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ACID MINE DRAINAGE AS A FACTOR IN THE IMPACTS OF UNDERGROUND MINEWATER DISCHARGES FROM GROOTVLEI GOLD MINE

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Introduction

The Blesbokspruit system has developed as a semi-natural-semi-artificial drainage course for one of the major industrial and urban conurbations within the Vaal River catchment. For many years the Blesbokspruit has received increasing quantities of urban, industrial and mining minewater, all of which have impacted on the system to cause an array of water quality and quantity concerns. However, the discharges, and associated activities of man in amending the natural water regimes and drainage cycles, has also resulted in the establishment of a wetland ecosystem which has been recognised as a site of special international scientific interest and registered as a Ramsar wetland.

During 1995, as a result of incremental closure of mining activities in the East Rand geohydrological regime, Grootvlei mine became the centre of attention as significant quantities of Acid Mine Drainage (AMD) contaminated underground water were discharged to the Blesbokspruit.

The discharges, carried out in terms of a Department of Water Affairs and Forestry (DWAF) permit, resulted in a precipitation of iron hydroxide which, by permeating the upper reaches of the wetland, caused unaesthetic conditions and fish kills. Following an analysis of the situation, the Minister of DWAF temporarily withdrew the discharge permit subject to water quality criteria which required that certain water treatment processes be installed at the Mine.

A High Density Sludge (HDS) pretreatment facility was erected to raise the acidic underground water pH and precipitate the iron hydroxides, prior to the release of the minewater into the Blesbokspruit. The impact of the discharge on the Blesbokspruit is being monitored in accordance with a permit issued by DWAF, whilst options for the desalination of the minewater salt concentrations, specifically sulphate, are evaluated.

The Grootvlei mine situation is not unique, with a number of major mines in the East and West Rand beginning to suffer similar problems of a need to discharge AMD contaminated minewater into the receiving water environment as the mine life comes to an end, and ground water levels rise to natural discharge elevations..

Relative Importance of the Blesbokspruit

The Blesbokspruit system has become perceived as an important water resource because of a number of assets and benefits it is seen to provide:

- It drains into the Vaal River where there is concern about increasing salinity and eutrophication and their effects on water supply to areas which are served downstream.

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Rand Water and the DWAF are pursuing a policy of limiting salt inputs to the system.

- The Spruit is characterized by large areas of wetland which have served a key function as biological filters and natural purifiers of the water for decades.

- Sections of the wetland have become increasingly important as conservation areas, particularly as a habitat for waterfowl. Part of the Blesbokspruit wetland area (1 858 ha), designated as a Ramsar wetland area in 1986, was originally donated by the Marievale Consolidated Mines to the Transvaal Division of Nature Conservation in the early 1970s.

- Water from the spruit is used for irrigation of adjacent farming land and for associated numerous riparian properties and interests.

Minewater Discharge from Grootvlei Mine

- Grootvlei mine lies at the bottom of a natural ground water drainage system, to where ground waters from the upper catchment, including several mining operations, gravitate. It has been the usual practice for the mining operations to abstract ground water from their working areas and discharge to surface, thereby controlling the relative ground water levels throughout the catchment and specifically at the lower Grootvlei position.

- As the operations in the upper catchment have increasingly amended their ground water abstraction practices, through closure of individual operations, the relative ground water loads arriving and accumulating at Grootvlei have steadily increased.

- Should Grootvlei not pump, not only would Grootvlei be forced to cease operations, but mines in the catchment which would also be subject to the flooding by rising ground water levels. Similarly, should Grootvlei not pump the ground water level will increase and within two-five years, discharge in the Nigel area. ie whether or not Grootvlei remain in operation there will be the discharge of AMD contaminated minewater into the Vaal system.

Geochemistry of the AMD Problem

- As a broad simplification ferruginous minewater is generated when pyritic rocks are exposed to air and water. The subsequent reaction is the oxidation of the pyritic material, FeS_2 to release the Fe and associated SO_4 as sulphuric acid, causing a lowering of the water pH. The Fe releasing, and acid generating, processes can basically be listed :

    - Oxidation of iron sulphide (pyrite and marcasite).
    - Oxidation of base-metal sulphides.
    - Oxidation of other sulphur forms (eg. sulphur, thiosulphates and polythionates).

- *Pyrite Oxidation*

    Pyrite oxidation can occur directly from the reaction with air and water, or indirectly from the reaction with ferric iron. The direct oxidation processes and associated biochemical reactions are considered to be the major contributors to AMD. The direct air and water oxidation of pyrite is described by the first three interdependent reactions, and an

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additional reaction (reaction 4) where trivalent ferric iron in solution will itself oxidise pyrite, resulting in acid generation, but without oxygen involvement.

Pyritic Sulphide Oxidation Reactions

$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+$ (equation 1)
$4Fe^{2+} + O_2 + 10H_2O \rightarrow 4Fe(OH)_3 + 8H^+$ (equation 2)
$2Fe^{2+} + O_2 + 2H^+ \rightarrow 2Fe^{3+} + H_2O$ (equation 3)
$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$ (equation 4)

- Although pyrite oxidation is exacerbated by the presence of ferric iron (equation 4) its formation is also accelerated by the chemosynthetic iron oxidising bacteria. Several species of chemosynthetic bacteria including *Thiobacillus ferrooxidans* are known to catalyse the oxidation of pyrite. These species are obligate chemo-autotrophic bacteria that use the energy obtained from the oxidation of Fe^{2+} for metabolic functions.

- Following the dissolution of pyrite, Fe^{3+} commonly forms a precipitate. The solid form is an orange coloured, gelatinous precipitate commonly referred to as ferric hydroxide or `yellow boy'. Its chemical make-up is complicated and its chemical configuration is ill defined. Hematite (Fe_2O_3) as a compound most often occurs in waterlogged soils, whereas jarosite [K-,Na-, or $Fe(SO_4)2(OH)_6$], or ferrihydrite $5Fe_2O_3.9H_2O$ also form.

- *Oxidation of Other Base-Metal Sulphides*

  Most base-metal sulphides are oxidisable, either directly by bacteria in the presence of air and water, or indirectly by ferric iron as either Fe^{3+} or ferric sulphate. For certain sulphides, such as galena (PbS) and sphalerite (ZnS), the rate of direct oxidation is slow and ferric iron oxidation is likely to be the only process which causes oxidation.

- *Oxidation of Other Forms of Sulphur*

  Secondary sulphur-bearing species can be important in acid generation from mine wastes, not only as intermediate products of reactions, but as sources of acid. Under certain conditions, sulphides can be partially oxidized to sulphites and thiosulphites, even at neutral or alkaline pH values. These are then subsequently oxidised to polythionate and eventually sulphuric acid, in the series:

$$S_2O_3 \rightarrow S_nO_6 \rightarrow S_3O_6 \rightarrow H_2SO_4$$

  where `n' is a number from 4 to 8.

- Ultimately all these reactions produce hydrogen ions, H^+, often in the form of H_2SO_4. The increase in acidity tends to mobilize other metals which may be present in the environment and the resulting cocktail is usually toxic to aquatic life and severely restricts the domestic use of affected surface waters.

Grootvlei Minewater Chemical Speciation Modelling

- The Grootvlei minewater is characterised by the elevated levels of iron and sulphate, with

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additional contaminants in the form of manganese, chloride, sodium and residual levels of zinc, cadmium, chromium, copper and cobalt.

- Although the minewater demonstrates the characteristic of being contaminated as a result of the oxidation of pyrites and associated AMD generation, the discharge pH of 5.6-6.4 is relatively neutral, indicating a high level of background buffering.

- Utilising the chemical equilibrium model MINTEQA 2 and the CSIR's Joint Expert Speciation System (JESS) model, an appreciation of the potential chemical quality of the minewater as it is pretreated, and subsequently enters the Blesbokspruit wetland has been developed. Table 1 illustrates the minewater quality as utilised for the assessment.

- Pretreatment for acid mine waters involves pH elevation above pH 8.5 through the addition of lime and aeration to precipitate metal hydroxides. Control parameters modelled were the direct discharge of minewater, and subsequently the affects of elevating the pH with and without aeration.

Table 1 Grootvlei Minewater Quality (Jan 96-July 98)

Constituent	Concentration mg/l	Constituent	Concentration mg/l	Constituent	Concentration mg/l
Alkalinity	138	Copper	0.03	Fluoride	1.7
Calcium hardness	1733	Nickel	0.76	pH	6.4
Electrical conductivity	438	Lead	0.34	Sulphate	2372
TDS	4203	Zinc	0.04	Chloride	203
Iron	191	Chromium	0.15	Sodium	370
Manganese	26	Cadmium	0.03		

- Chemical equilibrium modelling indicates the minewater will have a tendency to precipitate the iron oxide forms of hematite and jarosite, giving rise to the red/orange iron oxide sludge formation. Manganese, and other metals, do not precipitate as readily, and a small amount may remain after pretreatment though some will be expected to co-precipitate with the iron oxides, and the carbonates associated with the lime addition.

- Table 2 illustrates the projected forms of metal solid precipitates, that are expected to occur with physical-chemical pretreatment, and inherently as the residual components, are exposed to the aerobic and pH buffering conditions in the wetland.

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Table 2. Speciation of minewater metal components after pretreatment and during exposure to the wetland environment

Metal	Suspended Solid
Iron	$Fe(OH)_3$, FeOOH
Manganese	MnO_2
Copper	CuO, Cu_2O
Nickel	NiO, $Ni(OH)_2$
Chromium	Cr_2O_3, $Cr(OH)_3$
Cadmium	$CdCO_3$
Aluminium	$Al(OH)_3$

- Table 3 illustrates the calculated dissolved concentrations (mg/l) of untreated and pretreated minewater allowing for precipitation of selected solid phases over a settlement period of the order of 20 hours. Residual lead and zinc are not projected to precipitate as an oxide form, and are expected therefore to pass through the pretreatment stage relatively unaffected, however, within the wetland environment it is expected that the soluble fraction will be assimilated by adsorption and encapsulation.

Table 3. Dissolved concentrations of untreated and pretreated minewater allowing for precipitation of selected solid phases

Metal	Raw minewater	Untreated/ unassisted precipitation	Elevated pH + No Aeration	Aeration
Iron	210	3.27	0.002	0.001
Manganese	7.1	7.1	7.1	0.017
Copper	0.025	0.025	0.012	0.0001
Nickel	0.762	0.762	0.762	0.762
Chromium	0.150	0.005	0.0002	0.005
Cadmium	0.028	0.028	0.008	0.008
Aluminium	0.0004	0.0004	0.0001	0.0001
Lead	0.340	0.340	0.340	0.340
Zinc	0.040	0.040	0.040	0.040

- It is expected that most of the iron, manganese and zinc occurring in the sediment in the wetland environment will remain for extended periods in the residual and crystalline oxide. Indicating the limited affinity of these metals to form organic complexes, whilst it may be expected that the Cu and about 40% of the Al will be organically bound.

- Figures 1 and 2 illustrate the behaviour of the iron and manganese components relative

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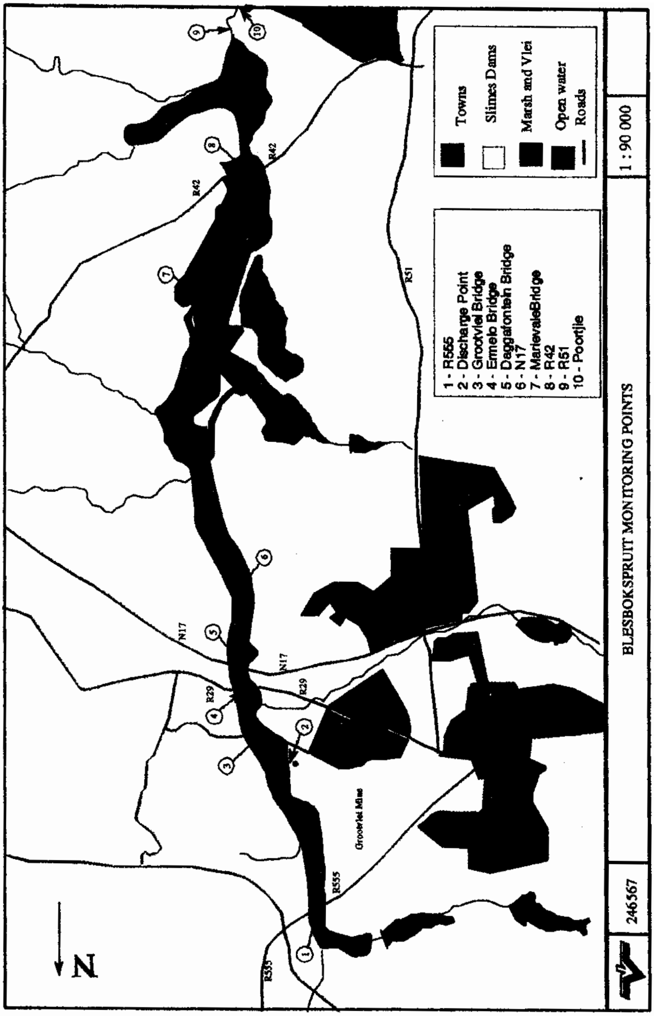

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to the variable pH and redox (oxidation) conditions experienced within a wetland environment, as derived by the CSIR JESS modelling exercise.

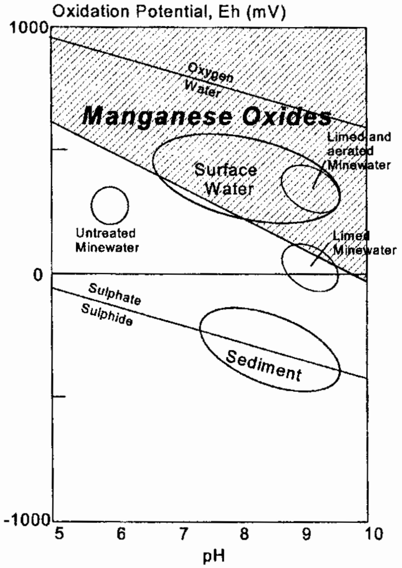

Figure 1 The region of thermodynamic stability of manganese oxides

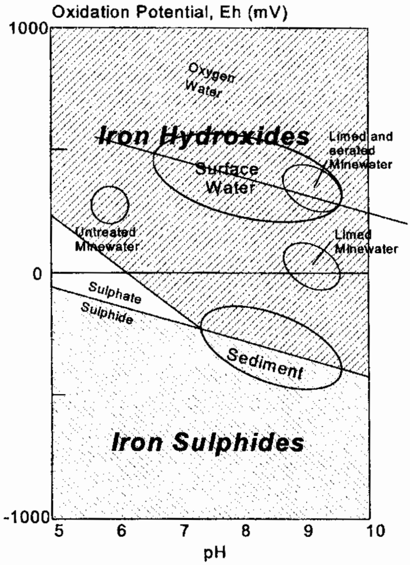

Figure 2 The region of thermodynamic stability of iron hydroxides and sulphides

Grootvlei Minewater Discharge Monitoring

- The water quality of the Grootvlei minewater discharges as well as monitoring points along the length of the Blesbokspruit system are collected on a bi-monthly basis, with daily monitoring of the discharge water quality, and treatment plant performance determined daily. Figure 3 illustrates the location of the monitoring points.

- As Total Dissolved Salts (TDS) levels has been taken as an indicator of water quality concern it is apparent that Grootvlei mine contributes significantly to the Blesbokspruit system, and consequently the Vaal system. The relative TDS and sulphate load can be appreciated from the significance of the contribution of the Grootvlei discharge of the order of 450 tons/d TDS and 250 tons sulphate.

- Where TDS or sulphate are used as a general indicator of water quality trends, it is apparent that the volume and character of the Grootvlei discharge has a significant impact upon the water quality at all points downstream of the discharge point.

- Comparing the salt ion profiles at all monitoring points with increasing distance from the discharge point as well as the upstream R555 monitoring points further illustrates the

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water quality impact of the Grootvlei discharge. Figure 4. There is a distinct change in shape of the Stiff diagram representing the water quality parameters in the points downstream relative to the upstream point.

- The shape of the Stiff diagrams of the downstream points have similar characteristics to that of the discharge, namely high calcium and alkalinity from the pretreatment and residual sulphate. Similar confirmation of the impact of the Grootvlei discharge on the Blesbokspruit water quality is illustrated by the Piper diagram, Figure 5, which again compares the relative proportion of anions and cations within the water at the individual monitoring points. The clustering within the Piper plot illustrates the comparability of downstream water quality characteristics as compared to the upstream R555.

- Of significance is that the water quality remains relatively constant with distance downstream from the discharge point illustrating the dominance of the Grootvlei discharge flow and quality on the Blesbokspruit hydrodynamics.

The Significance of AMD for Gauteng Goldmines

- As has been noted earlier, the example of Grootvlei as a discharger of AMD is not unique and an increasing number of mines in the Gauteng area are facing the need to assess AMD treatment and management options, specifically as they approach closure and ground water levels rise to a discharge condition.

- An assessment undertaken under the auspices of SWAMP, a consortium of mines and associated agencies in Gauteng, has been investigating the significance of potential future minewater AMD discharges and the options for treatment and recovery of water.

- Projections of total water and salt loads into the Gauteng system, and the contribution of future minewater discharges have been developed to assist evaluation of management options. The significance of potential minewater discharges is readily apparent.

Far West Rand:

Western Areas Gold Mine (WAGM) represents a significant potential AMD load to the Rietspruit catchment.

West Rand:

Being on the watershed between rivers flowing to the Indian Ocean and the Atlantic Ocean, the minewater impacted surface water is divided into the Crocodile River Catchment, and the Vaal Catchment, including the Klip River and Wonderfontein Spruit.

The Wonderfontein spruit drains a highly industrialised and mining area, which includes the dewatering of the Gemsbokfontein and Bank compartments and contributions from Randfontein Estates, Lindum Reefs, West Rands Consolidated and associated mine operations. It is also apparent that discharges from the mines, specifically Randfontein Estates can return underground via the Witpoortjie fault. Total discharge to the Lower Wonderfonteinspruit is currently given as 10 700 kg/d. However, the Randfontein Mine Void is projected to start discharging within 3 years.

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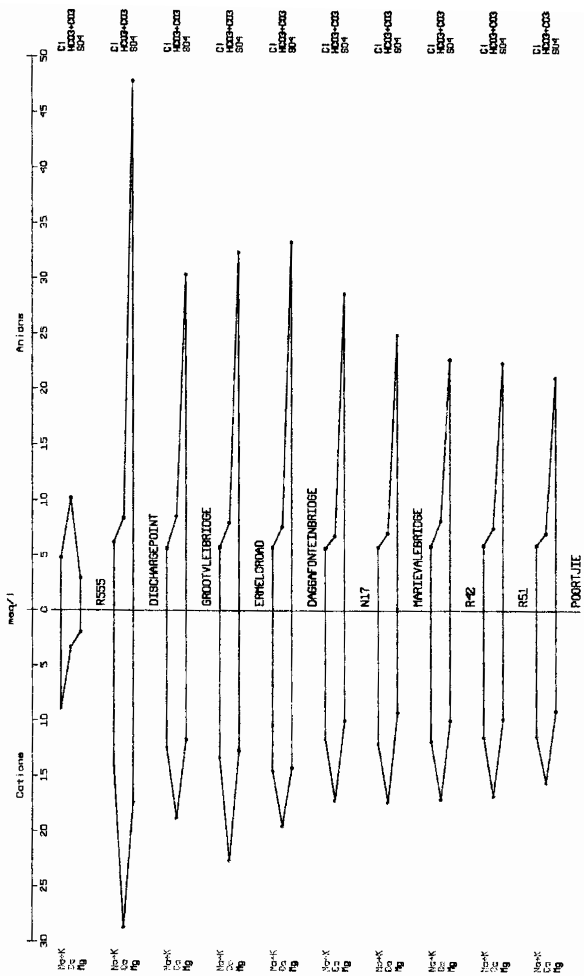

Stiff diagram for 16 April 1998 monitoring data

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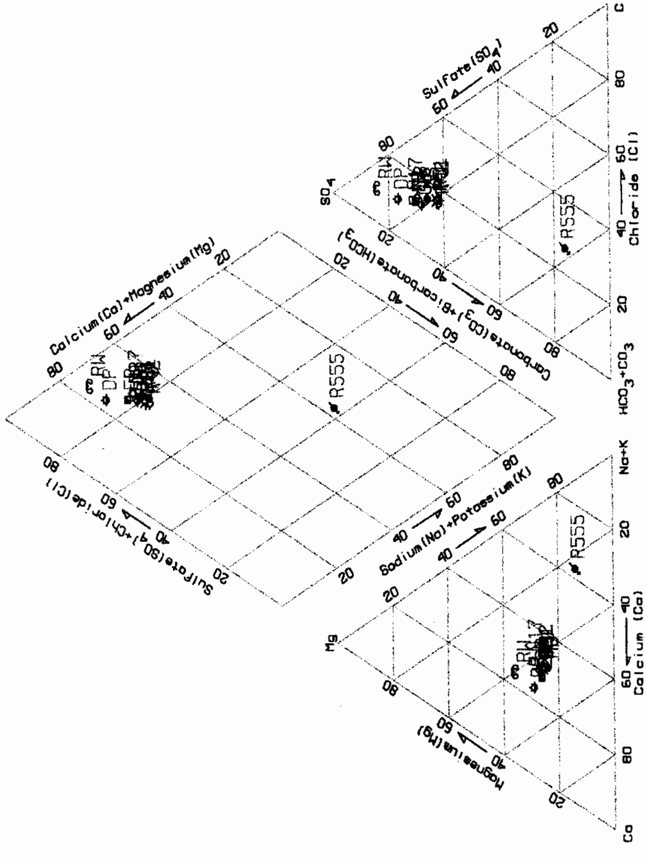

Piper diagram for 16 April 1998 monitoring data

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Central Rand:

The surface drainage of the Central Rand can be described as the Klip River draining to the Vaal River, the Natalspruit to the far west and the Rietspruit to the west draining the industrialised areas of Chamdor and including Durban Rooderpoort Deep. The Klipspruit drains areas influenced by Rand Leases Mines and ERPM.

East Rand:

The East Rand mines are drained by the Blesbokspruit, a tributary of the Suikerbosrand draining to the Vaal River. The Blesbokspruit can be divided into the Upper section above the Cowles Dam, and the Lower section which drains between Cowles Dam and the Suikerbosrand and is dominated by large wetland areas and the discharge from Grootvlei mine. Again, it appears that minewater discharges infiltrate back underground through the wetland system, to reappear as subsequent discharge.

Table 4: Minewater AMD Loads to the Vaal System by Region

Mining region	Total Surface Water Volume: kl/day	Total Salt Load kg/day	Minewater Volume: kl/day	Minewater Salt Load: kg/day
Far West Rand	123 836	104 260	63 300	61 900
West Rand	49 851	138 928	33 451	128 228
Central Rand	556 027	407 939	58 000	286 920
East Rand	315 526	390 781	120 000	368 328

Table 5: Total Minewater AMD Loads to the Vaal System

Total Volume kl/day	Salt Load kg/day	% Contribution by Mine AMD to Total Salt load
1 045 000	**1 042 000**	**81**

CONCLUSIONS

- The generation of Acid Mine Drainage is a natural consequence of mining activities where sulphur containing ores are exposed to water and oxygen and physico-chemical and biological interactions proceed to cause the release sulphuric acid and metals, principally iron and manganese and lesser levels of associated heavy metals and salts.

- Grootvlei mine lies at the bottom of a natural ground water drainage system to where ground waters from the upper catchment, including several mining operations, gravitate. As operations in the upper catchment have amended their ground water abstraction practices, the relative ground water loads arriving at Grootvlei have steadily increased and Grootvlei has been obliged to pump and discharge in order to protect its own operation, and associated mines in the ground water regime.

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- Geochemical modelling assists the appreciation of the effect of pretreatment upon the minewater quality and characteristics of the sludges generated and require management and disposal. The geochemical modelling also provides an insight into the implications of the untreated and pretreated minewaters on the receiving wetland water course.

- Monitoring of the Blesbokspruit over an extended period has illustrated the efficiency of the pretreatment programme and the significance of the water quality impact of the Grootvlei discharge. It is readily apparent that the discharge is responsible for a significant salt load, and dominates the chemical character of the Blesbokspruit Wetland throughout its length towards the Vaal system. It should be noted that ecological monitoring of the Blesbokspruit has not demonstrated significant long-term threat of the Grootvlei discharge after pretreatment, although water quality concerns are necessitating an assessment of desalination options for future operational conditions.

- Grootvlei is not unique and an increasing number of mines in the Gauteng area are facing the need to assess AMD treatment and management options, specifically as they approach closure and ground water levels rise to a discharge condition. It is projected that in the Gauteng region Gold Mines may contribute as much as 1042 tons/day of AMD derived salt load to the Vaal system representing approximately 81% of future salt loads.

- In closure, AMD is a significant factor of gold mining practices representing a significant liability in terms of long-term water quality management in the Vaal River system.

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