Optimal Acid Mine Water Treatment Network Design with Multipurpose Evaporation and Irrigation Regenerator Subnetwork

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Abstract**—** South Africa is a water strained country. It is speculated on good grounds that the demand for water is already equal to or exceeds the supply. The limited water supplies are frequently contaminated by acid mine water discharges which also poses huge environmental, ecological and health risks where water users are frequently exposed to high metal concentrations. In South Africa, like in other countries in the region, mining started over a century ago and most of the acid mine drainage (AMD) discharge is coming from abandoned mines and this leaves the government to carry the burden to avoid further decants and contamination of the scarce surface and underground water resource. The current estimated cost by the Department of Water & Sanitation for AMD neutralisation and desalination is R3.6 million/(ML/day) and R60 million/(ML/day) respectively. These figures are huge taking into consideration that the total flow in Gauteng province alone is 200 ML/day.

By using process integration and its enabling tools, the current study seeks to develop and evaluate a robust integrated acid mine water treatment network with multiple treatment or regeneration units. This allows for selective use of the treated mine water in agriculture, process industries, municipalities for drinking water purposes while simultaneously minimising the environmental impacts and costs. This was achieved by embedding a subnetwork of detailed evaporation and irrigation network linked to a neutralisation, softening and desalination (e.g. reverse osmosis and ion exchange) water treatment network. Based on the network and a fixed flow-rate of 30 ML/day for the Western Basin, a mathematical optimization model will be developed and optimised for optimal flow-rates of acid mine drainage into the treatment units and treated water into the distribution systems (Agriculture, Industry, rivers, environment and municipalities). The results of the preliminary water network development on the neutralisation stage have indicated that the total chemical cost for the neutralisation stage can be reduced from the estimated R3.6 million/(ML/day) to R1.9 million/(ML/day).

Keywords:

Keywords**—** Acid mine drainage, process integration, desalination, neutralisation.

I. Introduction

LARGE investments have been made in mine water treatment in South Africa. R2.50 billion was invested for neutralization of the mine water in the Western, Central and Eastern Basins and R2.95 billion for desalination of mine water in Mpumalanga. A further R10 billion needs to be invested, for desalination of the neutralised mine water in the Witwatersrand Western, Central and Eastern Basins. Despite these large investments, the environment is still threatened by the discharge of untreated or partly treated mine water into watercourses. The current cost of desalination, following neutralization, is estimated at R60 million/(ML/d). Despite the large investments made into research and development, construction of full-scale plants and strict legislation forcing industry to desalinate water, even at high cost, the environment is becoming more and more polluted.

The questions addressed in this investigation were:

- Can the projected desalination cost be reduced from R60 million/(ML/d) to less than R10 million/(ML/d)?;
- Is it possible for pollution due to disposal of solid waste and brines be turned into income through recovery of saleable products?
- How can large volumes of surface water be protected from salination by small volumes of un-treated or semi-treated mine water?.

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II. Cost of Water Treatment

Treatment of acid mine water includes neutralization and desalination. Acid mine water in the Wits, Western, Central and Eastern Basins is, or is shortly to be neutralized [5]. The cost of the three plants is R2.5 billion [6]. The construction cost of the plant in the Central Basin was R319-million and it was operational by August 2012 [7]. The cost of the plant in the Eastern Basin was estimated at R950-million and was projected to be operational by December 2015 [6]. In the Western Basin it was decided to upgrade the existing facilities at Harmony Gold Mine. The Trans-Caledon Tunnel Authority (TCTA) opted to employ proven local technology that uses limestone treatment for neutralisation of free acid, followed by additional lime treatment for removal of iron (II) and other heavy metals [8]. The projects made provision for pumping of mine water to the ECL of 165m, 168 m and 290 m for the Western, Central and Eastern Basins, respectively [7, 9]. Specialized submersible pumps (double suction, 2 400 kW, 6 600 V, 50 Hz) were

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installed in the three Basins to pump water to the ECL [10]. Two were installed in the Central Basin, three in the Eastern Basin and two in the Western Basin, while two were placed on standby. A tenth smaller pump was initially installed in the Western Basin. The cost of two large pumps amounted to R60-million [7].

After neutralisation mine water has to be desalinated. The gold mines in Gauteng produce 350 ML/d of mine water and the coal mines in Mpumalanga, 200 ML/d. Three mine water desalination plants have been constructed in Mpumalanga: at eMalahleni (50 ML/d at a capital cost of R900 million), Optimum Colliery (15 ML/d at a cost of R800-million) and Middelburg Colliery (25 ML/d at a cost of R1 250-million). The three plants treat 90 ML/d and had a total capital cost of R2 950-million [11, 12, 13, 14, 15, 16, 17]. At a treatment cost of R15/m3, the annual running cost amounts R493-million [11]. A large portion of the 75 ML/d treated at eMalahleni and Optimum is sold as drinking water. The balance is discharged into the Olifants River. As detailed above, three neutralization plants were constructed in Gauteng, or are under construction at an estimated cost of R2-billion [18]. This will be followed by three desalination plants at an expected cost of R10-billion [18]. These figures exclude the cost of sludge and brine disposal. The large, essential investments confirm the need for ongoing research and development to develop more cost-effective mine water treatment processes.

III. Sludge And Brine Disposal

South Africa's total waste stream amounts to 539 million t/a of which industrial and mining waste amounts to about 487 million t/a (90%) [19]. Mining waste contributes 72.3% to the solid waste stream. The legal definitions of waste are contained in the National Environmental Management: Waste Act, 2008 and the National Water Act, 1998. South Africa supports the waste hierarchy in its approach to waste management, by promoting cleaner production, waste minimization, water reuse, recycling and waste treatment, with disposal seen as a last resort [20]. The Act stipulates that acids should be neutralised to have a pH between 6 and 12 before discharge onto a landfill site. The TDS content of brine or waste with a high salt content should not exceed 50 000 mg/L and the TDS from leachables should not exceed 100 000 mg/L [21].

IV. Objectives

The purpose of this study was to investigate the changes required to current practices to reduce the negative environmental impacts of mine water. The following specific objectives were set:

- Reduce the cost of desalination from R60-million/(ML/d) to R10-million/(ML/d).
- Identify technologies that will protect large volumes of clean surface water from in-flows of small volumes of partially treated mine water.
- Identify technologies where disposal of waste sludge and brine streams is replaced by the recovery of saleable products.

V. Results and Discussion

A. Treatment

The capital and running costs are high for mine-water treatment plants, as indicated in Background (above). These high costs should serve as motivation for investigations into reducing the cost of mine water treatment.

Table 1 shows the costs of raw materials used during water treatment by various processes. Table 2 shows the chemical compositions of the raw and treated water, flow-rates and compositions of streams, mass of solid waste and estimated running and capital costs for the various neutralization technologies. Option A is when neutralisation is effected by the use of limestone for the removal of free acidity followed by lime for removal of metals. Option B utilises lime alone for neutralisation. In Option C, soda-ash is used for neutralisation. A combination of limestone and lime neutralisation, when given sufficient residence time, allows for partial sulphate removal through gypsum crystallisation (Table 2; Columns A & B). The cost of neutralization of Western Basin water with $CaCO_3$ and $Ca(OH)_2$ amounts to R2.72/m^3 compared to R5.00/m^3 when solely lime is used. Gypsum crystallization, results in partial sulphate removal from 3 500 mg/L down to 1802 mg/L. When Na_2CO_3 is used for neutralization, the alkali cost amounts to R8.64/m^3.

TABLE I
Prices of chemicals used in this investigation

Chemical	Source	Utilization	Purity	Price
		%	%	R/t
Ca(OH)2	Purchase	90	88	2 200
Na2CO3	Purchase	99	98	2 947
NaOH	Purchase	99	88	3 000
H2SO4	Purchase	99	98	1 800
BaCO3	Recover	95	98	5 000
HNO3	Purchase	99	65	4 000
NH4OH	Purchase	99	90	4 000
Al(OH)3	Recover	90	97	5 000

TABLE 2
NEUTRALIZATION OF WESTERN BASIN WATER WITH VARIOUS ALKALIS

Parameter	Units		Neutralization					
Parameter			Feed 1	Option A		Option B	A & B	Option C
		Eq mass		CaCO3	Ca(OH)2	Ca(OH)2	Gypsum	Na2CO3
Recovery	%							
Salt rejection	%							
Flow	m3/h		160,00	160,00	160,00	160,00	160,00	160,00
Flow	m3/d		3 840,00	3 840,00	3 840,00	3 840,00	3 840,00	3 840,00
CaCO3	mg/l			1 845,34				
Ca(OH)2	mg/l	37,00			434,46	1 800,02		
Na2CO3	mg/l	53,00						2 844,02
NaOH	mg/l	40,00						
H2SO4	mg/l	49,00						
Coal								
BaCO3	mg/l	98,50						
HNO3	mg/l	63,00						
NH4OH	mg/l	35,00						
Al(OH)3	mg/l	26,00						
Utilization	%			90,00	90,00	90,00		99,00
Purity	%			88,00	88,00	88,00		98,00
Dosage	mg/l			2 329,98	548,57	2 272,75		2 931,38
Price	R/t			650,00	2 200,00	2 200,00		2 947,00
Usage	t/day			8,95	2,11	8,73		11,26
Chemical cost	R/m3			1,51	1,21	5,00		8,64
Chemical cost	R/m3			2,72		5,00		8,64
CO2	mg/l	22,00						
Water			Western Basin					
pH		5,76	2,80	9,20	9,20	9,20	9,20	8,00
Carbonate	mg CO3/L	30,00	0,00	60,00	60,00	60,00	60,00	0,00
Sulphate	mg SO4/L	48,00	3 500,00	3 500,00	3 500,00	3 500,00	1 801,88	3 500,00
Chloride	mg Cl/L	35,50	30,00	30,00	30,00	30,00	30,00	30,00
H+	mg H+/L	1,00	13,38	1,00	0,00	0,00	0,00	13,38
Sodium	mg Na/L	23,00	50,00	50,00	50,00	50,00	50,00	1 284,20
Magnesium	mg Mg/L	12,15	150,00	150,00	50,00	50,00	50,00	50,00
Calcium	mg Ca/L	20,00	415,00	1 153	1 388	1 388	680	5,00
Aluminium	mg Al/L	9,00	50,00	0,00	0,00	0,00	0,00	1,00
Iron(II)	mg Fe/L	27,93	400,00	1,00	1,00	1,00	1,00	1,00
Iron(III)	mg Fe/L	18,62	50,00	0,00	0,00	0,00	0,00	0,00
Manganese	mg Mn/L	27,47	70,00	70,00	1,00	1,00	1,00	1,00
Barium	mg Ba/L	68,50	0,00	0,00	0,00	0,00	0,00	0,00
Strontium	mg Sr/L	43,81	0,00	0,00	0,00	0,00	0,00	0,00
Total Acidity	mg/L	50,00	1 797,13	37,23	1,29	1,29	1,29	71,89
Anion Sum			73,76	75,76	75,76	75,76	40,38	73,76
Cation Sum			73,76	75,76	75,76	75,76	40,38	73,76
Total Dissolved Solids	mg/L		4 728	5 015	5 080	5 080	2 674	4 886
Solids	kg/m3 feed			0,75	0,35	1,10	3,04	0,00

The following processes were evaluated for the desalination of 160m^3/h Western Basin water and evaluation of treated water qualities: HIPRO (reverse osmosis), $BaCO_3$ (chemical precipitation with barium salts), KNEW (ion-exchange), Savmin (chemical precipitation with an aluminium complex) and ROC (reverse osmosis/cooling) (Table 3)

The TDS content of Western Basin water after lime treatment, including gypsum crystallization, is 2 674 mg/L. During desalination with the HiPRO process, the TDS can be reduced to 28 mg/L, with the $BaCO_3$ process, to 604 mg/L, with the KNEW process, to 26 mg/L, and with the Savmin process, to 405 mg/L. The reason for the less efficient TDS removals by the chemical desalination processes ($BaCO_3$ and Savmin) is that sodium sulphate is soluble and cannot be removed with the $BaCO_3$ or Savmin (ettringite) processes. Monovalent ions such as Na^+ and Cl^- can be removed by adding ion-exchange as a polishing stage to the chemical desalination processes, as described by Ruto et al. [30].

The chemical costs for the various technologies are, R6.98/m^3 for HIPRO (Lime, H_2SO_4 and membrane cleaning chemicals); R15.82/m^3 for $BaCO_3$ ($BaCO_3$); R26.93/m^3 for KNEW (Na_2CO_3, HNO_3, NH_4OH); R12.41/m^3 for Savmin (Lime, $Al(OH)_3$ and H_2SO_4) and R8.19/m^3 for the ROC process (Table 3). The corresponding total running costs (including capital redemption costs) are R19.65 for the HIPRO process, R20.32/m^3 for the $BaCO_3$ process, R32.56/m^3 for the KNEW process, R18.44/m^3 for the Savmin process and R16.59 for the ROC process (Table 3). Table 4 shows the costs of the various technologies when a value was given to the treated water, as a function of its TDS content.

TABLE 3
DESALINATION OF NEUTRALIZED WATER UTILISING THREE DIFFERENT TECHNOLOGIES

Parameter	Units		Desalination Technology					
			Pre-treated	RO	BaCO3	KNEW	Savmin	RO/ F Desal.
Flow	m3/h		160,00	160,00	160,00	160,00	160,00	160,00
Recovery	%			97,30				98,80
Salt rejection	%			99,02				98,66
			Chemical dosage (mg/l)					
Chemical			**Pre-treated**	**RO**	**BaCO3**	**KNEW**	**Savmin**	**RO/ F Desal.**
Ca(OH)2				449,2			1 584,8	
Na2CO3						1 890,2		1 784,7
NaOH								
H2SO4				147,0			1 635,3	147,0
Coal					876,2			
BaCO3					2 876,8			
HNO3						2 402,9		
NH4OH						1 327,6		
Al(OH)3							867,7	
Chemical cost	R/m3		2,72	6,98	15,82	26,93	12,41	8,19
Membrane protection chemicals	R/m3			2,00	0,00	0,00	0,00	1,00
Electricity	R/m3		1,20	2,40	0,80	0,80	1,20	3,20
Labour	R/m3		1,00	2,00	2,00	2,00	2,00	2,00
Maintenance	R/m3		0,50	0,50	0,50	0,50	0,50	0,50
Membrane replacement			-	0,60	0,00	0,00	0,00	0,30
Admin	R/m3		0,15	0,25	0,25	0,25	0,25	0,25
Management			0,20	0,20	0,20	0,20	0,20	0,20
Running cost	R/m3		5,77	14,93	19,57	30,68	16,56	15,64
Capital redemption cost (10%, 20 y)*[1]			0,57	4,71	0,75	1,89	1,89	0,94
Running cost (incl Capital Redemption)			**6,34**	**19,65**	**20,32**	**32,56**	**18,44**	**16,59**
Capital cost (Rm/(Ml/d))			6,00	50,00	8,00	20,00	20,00	10,00
Electricity (kWh/m3)			1,50	3,00	1,00	1,00	1,50	4,00
Interest (%)			12,00	12,00	12,00	12,00	12,00	12,00
Term			240,00	240,00	240,00	240,00	240,00	240,00
Parameter			**Water Quality**					
	Units	**Feed**	**Pre-treated**	**RO**	**BaCO3**	**KNEW**	**Savmin**	**RO/ F Desal.**
pH		2,80	7,80	7,50	7,80	8,00	8,30	7,50
Carbonate	mg/l	0,00	60,00	1,16	60,00	0,00	60,00	1,68
Sulphate	mg/l	3 500,00	1 801,88	17,51	400,00	15,00	200,00	43,70
Chloride	mg/l	30,00	30,00	0,58	30,00	5,00	30,00	0,84
Nitrate	mg/l	0,00	0,00	0,00	0,00	0,00	0,00	0,00
H+	mg/l	13,38	0,00	0,00	0,00	0,21	0,00	0,08
Sodium	mg/l	50,00	50,00	0,97	50,00	5,00	50,00	17,91
Potassium	mg/l	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Magnesium	mg/l	150,00	50,00	0,02	50,00	0,50	50,00	1,40
Calcium	mg/l	415,00	680,43	7,50	96,32	0,50	12,98	0,20
Aluminium	mg/l	50,00	0,00	0,00	0,00	0,10	0,00	0,00
Iron(II)	mg/l	400,00	1,00	0,02	1,00	0,00	1,00	0,03
Iron(III)	mg/l	50,00	0,00	0,00	0,00	0,00	0,00	0,00
Manganese	mg/l	70,00	1,00	0,02	1,00	0,05	1,00	0,03
Anion Sum	meq/l	73,76	40,38	0,42	11,18	0,45	7,01	0,99
Cation Sum	meq/l	73,76	40,38	0,42	11,18	0,51	7,01	0,99
Total Dissolved Solids	mg/l	4 728,38	2 674,31	27,78	604,32	26,36	404,98	63,53
Value of water	R/m3		1,09	9,91	7,99	9,91	8,65	9,79

*[1] - Estimated figures; Correct figures need to be obtained from the suppliers of the various technologies

For zero mg/L TDS the value was taken at R10/m^3 and for 1000 mg/L, at R6.67/m^3. The cost of the KNEW process was the highest, at R22.65/m^3. When the values of its by-products are taken into account the process will be cost-effective. The cost of the ROC process, was the lowest, R6.80/m^3. The main reason is its lower capital cost and consequently lower capital redemption cost.

The second observation was that no brine was produced with the chemical desalination processes. The HIPRO process produces 4.32 m^3/h brine containing 18 157 mg/L TDS and the KNEW process, 12.96 m^3/h ion-exchange regenerant with a TDS of 70 000 mg/L (Table 5). The regenerant from the KNEW process can be processed to recover saleable $Ca(NO_3)_2$ and $(NH_4)2SO_4$. In the case of HIPRO process, the sludge that has to be disposed of amounts to 4.84 kg/(m^3 feed), 0.49 kg/(m^3 feed) in the case of $BaCO_3$, 0.18 kg/(m^3 feed) in the case of KNEW and 3.34 kg/(m^3 feed) in the case of the Savmin process (Table 5).

B. *Sludge Disposal versus Recovery Of Saleable Products*

The sludge resulting from mine water treatment systems usually contains elevated levels of contaminants that were originally contained in the mine water. Proper disposal of these solids with careful environmental considerations must be done to avoid shifting of the original pollutants in the waste-stream to the final disposal site where they may again become free to contaminate the environment [31]. A more reasonable approach to ultimate solids disposal is to recycle or reuse the sludge. Most sludge treatment methods aim to reduce the volume or to change its state or properties to facilitate safe disposal. These methods still leave residues which in most cases must be removed from the plant site. Treatment and final disposal of the primary and secondary sludge makes up a significant part of the material and financial resources of the wastewater treatment plant.

Zero waste disposal is a real and necessary aim due to the high costs of disposal of solid wastes and brines. Table 5, shows the costs associated with the disposal of sludge and/or brines that are produced by the various technologies. A cost of R3 100/t, was used as the typical cost for disposal at a toxic waste disposal site. The high costs that were calculated would be unaffordable and therefore, much emphasis should be towards the recovery of saleable products from waste streams.

During neutralization with limestone and/or lime, gypsum-rich sludge and metal hydroxides are produced. Such a mixed sludge has no value and has to be disposed of at a high cost. The gypsum that is produced during desalination with the HiPRO process is essentially pure or only contaminated with $Mg(OH)_2$. This pure gypsum has some value and can be used as building material or for processing into sulphur and $CaCO_3$.

The economic viability of several desalination processes is highly dependent on the feasibility of the recovery of process raw materials. Gypsum is produced as a by-product in the HIPRO process and $CaCO_3$ and sulphur can be recovered from the gypsum. Gypsum can also be sold as a soil conditioner or as a raw material to the cement industry. In the barium process, $BaCO_3$ can be regenerated from $BaSO_4$, or the $BaSO_4$ sold as a drilling mud. Other saleable products that can be recovered from the Barium process sludge are sulphur and $CaCO_3$. In the case of the Savmin process, $Al(OH)_3$ should be recovered from etteringite, $3CaO.3CaSO_4.Al_2O_3$, whilst gypsum and $CaCO_3$ are produced as by-products. In the case of the KNEW process, by-product $NaNO_3$ and $(NH_4)2SO_4$, can be sold to at least partially cover the cost of the ion-exchange elution raw materials, HNO_3 and NH_4OH.

TABLE 4
TOTAL OF WATER, PRODUCTS AND RUNNING COST

Parameter	Unit			Value					
				Feed	RO	BaCO3	KNEW	Savmin	RO/F Des
Values in R/m3									
Capital cost (estimate)	Rm/(ML/d)				50,00	8,00	20,00	20,00	10,00
TDS	mg/L			2 674,31	27,78	604,32	26,36	404,98	63,53
Value of water (Table 5)	R/m3			1,09	9,91	7,99	9,91	8,65	9,79
Running cost (Table 5)	R/m3				-19,65	-20,32	-32,56	-18,44	-16,59
Total cost	R/m3				-9,74	-12,34	-22,65	-9,79	-6,80

TABLE 5
SLUDGE AND BRINE DISPOSAL COST

Brine disposal cost		Units			RO	BaCO3	KNEW	Savmin	RO/F Des
Total dissolved solids		mg/l			18 157,24		70 000		53 569
Flow		m3/h			4,32		12,96		1,92
Flow		t/month			3 152		9 459		1 401
Disposal cost		R/t			3 100		3 100		3 100
Disposal cost		R/month			9 770 803		29 323 609		4 342 579
Disposal cost		R/m3 feed			83,70		251,20		37,20
Sludge disposal cost									
Solids (dry)		kg/m3 feed			4,83	0,49	0,18	3,34	0,37
Mass (dry)		kg/h			772,12	77,80	28,17	534,88	58,99
Sludge (30% solids)		t/month			1 878	189	69	1 301	143
Disposal cost (R3 100/t)		R/month			5 821 198	586 582	212 403	4 032 574	444 757
Disposal cost		R/m3 feed			49,87	5,02	1,82	34,54	3,81
Brine + Sludge disposal cost		**R/m3 feed**			**133,57**	**5,02**	**253,02**	**34,54**	**41,01**

Table 6 shows the value of saleable products that can be recovered from the various processes. Values between R0.93/(m^3 feed) and R14.18/(m^3 feed) were calculated. These costs only include the value of products that can be recovered from the desalination stage. The potential values of metal compounds, namely $CaCO_3$, magnetite and Na_2SO_4, which can be recovered during the pre-treatment and cooling stages were not calculated.

TABLE 6
VALUE OF PROCESS BY-PRODUCTS

By-product	Price (R/t)				Production (mg/l)				
					RO	BaCO3	KNEW	Savmin	RO/F Des
CaSO4.2H2O	300				3 103			2 870	
CaCO3	1 000					1 460		473	
BaCO3	5 000								
BaSO4	1 000					3 402			
Sulphur	1 400					0			
Al(OH)3	5 000							868	
H2SO4	1 800								
NaNO3	2 500						3 215		
(NH4)2SO4	2 500						2 457		
Na2CO3	2 947								
Na2SO4	2 000								1 354
Value (R/m3)					**0,93**	**4,86**	**14,18**	**5,67**	**2,71**

C. Protection of surface water

i. Volume of water

All mine water should be desalinated to protect surface water. It is environmentally futile if only a portion of the neutralized mine water is desalinated at high cost while the remaining neutralized mine water is allowed to be discharged into water courses. Alternative methods have to be considered on how to deal with the non-desalinated mine water, other than to discharge it into the environment.

The volume of AMD discharged in Gauteng amounts to 350 ML/d. This is only 3.4% of the total volume of river water in the region (Table 7). The percentage will be even less if mine water is allowed to rise to higher levels before it is pumped to surface. The individual figures for mine-water that is discharged into the two main rivers, the Vaal and Crocodile Rivers, amounts to 3.0% and 4.6%, respectively. Thus, since mine-water amounts to only 3.4% of the surface water, a cost comparison is needed for desalination of the mine-water versus complete prevention of mine-water discharge into rivers. Methods such as forced evaporation and/or irrigation should be considered in combination with treatment of the residual leachate. In the controlled release of mine-water, good quality water is used to dilute the resultant salinity of river water following mine-water discharge. Up to seven times more good quality water, compared to the mine-water, is used for dilution. It may be more cost-effective to keep surface water free from the salts in mine-water through forced evaporation or irrigation plus treatment of the residual water/leachate, than to desalinate mine-water.

TABLE 7
VOLUME OF MINE-WATER PRODUCED IN GAUTENG

River	Basin	Flow (Ml/d)			Mine water/ River water (%)
		Mine water	Mine water	River water	
Vaal				10 800	
	Central	60			
	Eastern	110	320		3,0
	Far Western	150			
Crocodile				650	
	Western	30	30		4,6
Olifants				2 728	
	Mpumalanga	130	130		4,8
Total			480	14 178	3,4

ii. Evaporation

Pond evaporation is widely used to separate pure water from hazardous waste and this greatly reduces the volume for further treatment or disposal. Reduction of water volumes enables the contaminated water to be easily managed and hence prevent the contamination from spreading to environmental water bodies. Convectional pond evaporation systems are driven by heat-energy and given sufficient energy, water molecules on the surface will evaporate. The quantity of water that will evaporate in the system will be directly proportional to the net heat absorbed from all sources less heat losses.

Pond evaporation is usually slow and often limited by land availability and the limitations of cost of constructing additional evaporation ponds and the added cost of clean-up and re-vegetation [32]. Forced evaporation is currently finding its way into mine water management with evaporation rates beyond the traditional evaporation ponds. Forced evaporation makes use of high pressures to force the water through a nozzle to produce fine droplets that will increase the surface area and hence improved evaporation rates. Most of these evaporators are compact, equipped with fine nozzles, a high-pressure pump and an air-fan to give the water droplets enough residence time in suspension, for evaporation. Suppliers of mechanical evaporators claim 70% evaporation rates and the current units on the South African market are operating at 50% evaporation rates, with each unit evaporating approximately 22.5m^3/h.

The two most significant sources of heat in forced evaporation are solar radiation and the heat extractable from moving air. Figure 1, shows mechanical evaporators installed at a mine closure site in South Africa, for management of mine water balances.

There are several forced evaporation units in operation at several mine sites. One case during this study revealed that, for the evaporation of 2 ML/d of water, a pump and 10 evaporation units would be required. The capital redemption and running costs were calculated at R2.90/m^3 as shown in Table 10. This is significantly less than the total running cost of R16/m^3 - R32/m^3 for the desalination technologies when the value of products is excluded. Forced evaporation therefore deserves to be considered as one of the processes that can be used in mine water treatment/disposal followed by neutralisation and desalination of the concentrated stream.

The major advantage of the mechanical evaporator is improved evaporation rates due to increased surface area. In the past decades, the process efficiencies and economic impacts of mechanical wastewater evaporation were underscored by the environmental impacts of the resultant spray-drift and this led to unwarranted public anxieties. Spray-drift and off-target losses are the inherent problems of conventional, air-assisted, fine droplet, mechanical evaporators. Due to concerns for environmental safety and process efficiency, it is important to maximize the amount of water evaporated and deposited back into the source or target site. Current installations include drift barriers to restrict drift to its source or the target site.

Fig. 1 Mechanical evaporator equipped with a booster pump

The net effect of evaporation is concentration of the wastewater for further treatment with other processes such as RO/Freeze desalination, reverse osmosis, ion- exchange, Savmin or the ABC process.

TABLE 8
COST OF FORCED EVAPORATION

Parameter	Value
Capacity (m3/d)	2 000
Capacity (m3/h)	83
Pump (110 kW; 24m3/h)	135 000
Beast (11 kW; 10 units)	2 450 000
Mother pipe (172 mm)	65 000
Distribution pipes (50 mm; 2 km; R15/	32 000
Nozzles (500; R50/nozzle)	35 000
Support + Cables	68 000
Nozzles	
Capital cost (R)	2 785 000
Capital cost (R/Ml/d))	1 392 500
Interest (%/a)	12
Term (Months)	60
Capital redemption cost (R/m3)	1,02
Velocity (m/sec)	1
Pipe ddia (mm)	172
Electricity (kW)	
Pump	110
Beast	110
Electricity (kW)	220
Power (kWh/d)	5 280
Power (kWh/m3)	2,64
Electricity cost (R/kWh)	0,60
Electricity cost (R/m3)	1,58
Labour (R/m3)	0,10
Maintenance (R/m3)	0,10
Admin (R/m3)	0,05
Management (R/m3)	0,05
Running cost (R/m3)	1,88
Total cost (R/m3)	2,90

iii. Irrigation

An alternative application of evaporation is when it is used to evaporate neutralised acid mine water through irrigation. The irrigation option is attractive as the relatively small volume of neutralized mine water (for example, 200ML/d from the three basins in Gauteng), is kept away from the far larger volume of surface water which is used for domestic purposes (Rand Water produces 4 000 ML/d and current irrigation in the Gauteng region is roughly estimated at 10 000ML/d). Through irrigation, depending on prevailing weather conditions, cropping system selection and irrigation management, around 80% of the mine water can be beneficially evaporated. This will result in precipitation in the soil of 80% of the soluble gypsum in the neutralised water. At an estimated average irrigation rate of 750 mm/year, an area of around 3.9 km x 3.9 km will be needed for irrigation of 30 ML/d, and 10 km x 10 km for 200ML/d. The areas will depend highly on the cropping system selection.

According to Annandale [33], irrigation with gypsiferous mine water is feasible and worth considering as part of the solution to South Africa's AMD problems. Irrigation provides some flexibility, while cropping systems and irrigation practices can be designed to optimise water use, evaporation rates, area needed for irrigation, gypsum precipitation, profit, or job creation. Makgae et al. estimated the capital cost for neutralization and irrigation at R4.9-million/(ML/d) [34].

The effect of leachate on groundwater can be addressed by careful site selection for irrigated fields and, if necessary, the installation of a drainage system. The collected leachate will have to be treated, where necessary, with RO/Freeze desalination to recover clean water and salt as in other mechanical evaporation processes. Possible scaling of the pivot system will be avoided by diluting the neutralized water with desalinated or fresh water. The volume needed for dilution will not exceed 10% as it is only to ensure that the saturation level of gypsum is not exceeded.

The irrigation application offers the following benefits: (i) Low initial treatment cost of acid water, as neutralization will only cost 46% of that of the current operation; (ii) Irrigation of mine water will result in job creation and the generation of agricultural products. The big benefit of irrigation is that it can handle large volumes of water, and if carefully designed and well managed, should be able to pay for itself. Even if irrigation is subsidised to a degree through the supply of irrigation and storage infrastructure, the supply of some farming equipment, and the pumping of water, this is likely to be a relatively small cost compared to other treatment options. (iii) There will be no need to contaminate large volumes of clean water with neutralized, saline mine water; (iv) There will be no or minimal waste sludge due to sludge processing into raw materials and saleable by-products; and (v) Limited pollution of groundwater.

The geohydrological setting will determine the approach to be followed to intercept and manage the leachate from the irrigated fields, e.g. minimizing the leachate to treat through interception and evapotranspiration with trees, freeze desalination or controlled release.

VI. Conclusions and Recommendations

The following conclusions and recommendations were made:

i. Large investments have been made for mine water treatment. This high cost can be lowered by upgrading the HiPRO process to include improvements of the ROC process or by considering alternative new technologies such as the CSIR ABC process ($BaCO_3$), KNEW process (ion-exchange) or Savmin process (chemical desalination).

ii. Zero waste disposal requires processing of sludge and brine streams that are generated during neutralization and desalination of mine water. Technologies will have to be selected that allow the recovery of saleable products during mine water treatment. With the ROC process, metal compounds can be recovered selectively, including magnetite, $CaCO_3$ and Na_2SO_4.

iii. Surface water must be protected by avoiding discharge of untreated or only neutralized mine water into rivers. Since mine water amounts to only 3.4% of the volume of surface water, alternative methods, such as forced evaporation or irrigation should also be considered

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