

Simulation of Water Quality in Underground Gold Mine Service Water Circuits

By J. G. MACKAY¹ and H. N. S. WIECHERS¹

Environmental Engineering Laboratory
Chamber of Mines of South Africa
Research Organization
P O Box 91230
Auckland Park 2006
South Africa

ABSTRACT

The mechanisms and chemical processes underlying mine service water salination, conditioning and purification have been investigated for a number of gold mines. Based on the results of these studies, unit process models have been developed to form building blocks for a systems model for simulating water quality in underground mine service water circuits. The unit process models developed include a stope leaching, a neutralization and a desalination model and were used to develop a mine service water circuit simulation program, AQUA-Q. This user-friendly interactive program assembles a network of unit processes and connecting links to describe the system under consideration. Total dissolved solids, alkalinity, calcium and sulphate concentrations as well as pH are simulated at specific points within the system as functions of time. Case studies, demonstrating the program's application for design of underground mine service water circuits and the development of operational strategies for existing circuits, are given.

INTRODUCTION

Service water is used underground for a variety of purposes in the South African gold mining industry, including, dust suppression, watering down of working areas, water jetting and the cooling of ventilation air. These activities as well as the ingress of saline fissure water and drainage of water from old worked out areas result in the water being pumped out of the mines being of a significantly poorer quality than the service water gravitated down the mines. Restrictive costs and limited availability of fresh make-up water have made it necessary to re-use mine service water wherever practical. However, recycling of service water results in a deterioration in the quality of this water with attendant increases in problems of corrosion, erosion and scale formation - often with severe practical and economic consequences [1]. Corrective action therefore needs to be taken, for example by better water quality management, by prevention of pollution at source and by treating polluted water to an

The Third International Mine Water Congress, Melbourne Australia, October 1988

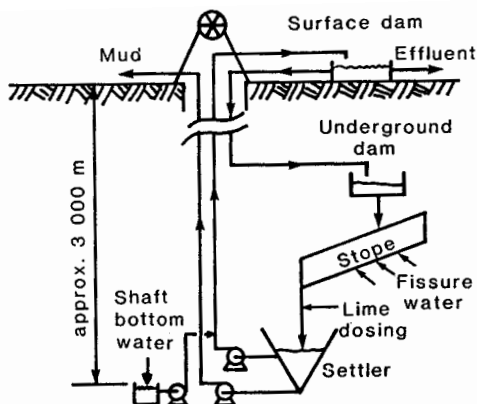


Figure 1 Simple underground mine water circuit

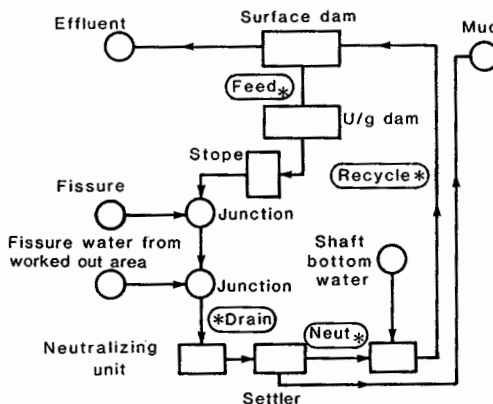


Figure 2 Schematic network for a typical underground mine service water circuit

adequate quality appropriate to its particular use. Figure 1 illustrates a very simple underground water circuit, while Figure 2 shows a simple process network.

In order to facilitate cost-effective remedial action, water qualities within mine service water circuits need to be simulated. Some work has been done in the past [2] to model water quality in gold mine water circuits. However, serious limitations of these models were that they did not adequately simulate the chemistry of mine water or the mechanisms underlying the various water-related unit processes operative in gold mines. In order to resolve this problem, an interactive computer program (AQUA-Q), which simulates dynamic water quality changes in complex mine service water circuits, was developed. This program was developed as a research tool, but the final objective is to issue a software package to be used for the design and operation of water treatment systems and for optimizing water quality management.

Simulation of water quality in mine water circuits requires a quantitative understanding of mine water chemistry and the water related unit processes operative within the mines. This paper outlines the major sources of water contamination, the relevant mine water chemistry, the development of unit process models, the development of a simulation program and some typical design and operational applications.

MINE WATER CHEMISTRY

Studies by the Chamber of Mines Research Organization (COMRO) have identified the following major sources of mine water contamination:

- (a) salts from fissure water, explosives and leached from broken rock,
- (b) sulphuric acid formed by the oxidation of pyritic minerals,
- (c) chemicals added to neutralize acidic mine water, e.g. lime ($\text{Ca}(\text{OH})_2$), soda ash (Na_2CO_3) and bicarbonate of soda (NaHCO_3), and
- (d) suspended solids from mining activities such as drilling and blasting of rock.

Models developed for these sources of contamination are detailed below.

Mine water comprises a complex matrix of dissolved salts, as well as suspended solids and colloids. The cations that may be present include calcium, magnesium, sodium, ammonium and hydrogen (H^+), while the anions include chlorides, sulphates, nitrates, carbonates and bicarbonates, and hydroxyl ions (OH^-). Owing to the presence of weak

The Third International Mine Water Congress, Melbourne Australia, October 1988

acids and bases (which do not dissociate completely), such as the carbonate/bicarbonate, the sulphate/bisulphate and the ammonia/ammonium systems, the relative concentrations of the various ionic species (e.g. H^+ , OH^- , CO_3^{2-} and HCO_3^-) are governed by aqueous chemical equilibria [3]. Certain of the dissolved ionic species present in mine water also form sparingly soluble precipitates, such as calcium sulphate (2 090 mg/ℓ at 25°) and calcium carbonate (14 mg/ℓ at 25 °C). The solubilities of these salts are defined by their solubility product constants, and governed by aqueous/solids and ion-pair equilibria [3].

In the present study five water quality parameters are considered, viz. calcium (Ca^{2+} and $CaSO_4^*$), sulphate (SO_4^{2-} and $CaSO_4^*$), alkalinity (CO_3^{2-} , HCO_3^- , H^+ and OH^-), TDS and pH. The alkalinity is associated primarily with the level of carbonic species in solution, while TDS is a measure of total ionic strength. In order to allow for the presence of unspecified components in the solution (e.g. Mg^{2+} , Na^+ , NH_4^+ , Fe^{2+} , NO_3^- , Cl^-), the assumption is made that these components do not take part in ionic reactions to a significant extent and a lumped parameter is made use of in the water chemistry subroutines of the simulator. Aqueous solutions must always be electrically neutral, and hence a lumped parameter, called the net unspecified species (NUS), can be defined as follows:

$$[NUS] = [HSO_4^-] + 2[SO_4^{2-}] + [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - 2[Ca^{2+}] - [H^+] \quad (1)$$

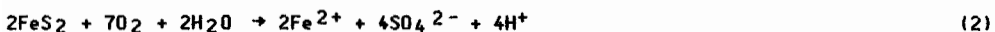
Based on the definition of the chemistry of mine service water described above, models of the more important unit processes were developed for use in the simulator.

UNIT PROCESS MODELS

The unit processes operative in underground gold mine service water circuits, and which significantly affect water quality, are leaching in stopes, neutralization of acid mine drainage, mixing or blending of streams of different qualities and possibly surface desalination to remove dissolved salts. Models of each of these processes, i.e. sources and sinks of contaminants, as well as the equilibrium chemistry have been developed for use in the network water quality simulator, AQUA-Q.

Stope Leaching Model

Chemical leaching of the pyrite (FeS_2) from broken rock is a slow process involving a number of reactions, but can be summarized by the reaction:



This results in an increase in sulphate concentration, half of which is due to dissolved ferrous sulphate and the rest as sulphuric acid which causes the pH to drop and the acidity of the water to increase. Bacterial activity can accelerate the leaching process by up to a million times by means of a similar reaction [4]. Underground trials on a complete shaft system have been carried out to determine rates of mine water contamination. It is intended to build up an extensive catalogue of information for different reefs with different mineralogies. Table 1 gives an example of some of the information collected to date, i.e. comparative leaching rates for the Ventersdorp Contact (VCR) and Kimberley Reefs.

The incremental change in concentration of TDS and sulphate is modelled in terms of the leach rates P_{TDS} and $P_{sulphate}$ (g/t rock broken and removed), and the amount of water used per ton of rock broken and removed, A (m^3/t).

The Third International Mine Water Congress, Melbourne Australia, October 1988

Table 1 Estimated leach rates of VCR and Kimberley Reefs

Reef Type	Sulphate Leach Rate (g SO ₄ ²⁻ /t rock broken and removed)	TDS Leach Rate (g TDS/t rock broken and removed)
VCR	23	72
Kimberley	8	27

The following dissolved species concentrations, i.e. [SO₄²⁻]_i, [HCO₃⁻]_i, [CO₃²⁻]_i, [Ca²⁺]_i, [CaSO₄⁰]_i, [H⁺]_i and [OH⁻]_i, in the service water entering the stope, (denoted by subscript 'i') are calculated from the equilibrium relationships discussed in the previous section. Equation 1 is then used to calculate NUS. Stope effluent concentrations, denoted by subscript 'e', are then calculated, e.g.

$$TDS_e \text{ (mg/ℓ)} = TDS_i + P_{TDS} / A \quad (3)$$

Allowance is made for the leached ferrous ion by increasing NUS appropriately, while the alkalinity is decreased by an equivalent amount of sulphuric acid. The effluent pH is found iteratively, by calculating the ionic species concentrations from estimates of pH, using the equilibrium relationships, until the electro-neutrality condition (Equation 1) is satisfied. An example of water quality deterioration in stopes predicted by the Stope Leaching Model for a VCR reef being mined at 60 t/d and with a water usage rate of 0.5 m³/t rock broken and removed, is given in Table 2.

Table 2 Prediction of Effluent Quality using Stope Leaching Model

Parameter	Influent	Effluent
Calcium (mg/ℓ as Ca)	200	200
Sulphates (mg/ℓ as SO ₄)	1 460	1 551
Alkalinity (mg/ℓ as CaCO ₃)	20	-31
TDS (mg/ℓ)	2 650	2 794
Temp (°C)	25	25
pH	7,00	3,30

Mine Water Neutralization Model

In order to make acidic mine waters less corrosive, they are usually neutralized to a pH of about 6 or 7. Most gold mines neutralize water by means of lime (Ca(OH)₂), as it is a cheap locally manufactured chemical. The addition of calcium ions to spent mine service water with high sulphate levels can result in water supersaturated with respect to calcium sulphate and may cause scaling of pipes and machinery in contact with this water. For this reason some mines have changed from lime to soda ash (Na₂CO₃) or bicarbonate of soda (NaHCO₃).

Given the initial state of the water before neutralization (denoted by subscript 'i'), the concentrations of all of the ionic species may be calculated from the equilibrium relationships discussed in a previous section. The species concentrations after the addition of the neutralizing agent (denoted by subscript 'e') are similarly calculated at the final (or target) pH. Provided that no salts precipitate, the dosage of neutra-

lizing agent necessary to reach the target pH can be calculated by using a charge balance equation. For example for lime addition:

$$2[\text{Ca}^{2+}]_e - 2[\text{Ca}^{2+}]_i = \Delta[\text{HCO}_3^-] + 2\Delta[\text{CO}_3^{2-}] + \Delta[\text{OH}^-] - \Delta[\text{H}^+] \quad (4)$$

The only unknown in Equation 4 is $[\text{Ca}^{2+}]_e$ for which value the equation may be solved. The lime dosage in mg/l is then calculated from this value i.e.

$$74 \times 10^3 \times ([\text{Ca}^{2+}]_e - [\text{Ca}^{2+}]_i).$$

If it is found that the neutralized water is supersaturated with respect to either CaSO_4 or CaCO_3 , then the charge balance is solved again simultaneously with the relevant precipitation equilibrium equation. Table 3 gives typical predictions of lime neutralization with and without CaSO_4 precipitation using the Mine Water Neutralization Model.

Table 3 Mine Water Neutralization Model prediction for lime neutralization

Parameter	With Precipitation		Without Precipitation	
	Initial	Final	Initial	Final
Calcium (mg/l as Ca)	400	587	370	377
Sulphates (mg/l as SO_4)	1 920	1 897	1 728	1 728
Alkalinity (mg/l as CaCO_3)	-312	9	-4	9
TDS (mg/l)	2 800	2 964	2 500	2 507
pH	2,30	7,50	4,00	7,50
Temp ($^{\circ}\text{C}$)	25,0	25,0	25,0	25,0
Lime dosage (mg/l)	364	-	12	-
CaSO_4 precipitated (mg/l)	-	33	-	0
Saturation w.r.t. CaCO_3 (%)	<0,1	19	<0,1	12
Saturation w.r.t. CaSO_4 (%)	65	100	67	68

Blending Model

Blending processes take place whenever streams mix, for example in junctions, tanks and dams. Junctions are assumed to perform instantaneous perfect mixing while tanks and dams are assumed to be completely mixed vessels with relevant storage capacity and related time constants. All of the ionic species for each of the incoming streams, are calculated from the equilibrium relationships discussed earlier, and these are used to estimate a lumped parameter $[\text{NUS}]_i$ for each stream using Equation 1. A mass balance then gives the blended concentrations of calcium, sulphate, alkalinity, TDS and NUS. As the blended mixture must be electrically neutral, the pH which satisfies the charge balance (Equation 1) can be estimated using the same iterative method used in the Stope Leaching Model. Table 4 gives an example of the application of the Blending Model to two streams of different compositions blended to give a third stream.

Desalination Model

Desalination processes are designed to remove dissolved salts from a contaminated feed stream, thus generating a dilute, relatively pure product stream and a concentrated brine stream. The efficiency of salt removal is defined by the rejection, as follows:

The Third International Mine Water Congress, Melbourne Australia, October 1988

Table 4 Blending Model prediction for mixing of two streams

Parameter	Stream 1	Stream 2	Blend
Proportion in blend (%)	50	50	100
Calcium (mg/l)	20	370	195
Sulphates (mg/l)	17	1 726	872
Alkalinity (mg/l as CaCO ₃)	68	-3	32
TDS (mg/l)	100	3 012	1 556
Temp (°C)	20,0	20,0	20,0
pH	8,23	4,14	5,94
Saturation w.r.t CaSO ₄ (%)	<1	63	27

$$\text{Salt rejection (per cent)} = \frac{Q_F \cdot \text{TDS}_F - Q_P \cdot \text{TDS}_P}{Q_F \cdot \text{TDS}_F} \times 100 \quad (5)$$

where Q denotes flow rate and subscripts F and P denote the feed and product streams, respectively. The overall process rejection depends on the physical process selected and on the specific species in solution. Rejections are typically 80 to 95 per cent for most processes. Desalinated water production rate is defined by the recovery ratio, as follows:

$$\text{Water recovery (per cent)} = (Q_P/Q_F) \times 100 \quad (6)$$

Recoveries are typically 80 to 90 per cent. The Desalination Model simply calculates species concentrations in the product and brine streams from a specified salt rejection and product recovery. A typical performance of a desalinator with a water recovery of 85 per cent and an overall process salt rejection of 80 per cent is given in Table 5.

Table 5 Desalination Model example

Parameter	Feed	Product	Reject
Calcium (mg/l)	85	20	453
Sodium (mg/l)	1 388	327	7 403
Sulphate (mg/l)	68	16	363
Chloride (mg/l)	1 655	389	8 827
TDS (mg/l)	3 185	749	16 987

MINE WATER NETWORK SIMULATOR

A computer program (AQUA-Q) has been developed for simulating underground mine water circuits. The simulator allows the user to build a network of unit processes - referred to as modules and connected by pipes or channels - referred to as links. Both closed, i.e. recirculating circuits, and open circuits can be simulated. Each element of the network has to be specified initially by the program user and the simulation proceeds over a time span also determined by the user. The program is designed to run on an IBM PC or compatible microcomputer and a network of up to fifty modules and up to ninety connecting links may be assembled. Standard screen forms are provided to facilitate specification of the various unit processes and the system geometry. An on-line 'help' facility which gives information and instructions about running the program, is provided to assist and teach new users.

The Third International Mine Water Congress, Melbourne Australia, October 1988

Simulation of the water quality within the network proceeds as follows:

- The user enters default or actual starting qualities (e.g. pH, alkalinity, calcium, sulphate and TDS) at the input to each link to represent the first instant in time.
- The program then calculates the concentrations of each of these parameters at the input to every link for a user defined time interval (any step length between 0,1 hour and 0,5 hours may be chosen) using the starting values, thus giving a quality profile over the entire system.
- The process is repeated at fixed time steps, using the values calculated at the previous time interval. A set of profiles, or a concentration history, is thus compiled for a user defined time span (any time span from 1 day to 3 months may be chosen).

APPLICATION OF SIMULATOR

The program has been tested on daily average water quality data for an existing gold mine which consists of a vertical shaft and an inclined shaft which drain into a single neutralization and settling system (Figure 2). Lime in the form of a dense slurry is used for neutralization but pH control tends to be poor with a variation in pH from the settler of 7,5 to 10,8. Poor control of the neutralization process as well as considerable sulphate contamination result in a water that tends to be scaling with respect to calcium sulphate. There is a large underground fissure of relatively pure water as well as some fissures which percolate through worked out areas and result in a substantial source of highly saline, low pH water. Long term average daily flow rates were measured (Table 6). It was also known that approximately 65 per cent of the total daily volume of service water passed through the stopes was used during the drilling shift, while 35 per cent was used during the cleaning shift and this was assumed to be the case in the example. Ranges of the measured and predicted concentrations of Ca, SO_4 , TDS and the pH of the major streams are shown in Table 6 and it can be seen that the program models the mine water circuit qualities reasonably well. The best fit between measured and predicted dissolved species was obtained when a neutralization pH setpoint of 9 was assumed. The predicted average lime dosage, however, was only 168 mg $Ca(OH)_2/l$, indicating that a considerable excess of lime was used in practice, i.e. 1 500 - 1 900 mg $Ca(OH)_2/l$. This was not an unexpected result since very little time (about 10 seconds) is allowed for lime dissolution between the point of addition and the settlers, and hence much of the lime settles without dissolving and is pumped to surface with the sludge from the settler.

Figures 3 and 4 illustrate the variation in TDS and calcium of the feed from the surface dam, stope drainage and neutralizer streams over a three day period. They show a

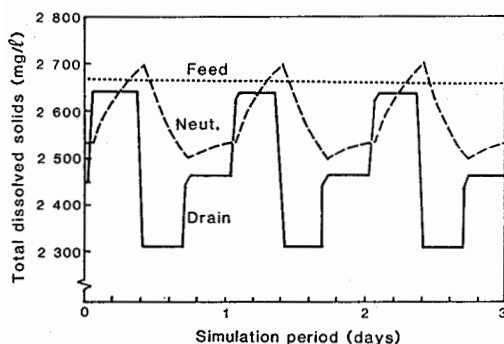


Figure 3 Simulated variation in total dissolved solids for lime neutralization.

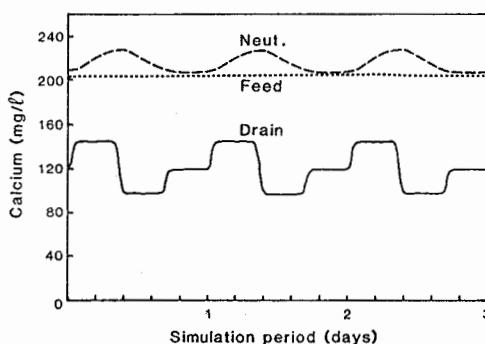


Figure 4 Simulated variation in calcium for lime neutralization.

The Third International Mine Water Congress, Melbourne Australia, October 1988

a stepwise cyclic variation of TDS and Ca concentrations in the stope drainage due to the cyclic demand for water which is slightly damped after neutralizing and settling, and completely damped in the large surface dam (which has a residence time of six to eight days) as seen in the feed water leaving the surface dam.

AQUA-Q was used to evaluate a change in operational strategy, i.e. substituting soda ash for lime as a neutralizing chemical in the existing system in order to reduce the possibility of calcium sulphate scaling. It was assumed that an instantaneous switch to soda ash could be made and the neutralization pH was controlled at a value of 7 in order to prevent calcium carbonate scale formation. Figures 5 and 6 show the transient changes to the TDS and calcium levels and indicate that the TDS of the feed water would climb to a new steady value (of 3 020 mg/ℓ), while the calcium level would be dramatically reduced to 65 mg/ℓ. Steady state values would be achieved in about 50 days.

The design capabilities of AQUA-Q were then tested by using it for sizing a desalination plant for a hydro-power mining system [5], which requires high pressure service water with a TDS of 1 500 mg/ℓ for powering mining equipment. A desalinator, a bypass line, and a storage dam were therefore inserted between the surface feed dam and the underground dams. The desalinator was assumed to run continuously at a water recovery of 85 per cent and a salt rejection of 80 per cent. It was found that a 9 ℓ/s

Table 6 Ranges of measured and AQUA-Q predicted water qualities at various points

Stream		Calcium (mg/ℓ)		Sulphate (mg/ℓ)		TDS (mg/ℓ)		pH		Daily Ave. Flow Rate (Mℓ/d; ℓ/s)
		Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	
Feed service water	Min.	192	200	1 450	1 330	2 500	2 650	6,8	7,4	1,7; 19
	Max.	224	210	1 500	1 350	2 800	2 690	8,3	7,4	
Fissure water *	Min.	24	60	340	615	610	1 400	3,0	3,0	1,3; 15
	Max.	48	60	620	615	1 400	1 400	4,2	3,0	
Fissure water/ worked out areas*	Min.	32	50	1 750	1 850	3 350	3 475	2,1	2,2	0,5; 6
	Max.	64	50	1 950	1 850	3 600	3 475	2,7	2,2	
Stope drainage	Min.	80	95	1 100	1 130	2 400	2 250	2,6	2,5	3,5; 40
	Max.	120	145	1 510	1 425	2 550	2 720	3,2	2,7	
Clear water from settlers	Min.	200	200	1 400	1 330	2 500	2 650	7,5	9,0	2,6; 30
	Max.	224	210	1 510	1 350	2 800	2 690	10,8	9,0	
Mud from Settlers	Min.	200	200	1 400	1 330	2 500	2 650	7,5	9,0	0,9; 10
	Max.	224	210	1 510	1 350	2 800	2 690	10,8	9,0	
Shaft bottom water	**	40	-	1 850	-	3 475	-	7,0	-	0,3; 3

The compositions of these water sources were assumed to be constant - the value chosen for the simulation is given in the 'predicted' column.

* The composition of the shaft bottom water was estimated from measurements of the recycle and settler product qualities.

The Third International Mine Water Congress, Melbourne Australia, October 1988

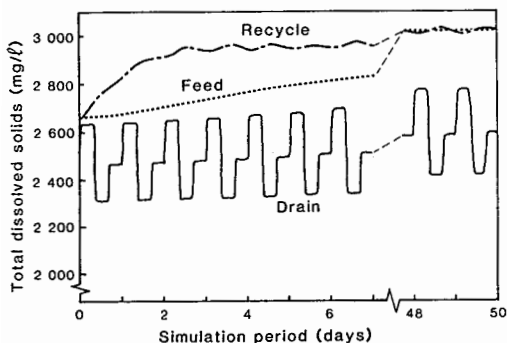


Figure 5 Simulated TDS variation when changing from lime to soda ash.

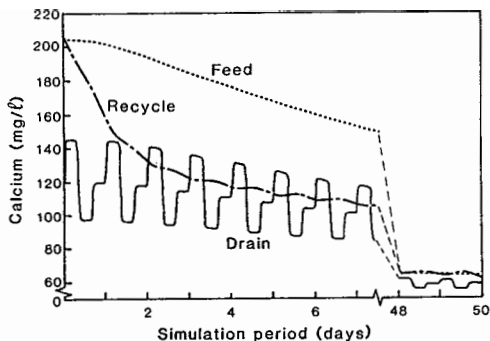


Figure 6 Simulated calcium variation when changing from lime to soda ash

(0,8 Mℓ/day) unit was required to give a blended product stream (19 ℓ/s, 1,7 Mℓ/day) with a TDS of 1 500 mg/ℓ. Figure 7 shows the transient change from the existing conditions after introducing the desalinator into the mine water circuit. The program predicted that the system would reach a steady state TDS of 1 500 mg/ℓ within approximately 50 days.

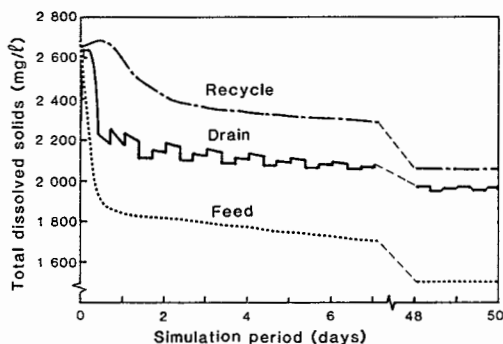


Figure 7 Simulated TDS variations after introduction of desalinator.

CONCLUDING REMARKS

A user-friendly interactive computer program, AQUA-Q, has been developed that dynamically simulates water quality (pH, alkalinity, Ca, SO₄ and TDS) in underground mine service water circuits. Predictions for average daily water quality at various critical points within the mine water circuit agree reasonably well with measured values for an operating gold mine. The program serves a useful function as a research tool, as well as having demonstrated capability as an aid for the design and operation of mine service water circuits, and for water quality management.

AQUA-Q is being developed further and refined with a number of areas currently receiving attention.

(a) An extensive survey on numerous mines is being undertaken in order to provide data against which the simulator will be further validated.

The Third International Mine Water Congress, Melbourne Australia, October 1988

- (b) Additional water quality parameters are being considered and include chlorides, ammonia, magnesium, silicates and suspended solids.
- (c) The sophistication of the chemical equilibria subroutine will be improved by including additional ion-pairs such as CaHCO_3^+ , MgHCO_3^+ and MgSO_4^+ , and considering gas/liquid equilibria.
- (d) The Desalination Process model will be refined by modelling pilot plant data, which has resulted from the COMRO test programme, for Electrodialysis Reversal, Tubular Reverse Osmosis, Seeded Reverse Osmosis and Freeze Desalination processes.
- (e) Empirical work on salination in the stope including aspects such as bacterial leaching and its control, as well as the effect of different explosives and the sulphur content of the pyrite bearing rock on water quality, is being undertaken to improve current understanding of leaching in stopes and hence will allow the development of a more accurate Stope Leaching model.
- (f) Other unit process models, for example models for direct-contact bulk air coolers, heat rejection cooling towers, and solid/liquid separation, may be developed.

The application and further development of AQUA-Q is currently being undertaken in collaboration with water specialists in the mining industry, after which a software package will be released for general use.

ACKNOWLEDGEMENT

This work forms part of the research programme of the Chamber of Mines of South Africa Research Organization.

REFERENCES

1. Bosman, D.J. 'Water quality problems in the mining industry', I.W.P.C., Johannesburg, South Africa (April 1987).
2. Holten, M.C. and Stephenson, D. 'A computer model of circulating service water in South African gold mines'. *Int. J. Mine Water*, 2(2), (June 1983).
3. Loewenthal, R.E. and Marais, G.v.R. 'Carbonate Chemistry of Aquatic Systems: Theory and Application', Ann Arbor Science, Michigan, USA (1976).
4. Singer, P.C. and Stumm, W. 'Acid mine drainage: the rate determining step', *Science*, Vol. 1, 67, (1970).
5. Joughin, N.C. 'A system for providing mechanical and cooling power in deep mining', 13th CMMI Conference, Singapore, (1986).