The green line is the water demand by the Emalahleni Local Municipality as indicated by Hodgson (2005).

Coal mines have adopted a water management policy (which includes the principles of the DWAF hierarchy of water management), which aims to maximise clean and dirty water separation, minimise the import of clean water, maximise the reuse of dirty water, discharge dirty water through the managed release scheme (utilises periods of assimilative capacity in the Upper Olifants River) and the treatment of dirty water. Over the past ten years mines have populated and produced detailed water balances, which have been applied to the principles of the DWAF hierarchy. However, some mines have a high positive water balance and not all the water can be managed according to these principles only. Water treatment of these waters is inevitable, but historically has required complex technologies associated with high costs and the generation of large waste loads.

Evolution of water treatment in Anglo Coal

Most coal mines in this catchment have a calcium- magnesium-sulfate, neutral type of water quality. Some mines do have additional problems of acidic types of waters yielding pHs below three.

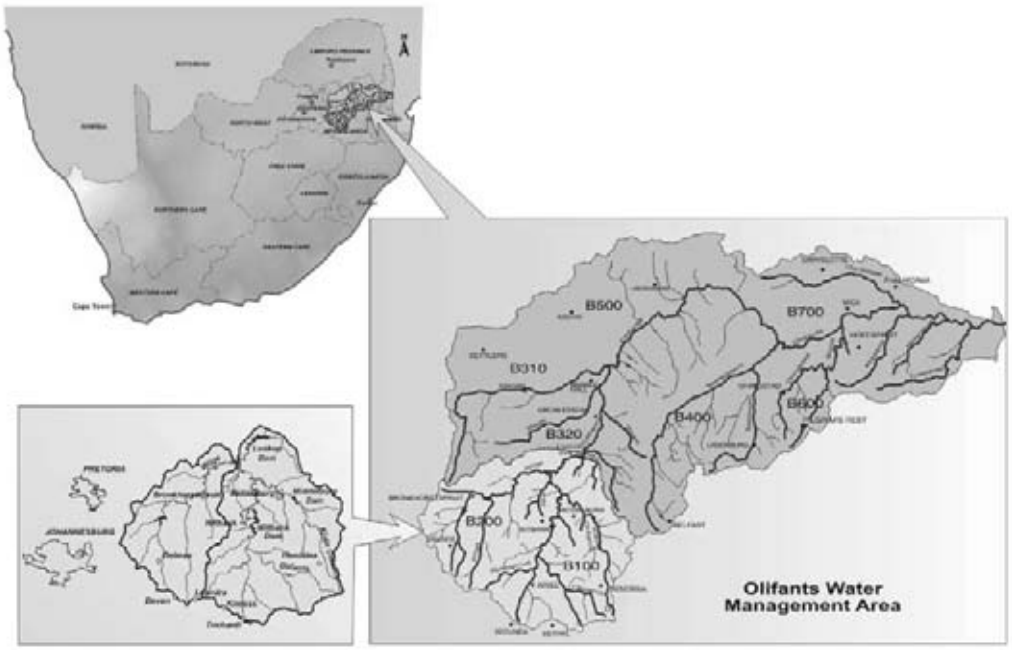


FIG 1 - Locality plan of Witbank and Middelburg municipalities (Mpumalanga Province), Republic of South Africa.

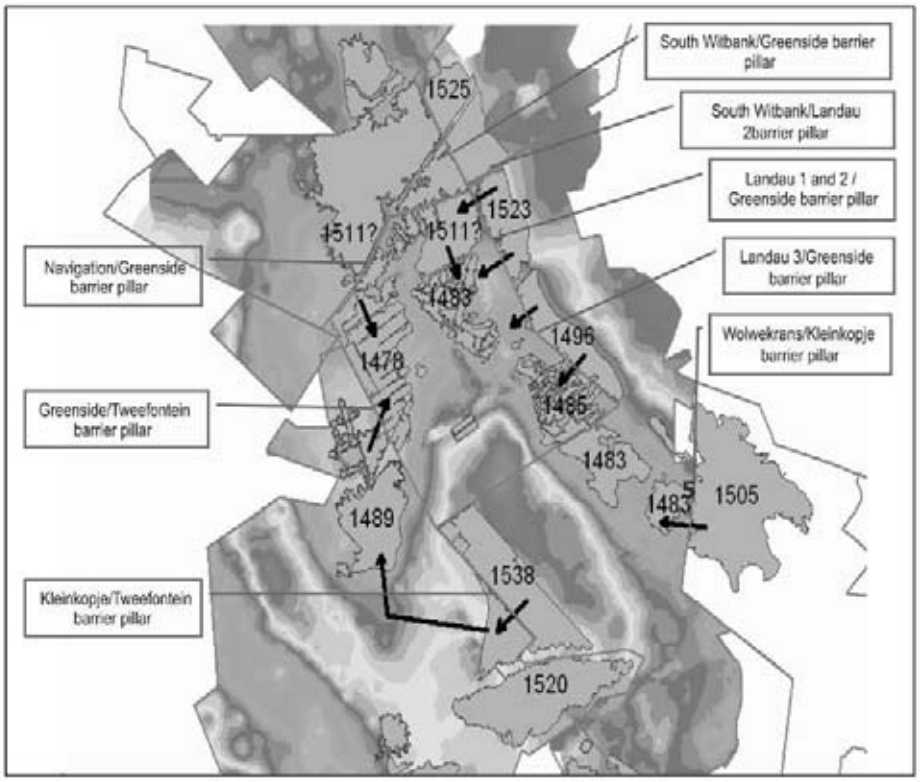


FIG 2 - Geohydrological model of the No 2 seam.

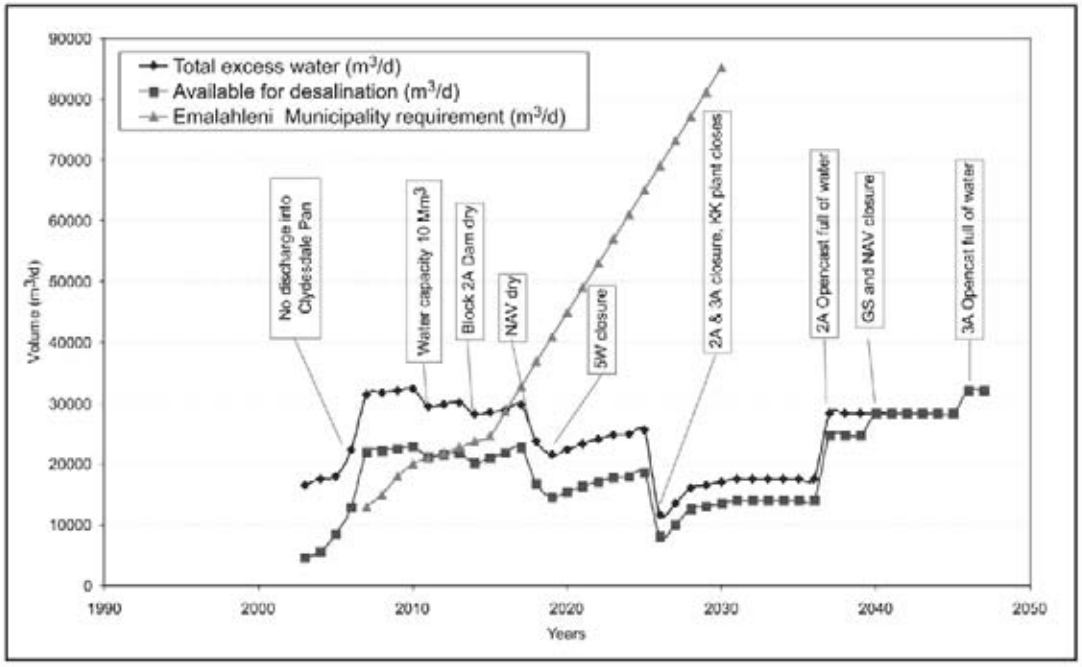


FIG 3 - Geohydrological model output.

Anglo Coal's Landau Colliery currently mines, using opencast methods, the remaining pillars of coal left behind from underground mining, which took place from the start of the 20th century. This coal is fairly shallow (25 - 35 m deep for 2 and 1 seams) and over the past 100 years the calcite (CaO) in the coal has been leached allowing the net neutralisation reactions to tend towards producing acidic leachates. The water quality has a pH <3, calcium ~500 mg/L, magnesium ~100 mg/L, sulfates ~2500 mg/L and acidity associated with iron, manganese and aluminium.

In the early years of production at Landau Colliery the impact of the water quality was not understood and no focus was placed on its management. The water quality was perceived to be slightly acidic and a lime neutralisation plant was assumed to be able to solve any water quality issues and was not operated effectively. In the first years (1994 - 1995) of operation, almost 70 per cent of all steel piping in the plant, as well as associated minerals processing equipment was replaced because of corrosion due to acidic water qualities.

Dr J P Maree of The Council for Scientific and Industrial Research (CSIR) was consulted to assist with rectifying the problem. This lead to optimising the lime neutralisation system, pioneering the limestone substitution of lime for the neutralisation process and solving the acidic water quality issue, but resulted in a secondary problem through gypsum (calcium sulfate) precipitation. Membrane water treatment technology was the only commercially proven treatment option at the time, but had disadvantages of high capital and operating costs, relatively low water recoveries and a high generation of waste streams (particularly the dissolved brine stream). A number of active water treatment technologies (some novel and not commercially proven) were piloted and demonstrated up to full scale over the past ten years at Landau Colliery Plant. Table 1 summarises the technologies evaluated over ten years of investigation.

Through these investigations a number of key lessons were learnt, which are:

- to understand the feed water quality and the applicability/ suitability of water treatment technologies to produce the desired water quality;
- the importance and knowledge gained by scaling up successfully from laboratory to pilot to demonstration and finally to full scale plant installations;
- to determine the optimal performance, with cost efficiency, of the selected water treatment technology through intimate involvement from the mine with the treatment technology supplier;
- to dovetail the water treatment technology with that of the mine's water needs;
- not to accept what was done before, but rather to maximise the performance criteria of each water treatment technology to meet the mine's overall requirements, ie maximising water recovery from ~65 per cent to >97 per cent;
- utilise a scale-up factor of ten for new technologies from demonstration plant scale to full scale;
- to determine the correct skills level of operators required to operate the plants, perform analytical procedures, data capture on computer, operate SCADA plant control computer systems, manage downtime, etc;
- the development of an operator performance management assessment program to measure the operators against a fixed scorecard and other operators is required; and
- that tertiary education is not a prerequisite for the operator but rather a grade 12 mathematics and science combination is required.

TABLE 1

Evaluation of water treatment technologies.

Technology supplier	Type of active treatment process	Purpose of treatment	Year	Water recovery (%)
Debex	EDR	HM & S removal	1994 - 1995	65
Keyplan	RO	HM & S removal	1995 - 2006	97
CSIR	HDS (lime)	HM & neutralisation	1995 - 1999	99
	HDS (limestone)	HM & neutralisation	1995 - 2005	99
	BSR (CSIROSURE)	HM & S removal	2000 - 2004	98
Gyp-Cix	IX	HM & S removal	1997 - 1999	79
Savmin	Entringite	HM & S removal	2000	95
Lektratek	Electrochemical	HM & S removal	1997 - 2000	95
IST Technik	BSR (Paques)	HM & S removal	1998 - 2003	99
Veolia	RO	HM & S removal	2004 - 2005	95
Wren	Hydrothermal	HM & S removal	2002 - 2004	95
Bateman	RO and hydrothermal	HM & S removal	2004 - 2005	99
Weir-Techna	RO	HM & S removal	2004	95

Note: HM = heavy metals, S = sulfate, BSR = biological sulfate removal, RO = reverse osmosis membrane, IX = ion exchange, HDS = high density sludge, EDR = electro-dialysis reversal.

To summarise, the success of the pilot and demonstration plants is due to the facts that they were fully automated, operated on a 24-hour shift basis and were sized at a flow rate of equal to or greater than 200 m^3/day. The treatment of the calcium – magnesium, acidic, heavy metal (iron, manganese, aluminium) and saline (sulfate) waters has matured through these investigations resulting in a very clear, confident understanding of what technology is suitable to treat this water in an optimal engineered and cost-effective manner.

EMALAHLENI WATER TREATMENT PLANT PROJECT

In September 2005, the Anglo American plc Executive Board approved R296.3 million for the construction of the 20 ML/day mine water treatment plant to treat the waters from Kleinkopje, Greenside and South Witbank Collieries and produce potable water for distribution into the Emalahleni Local Municipality water system as detailed by Günther, Brett and van Niekerk (2005).

The proposed project will produce 20 ML/day of potable water and will have the following main physical components:

- mine water collection pump stations and pipework from three contributing mines; Kleinkopje, Greenside and South Witbank Collieries to the central treatment facility;
- central mine water storage dam;
- mine water treatment plant;
- potable water storage reservoirs;
- potable water distribution pipeline to the municipal reservoirs; and
- waste disposal distribution systems and disposal facilities.

Figure 4 shows the general location of the main project components.

Mine feed water quantity basis of design

Based on the current dewatering rates of the mines, Prof FD Hodgson's geohydrological model and the future mining plans, the following water quantity basis of design was used. This is shown in Table 2.

TABLE 2

Mine feed water quantity basis of design.

	Flow (ML/day)
Kleinkopje	11.5
Greenside	7.0
South Witbank	1.5
	20.0

Each mine will provide, as shown in Figure 4, a water collection system comprising of a borehole abstraction system, a pumpstation and a distribution pipeline into the central water storage dams located at the water treatment plant site. The central water storage dams (46 ML) will blend and balance the mine water collected from Kleinkopje Colliery, Greenside Colliery and South Witbank Colliery. It was considered prudent to provide a buffer facility between the mine water collection system and the treatment plant of a two-day storage capacity.

Mine feed water quality basis of design

The design will treat water from three mine sources based on the 95 percentile acidic water quality of the Landau Colliery Plant, to produce 20 ML/day of potable (South African Bureau of Standards (SABS) 241 Class 0 water quality) water.

Summarised in Table 3 is the design feed water qualities, with corresponding treated water qualities. The overall design performance criteria of the plant are described in Table 4.

Kleinkopje, Greenside and South Witbank Collieries provided extensive historical water quality databases of the main physical and inorganic water qualities. These were statistically modelled to produce the 5, 50 and 95 percentile water quality of each water source. The desired blend of 11.5 ML/day Kleinkopje, 7.0 ML/day Greenside and 1.5 ML/day South Witbank water quality was also determined for the 5, 50 and 95 percentile water quality. The same exercise was done on the Landau Colliery Plant water, because it is an older mining operation and the water is already acidic. Both Kleinkopje and Greenside Collieries water has showed signs of deterioration over the past few years with the alkalinity decreasing, acidity increasing and heavy metals like iron, manganese and aluminium increasing simultaneously. Refer to Figure 5 and Figure 6, which graphically show the deteriorating water quality.

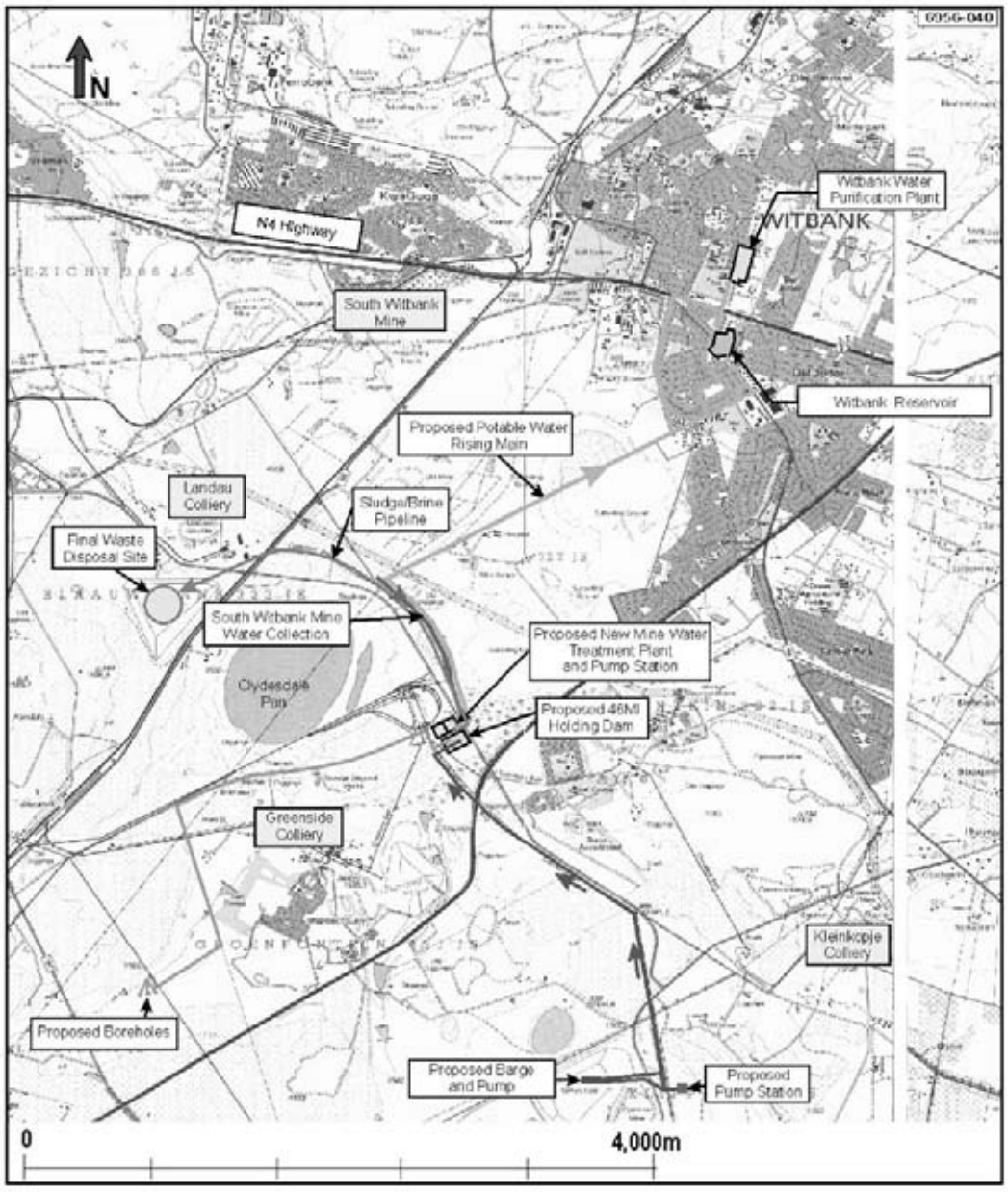


FIG 4 - Main physical components and location of key infrastructure elements.

Therefore, based on this deteriorating effect, the 95 percentile Landau Colliery Plant water quality was used as the feed design water quality listed in Table 3.

ENQUIRY FOR THE 20 ML/DAY EMALAHLENI DESALINATIONPLANT

The enquiry document was drafted by the client, the client's consultant company Golder Associates Africa and a quantity surveyor company Venn and Milford. An enquiry was issued by Venn and Milford Quantity Surveyors in November 2004, which invited four treatment technology suppliers to submit tenders for the engineering, construction, commissioning and initial three-year operation and maintenance of the mine water treatment plant, as described by Calder *et al* (2004). Four tenders were received from the following companies:

- Bateman Africa (Pty) Ltd,
- IST Technik (Pty) Ltd,

TABLE 3

Design feed and treated water qualities.

Water quality parameter	Units	Feed water (95 percentile)	Treated water
pH	-	2.7	6.0 - 9.0
Acidity	mg/L as $CaCO_3$	1050	0
Electrical conductivity	mS/m	460	<70
Total dissolved solids	mg/L	4930	<450
Calcium, Ca	mg/L	660	<80
Magnesium, Mg	mg/L	230	<30
Sodium, Na	mg/L	130	<100
Potassium, K	mg/L	13	<25
Sulfate, SO_4	mg/L	3090	<200
Chloride, Cl	mg/L	70	<100
Iron, Fe	mg/L	210	<0.01
Manganese, Mn	mg/L	35	<0.05
Aluminium, Al	mg/L	40	<0.15

TABLE 4

Overall design performance criteria.

Parameters	Units	Value
Treated water flow rate	ML/day	20
Water recovery	%	>95
Engineering availability	%	>95
Operational utilisation	%	>95

- Keyplan (Pty) Ltd, and
- Veolia Water (Pty) Ltd.

A key element to evaluating the technologies was to perform a complete life cycle costing analysis of the processes over 20 years, including the cost of waste disposal, which was evaluated by Johnson *et al* (2005). Through a series of individual workshops held with each of the tenderers focusing on waste minimisation, the technology suppliers were advised to minimise the hazard rating of the wastes and increase water recovery so as to minimise waste disposal costs. Furthermore, prefeasibility and feasibility studies were undertaken to optimise the best method of waste disposal.

After the technical by van Niekerk *et al* (2005) and financial adjudication by Johnson *et al* (2005) was finalised, Keyplan (Pty) Ltd were awarded the contract to design and construct the plant as shown by Rooza, Calder and Günther (2005). A combination of two CSIR processes, namely the limestone/lime neutralisation and gypsum crystallisation processes, is used as pretreatment, followed by green sand filters to remove residual manganese, before being processed through the ultrafilters to remove any microorganisms and suspended solids. The final processing step of desalination is performed using reverse osmosis (RO) membranes. The brine (dissolved salts removed from the RO membranes), which is highly oversaturated in gypsum salts is treated with lime to remove the oversaturation. This last cycle is performed a total of three times to increase the water recovery, maximise the solids removal and minimise the volume of brine. The basic process flow diagram is depicted in Figure 7.

In Keyplan's tender submission, they included the costs of a demonstration plant to operate concurrently with the detailed design of the plant to confirm/finalise design parameters.

The demonstration plant was designed for a flow rate of 120 m^3/day and was fully automated and computer SCADA controlled. The demonstration plant operated successfully from October to December 2005 confirming process and engineering aspects.

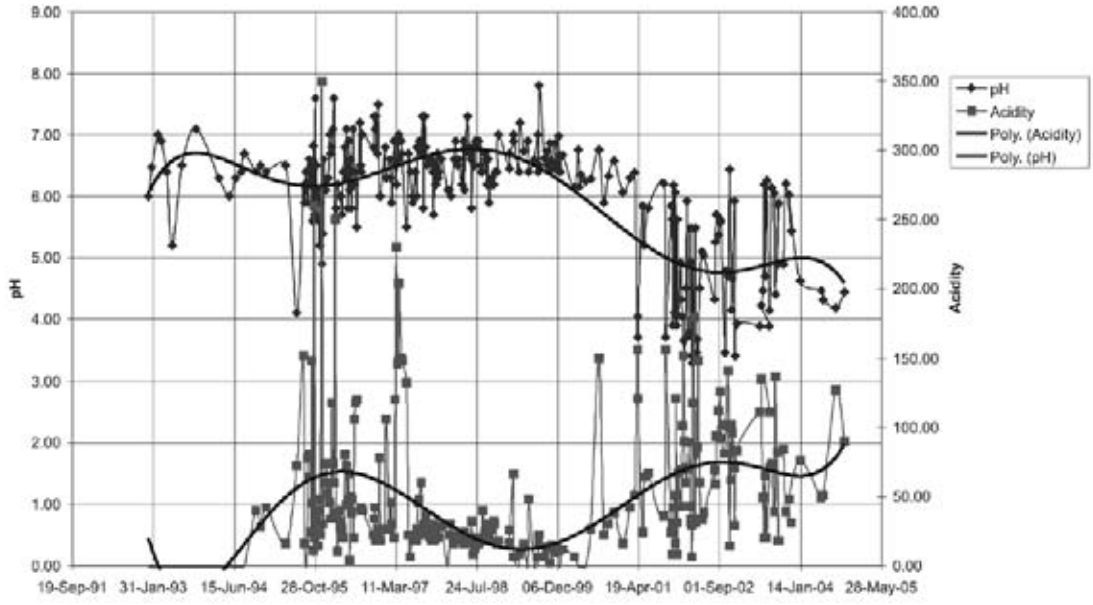


FIG 5 - Kleinkopje Colliery historical water qualities.

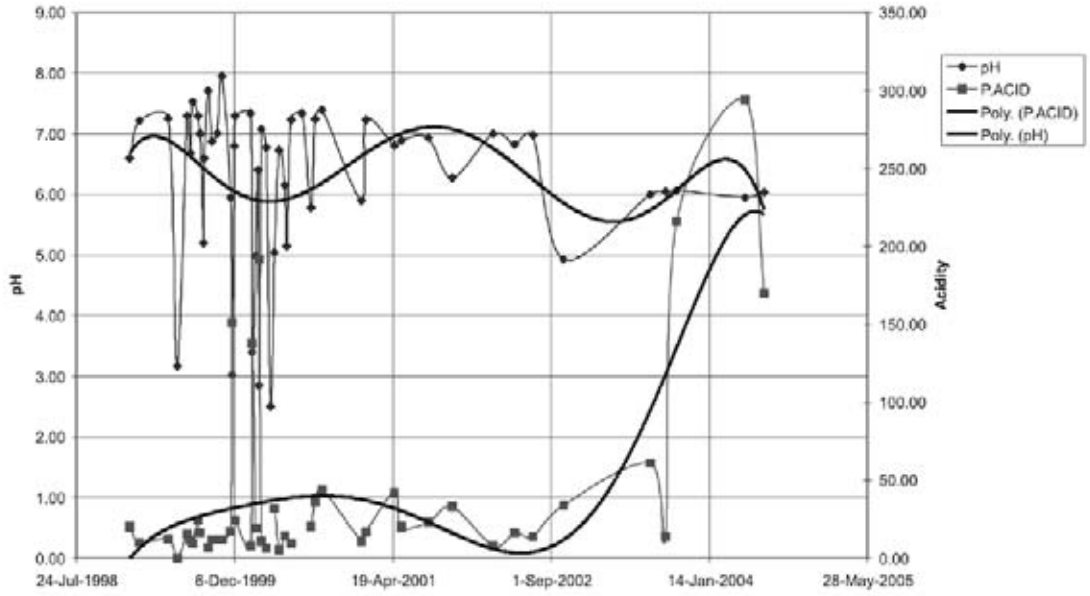


FIG 6 - Greenside Colliery historical water qualities.

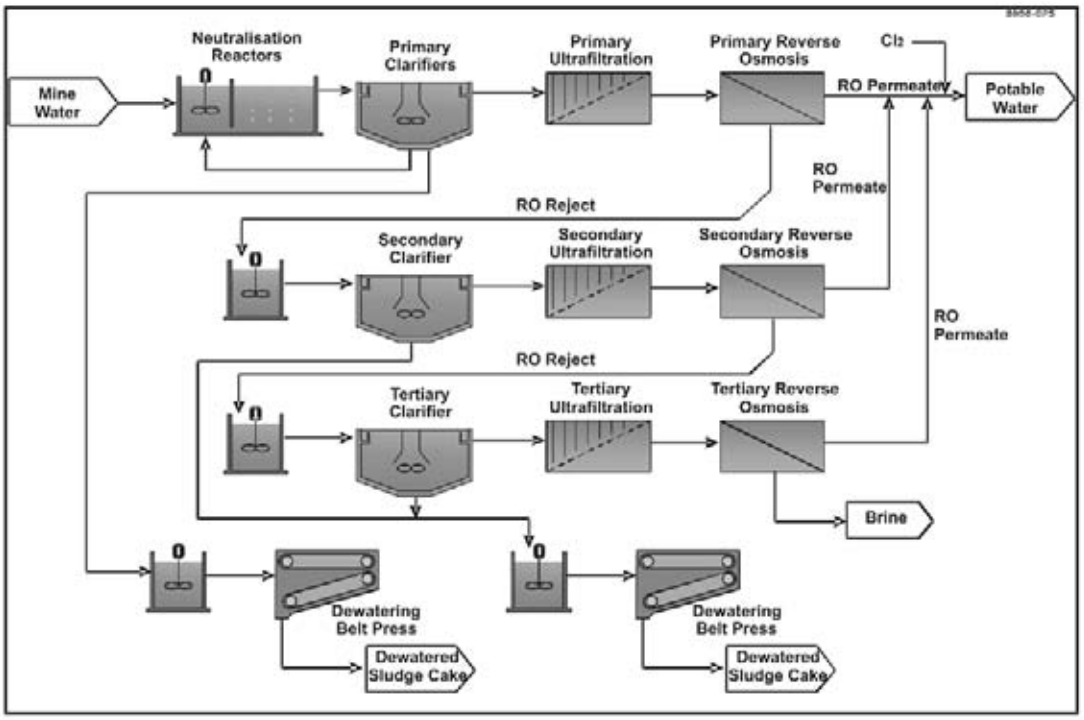


FIG 7 - Keyplan process flow diagram.

SITE SELECTION FOR THE PLANT AND WASTE DISPOSAL FACILITIES

A number of different potential plant and waste disposal sites were identified and evaluated from a mining and rock mechanics perspective and from an available land perspective. Five potential plant sites and seven waste disposal sites were identified and evaluated. As most of this area has been undermined the best site for the water treatment plant is located next to the Rapid Loading Coal Terminal, which has only been partially mined on the 2 seam and has no future mining prospects. It is also big enough to expand the plant up to 60 ML/day and include a brine evaporation pond, as well as being central to all the feed water sources. This plant site also ranks as low to medium risk in terms of the rock engineering properties.

Depending on the final selected sludge/brine disposal method, a dedicated waste disposal area of 30 to 40 hectares may be required over a 20-year life of the project. The size requirement placed a significant constraint on the selection of viable sludge/brine disposal sites. In the final design the solid dewatered gypsum waste will be disposed of at the Blaauwkrans Mine Residue Disposal (MRD) facility at the Landau Colliery Plant and the liquid brine will be disposed of in a properly designed hazardous lagoon at the water treatment plant site. These sites have sufficient space and are ranked as low to medium risk in terms of rock engineering properties.

REGULATORY AND LICENSING REQUIREMENTS

Licensing/permitting requirements

The project has several physical components and different operational aspects. The main pieces of legislation driving the authorisations for the project include the following:

- *National Environmental Management Act 1998*;
- *National Water Act*, No 36 of 1998;
- *Water Services Act*, No 108 of 1997; and
- *Mineral and Petroleum Resources Development Act*, No 28 of 2002.

Anglo Operations Limited (AOL), as the lead mine, will act as the official proponent for the project in all the licence and permit applications.

Integrated approach

An integrated approach to the licensing and permitting of the project has been adopted and agreed to by all the regulatory authorities. The three main licensing/permitting processes that require integration are:

- environmental impact assessment,
- water abstraction and use licences,
- sludge/brine (waste) handling and disposal permit/licence, and
- amendment to the mines' environmental management program reports (EMPRs)

An Authorities Steering Committee was established for the purpose of the project. All the main regulators, including the Mpumalanga Department of Agriculture and Land Affairs (MDALA), Department of Water Affairs and Forestry (DWAF), Department of Minerals and Energy (DME) and the Emalahleni Local Municipality are all represented on the Committee. The objectives of the Committee are to collectively consider the licence and permit applications, enhance corporate governance amongst different regulators and expedite decision making. The individual mines participating in the project will also have to update their EMPs to reflect the changes in their respective water systems resulting from the implementation of the project. The public participation and stakeholder consultation requirements for all the main licensing/permitting processes are coordinated and integrated. The integrated licensing/permitting approach is shown graphically in Figure 8.

LEGAL AND CONTRACTUAL ASPECTS

Contracts with participating mines

The three participating mines; Kleinkopje, Greenside and South Witbank, have to enter into long-term mine water supply contracts with AOL as the lead entity. The contracts governing the relationship between AOL and the participating mines will address a number of issues related to:

- surety of delivery of mine water to the project;
- conditions under which a mine may discharge water to the project;
- the right of use of the project facility by each participating mine;
- the basis and calculation of a tariff for the discharge of mine water to the project, incorporating flow, acidity and salinity of mine water;
- monitoring and metering arrangements; and
- recourse in the case of non-performance of any party to the contract.

Water supply contract

A long-term water supply contract is being negotiated between AOL and the Emalahleni Local Municipality. This contract will regulate the long-term relationship between AOL as the supplier of potable water and the Municipality as buyer (user) of potable water.

The contract will deal with aspects related to:

- technical aspects – potable water volume, water quality, water delivery points, routine and emergency operations, metering and monitoring issues;
- regulatory aspects – regulatory requirements to be satisfied by both parties in terms of the *National Water Act*, No 36 of 1998 (NWA), *Water Services Act*, No 108 of 1997 (WSAct) and other environmental legislation;
- institutional aspects – organisational structure required to manage the relationship between AOL and the Municipality;
- financial aspects – development of water tariff, escalation of future water tariffs, payment terms and default of payment; and
- standard legal aspects related to dispute resolution, reporting requirements, breach of contract, etc.

Waste sludge/brine disposal contract

The preferred site for the solid waste gypsum is within the Blaauwkrans Mine Residue Deposit (MRD). The Blaauwkrans MRD is located on Landau Colliery Plant property. AOL will have to negotiate a long-term waste sludge/brine disposal contract with Landau Colliery.

Surface rights and servitudes

The project will be constructed on land to which AOL (Kleinkopje Mine and Greenside Mine) and Ingwe Collieries Ltd (South Witbank Mine) hold the surface rights.

The potable water supply pipeline to the Municipality will run along an existing servitude and along municipal road reserves.

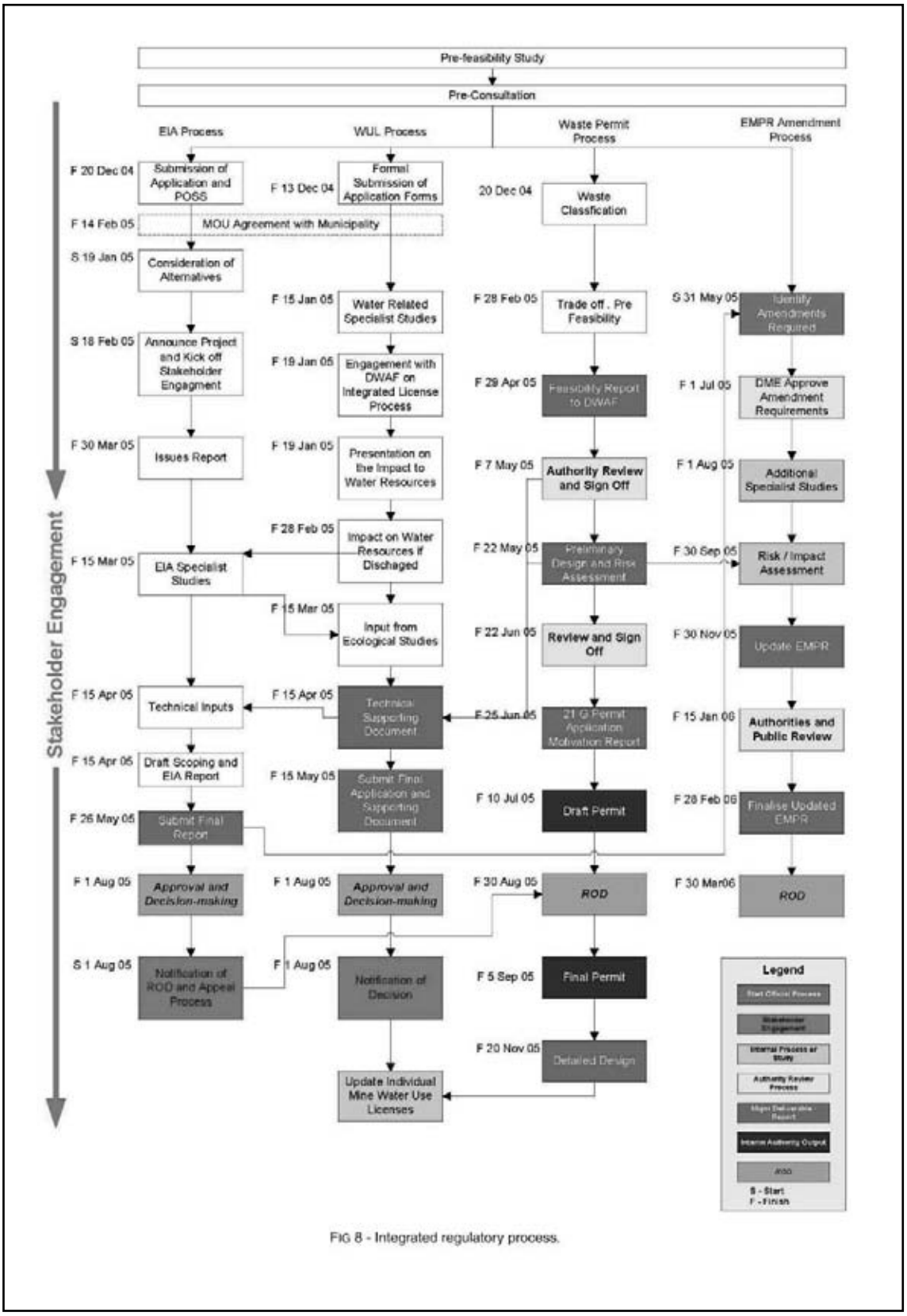


FIG 8 - Integrated regulatory process.

Servitude drawings will be prepared and approved for all aspects of the project, ie the pipeline and electrical power line routes, the plant site and waste disposal sites.

CONCLUSIONS

Together the mining companies and water treatment technology suppliers have to continue a cooperative relationship to make further advancements in mine water treatment. By making the decision, through a well-researched prefeasibility study, the treatment of mine waters to potable standard has converted an environmental liability into a public-private partnership asset.

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