Mine Closure 2023 - Behrooz Abbasi, Jeff Parshley, Andy Fourie & Mark Tibbett (eds)
ISBN 978-0-6450938-7-2
doi:10.36487/ACG_repo/2315_003

An innovative approach to accommodate the draft National Mine Closure Strategy in South Africa by predicting pit lake water quality and generating a post closure resource using passive treatment

J Robinson *SLR Consulting Limited, UK*
P Klimczak *SLR Consulting Limited, UK*
N Smyth *SLR Consulting Limited, South Africa*

Abstract

South African regulators have published the draft National Mine Closure Strategy, with the objective of addressing the challenges commonly associated with mine closure. The draft Strategy highlights the adverse impacts of mining, most notably the irreversible environmental degradation and socio-economic challenges that are associated with mine closure, particularly where employment ceases after mine closure. The Draft Strategy makes provision for the consideration of mine closure options through Environmental and Social Governance that focusses on:

- *managing the closure of mines in an integrated and sustainable manner, where mines located within the same geographical regions work together to achieve self-sustaining ecosystem after closure.*
- *mines do not impact negatively on the sustainability of adjacent mines.*
- *making provision for post-closure stewardship and socio-economic sustainability, to the implementation of individual and regional mine closure plans.*
- *integrating environmental management and related closure activities with socio-economic interventions and align these with development of a post-closure economy, by reducing duplication of efforts and spending and aggregating available funding for coordinated regional projects.*

The draft Strategy provides a mechanism for transitioning towards an integrated approach to mine closure where the emphasis is placed on environmental remediation, with integration of positive and sustainable post-mining socio-economic impacts. South African regulators have traditionally pursued complete backfill of open pits at closure to reinstate the pre-mining environment, however, this requires huge earthworks with a high carbon footprint. The draft Strategy allows for a mind shift by considering alternative cost effective closure scenarios, which also present a resource for the community upon closure.

The mine in South Africa considered four closure options including contemporaneous backfilling, complete back filling or no filling. Two of the options predicted the generation of a pit lake and the quality of this resource was explored through several modelling stages. These included the use of Goldsim combined with geochemical modelling to predict the water quality over many years. When water quality parameters were found to exceed regulator guidance for irrigation and/or livestock use, passive treatment options were explored which included the use of wetlands modelled using first order kinetics. The results predicted that the best option of closure was partial filling of the pit and allowance of a pit lake to form. The quality of the water in pit lake was predicted to be viable as a community resource for over 50 years and suitable for supporting livestock watering for several years post closure, followed by irrigation of saline tolerant crops such as pomegranates (agri-processing activities). Outside of the pit, several buildings could be repurposed to suit food processing, thereby maximising the value of the food produced and maximising economic benefits of the site to the local community post-closure.

Keywords: *Pit Lakes, water quality, Goldsim, PHREEQ, passive treatment, wetland, water use, South Africa*

1 Introduction

In developing the Draft Mine Water Closure Strategy (DMCS), the South African Regulators, state that land rehabilitation to its pre-mining state is not considered sustainable (complete backfilling). The DMCS emphasises the need for mines to consider economic diversification at closure with a focus on creating job opportunities during the post-closure phase. Therefore, the option of generating a resource such as pit lake water, with the opportunity to encourage agricultural and farming use is an attractive option. To enable this the pit lake water quality needs to be predicted and mitigation measures identified that are cost effective and sustainable. Pit lake water quality model prediction is not new and there have been some pertinent studies undertaken relatively recently(e.g. Carlino and McCullough, 2019; and Hilderbrandt et al, 2020)

2 Methodology

Given this background, SLR Consulting (SLR) was appointed to investigate viable mine closure solutions, for a manganese mine in South Africa. The options included concurrent backfilling, no backfilling and complete backfilling, with the former two options generating a pit lake. The modeling required the integration of individual technical components (surface water, groundwater, climate and geochemistry) using a Goldsim model which was adapted to include the geochemical model PHREEQC. The approach and how each technical element's dependencies are presented in Figure 1.

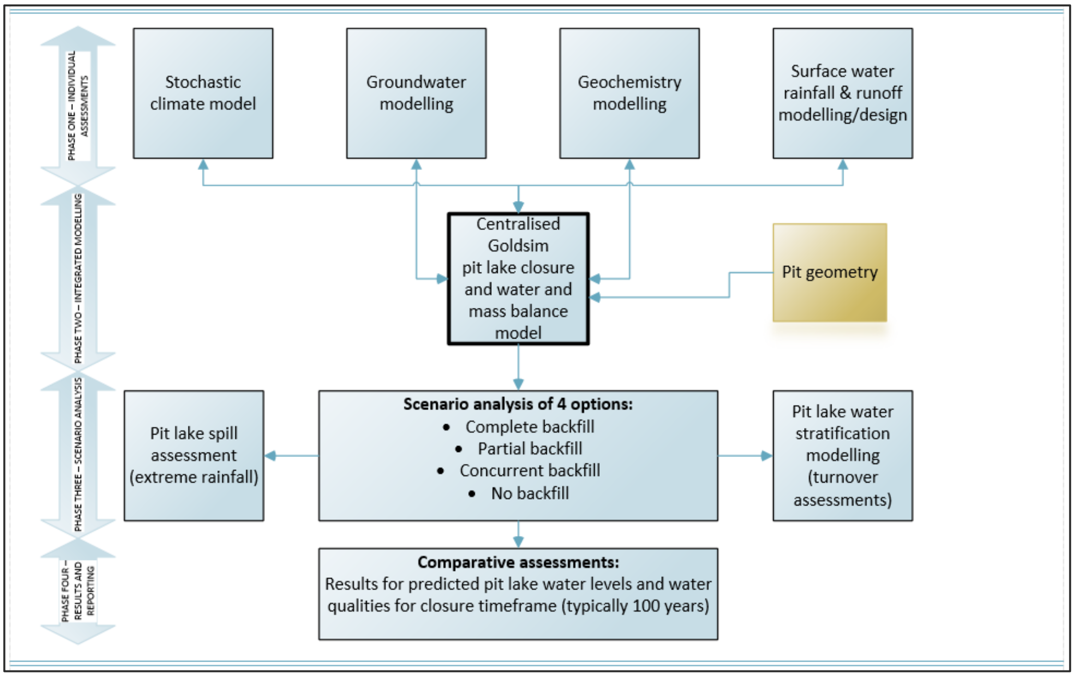


Figure 1 **Integrated modelling approach**

This paper focusses on the prediction of water quality generated in the pit lake and the use of passive wetland technology to produce a viable water resource to support post-closure land use. The complex chemical processes of chemical equilibration and aqueous speciation uses GoldSim's dynamic link library (DLL) element. The use of the DLL is based on the following the work published at the GOLDSIM user conference in 2007.[1]

---

[1] Ted Eary MWH Americas, Inc, Goldsim Users Conference, San Francisco

The DLL is written in C++ and compiled with Microsoft Visual C++ Studio. This approach has the advantage of providing a generalized procedure to model complex chemical processes at each time step. To allow decision making regarding the run times, an input sheet was developed to assist users with running the model in the four closure scenarios as shown in Figure 2.

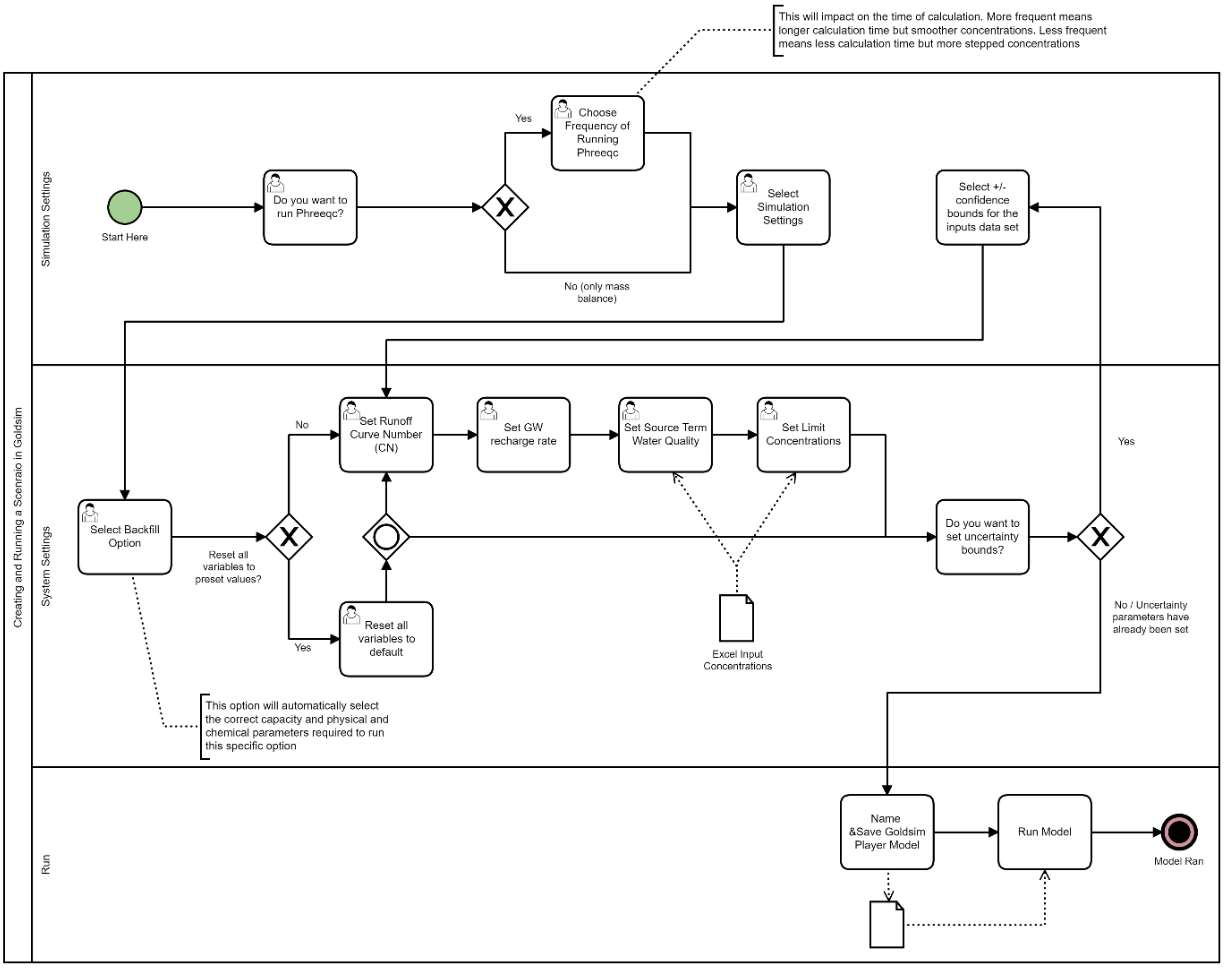


Figure 2 Input sheet for running the four closure scenarios

2.1 Methodology: source definition and hydrology modelling

Site specific information regarding the topography, pit shape, hydrology, hydrogeology and geology were all used to populate the Goldsim and PHREEQ models.

2.1.1 Climate model – type and description

Accurate, future rainfall predictions are required for mine closure applications. Mathematical models of the physical processes involved in generating rainfall are often used to make these evaluations. In addressing the response of these processes to weather inputs, it is seldom sufficient to examine only responses to observed weather events. For closure timescales (often measured in centuries from date of closure), it is desirable to have the capability of generating synthetic weather & rainfall data with the same statistical characteristics as the actual weather at the location of the mine. This study selected computer simulation model called WGEN (Weather Generator) to generate values for precipitation.[2] The model uses monthly and annual statistics to

---

[2] WGEN is a stochastic weather generator originally developed in the 1980s in FORTRAN at the US Department of Agriculture Agricultural Research Service.

generate daily time series of precipitation, minimum temperature, maximum temperature, and solar radiation into the future. This was developed in GoldSim and used in the centralised model.

The precipitation component of WGEN is a Markov chain-gamma model. A first order Markov chain is used to generate the occurrence of wet or dry days. When a wet day is generated, the two-parameter gamma distribution is used to generate the precipitation amount. With the first-order Markov chain model, the probability of rain on a given day is conditioned on the wet or dry status of the previous day. A wet day is defined as a day with c. 0.25 mm of rain or more.

Further comparison of modelled vs observed data include:

- Modelled precipitation amounts and seasonal variation were accurately represented in the model.
- No significant difference occurred between observed and generated mean monthly and annual precipitation amounts at any location.
- Mean numbers of wet days per month accurately simulated.
- Persistence of wet days (max length of consecutive wet days for each month) & occurrence of daily precipitation more than 50 mm compared favourably.
- Mean monthly precipitation amounts are excellent representations of the observed data.

On cessation of mining, groundwater levels will begin to rebound. The water level will begin to rise back towards the pre-mining level. If there is void space, a pit lake will form and the final water level of the pit lake will be determined by the eventual balance between hydrological inflows and evaporation and any other losses.

The main water sources (inflows) to the proposed pits are:

- Direct rainfall onto the surface of a pit lake/flood of pit;
- Runoff from rainfall falling onto the pit walls (high-wall runoff);
- Groundwater which seeps into the pits; and
- Any storm water from external catchments that is directed towards the pit.

Water losses (outflows) occur as follows:

- Evaporation from the pits; and
- Seepage to groundwater through the base of the pit (assumed to be zero here).

All these components of the water balance, except for storm water into the pit, are functions of the level of the pit lake. As the pit lake level rises inflows usually diminish until a quasi-stasis is reached. The lake level at which this equilibrium exists (and the quality of that water) was the focus of this study.

There are two basic types of pit lakes (1) Terminal; and (2) Flow-through. Terminal pit lakes are normally found in arid climates. Initially, inflows are high, because the hydraulic gradient driving inflows from the aquifer would be at a maximum due to the water level being at base of the pit. Due to evaporative loses and pit geometry the terminal lake becomes a cone of depression in the water table with the groundwater gradient towards the pit (a groundwater discharge zone). As evaporation is the only discharge pathway, soluble metals accumulate due to evapo-concentration.

The rate of infilling of the pit is greatest during early recovery and decreases with time. The pit lake water balance at can be described as:

$$P + SW + PW + GW - E = \Delta S$$

Where:

- P = Direct precipitation on lake surface
- SW = Storm water from external catchments
- PW = Runoff from the pit walls
- GW = Groundwater inflow
- E = Evaporation
- ΔS = change in lake storage volume

Closure pit lake analysis consists of two important components:

- estimating the final pit lake elevation; and
- timing of pit lake formation.

2.2 Hydrological Modelling Results

The water levels in the pit were calculated based on the volume of the pit per depth and accumulated water within them for all four scenarios. This calculation was performed at monthly time steps until quasi-stasis conditions were achieved. The "stasis" condition is defined as the hydraulic condition when mean annual, or longer period, outflows equal inflows. This is shown in Figure 3 below for the contemporaneous backfilling option.

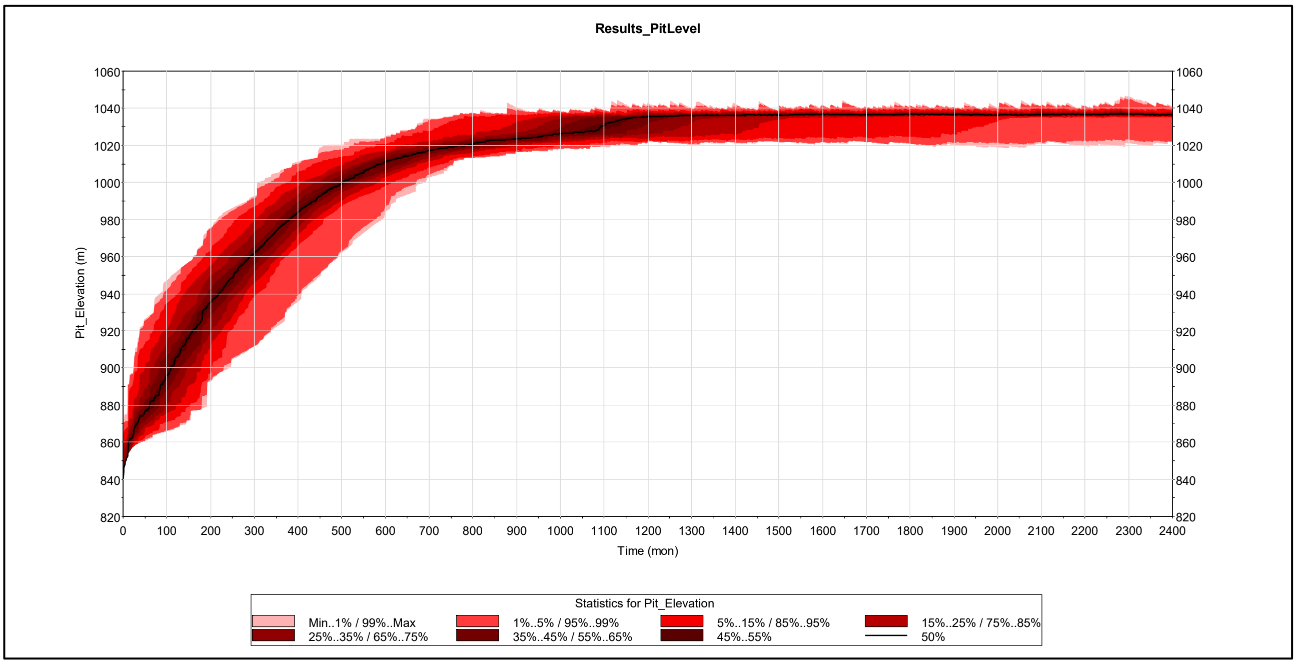


Figure 3 Filling rate for concurrent backfill assessment

2.3 Methodology: water quality prediction

The purpose of the modelling was to generate source terms to be used in the geochemical and GoldSIm modelling. These source terms are populated following the development of a Conceptual Site Model for the pit lake generation and included assessing the likely geochemical changes and layer development in the pit lake upon filling. The PHREEQC model for the thermodynamic data used the Lawrence Livermore data base. The geochemical source terms applied were as follows:

2.3.1 Wall rock runoff water chemistry

The chemistry of the wall rock runoff was established by review of the waste classification work undertaken for the site. As part of the waste classification 20:1 leach testing was undertaken to predict the leaching of acidity and metals/metalloids and inorganic substances. The results, coupled with whole rock analysis, confirmed the rock is not acid producing with low to moderate leaching of metals.

2.3.2 Groundwater chemistry

The initial concentration of the analytes was prepared for all analysis from 2008-2022, with non-detects assumed to be half the detection limit when calculating statistics to be used in the modelling. This information is deemed suitable for use as the water quality source term for the groundwater entering the pit upon the cessation of dewatering.

2.3.3 Rock mineralogy

The minerology of the waste rock has been reviewed and those minerals deemed to be reactive were used to equilibrate the concentration of the incoming and rising groundwater with the waste rock geochemistry. SLR collated information from the area which shows that the following mineral phases are likely to be present in the rock lithologies.

Table 1 Typical mineralogy for wall rock and runoff lithologies

Mineral	Phase Composition	Relative Abundance
Calcite	$CaCO_3$	High
Ankerite	$Ca(Fe,Mg,Mn)(CO_3)_2$	Low
Chlorite	$(Mg,Fe)_5Al(AlSi_3O_{10})(OH)_8$	Low
Hematite	Fe_2O_3	High
Magnetite	Fe_3O_4	Moderate
Microcline	$KAlSi_3O_8$	Moderate
Palygorskite	$(Mg,Al)_2Si_4O_{10}(OH)_4(H_2O)$	Moderate to high in clays
Plagioclase	$(Na,Ca)(Si,Al)_4O_8$	Low
Quartz	SiO_2	High
Smectite	$(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2\cdot nH_2O$	Moderate to high in clays

Equilibration with less reactive minerals is relatively slow, when compared to more reactive mineral phases such as carbonates. Whilst PHREEQ does not use kinetic phrases when allowing equilibration, the user has to select and justify those phases which are involved and these, in this pit lake scenario, will be the reactive minerals. Studies regarding the solubility controls of iron at other pits lakes (Eary, L.E. 1999) have shown the most likely form of iron is ferrihydrite and this has been used as the equilibration phase for this modelling. Examples of the results of the source term PHREEQC modelling are shown below along with the chemistry of the walk rock runoff and rainwater.

2.3.4 Water chemistry

The chemistry of the source terms used in the modelling are shown below in Table 2.

Table 2 Chemistry of water constituents used in the modelling

Analyte **All mg/l unless shown.**	**Groundwater pre-Equilibration with minerals**	**Groundwater Post Equilibration**	**Runoff**	**Rainwater[3]** **(2005 – 2007)**
pH	8	7.25	7.95	5.3
Alkalinity (total)	268	282	37	7
Fluoride	0.3	0.3	0.26	
Chloride	223	223	0.98	0.37
Nitrate	42	42	3.5	0.14
Sulfate	50	50	5.2	0.14
Aluminium	0.031	0.031	0.13	
Arsenic	0.006	0.006	0.0013	
Boron	0.5	0.5	0.081	
Barium	0.059	0.059	0.11	
Calcium	21	144	8.46	0.4
Copper	<0.001	<0.001	0.0017	
Chromium	0.002	0.002	0.0023	
Iron	0.3	0.097	0.15	
Lead	0.003	0.003	0.0023	
Potassium	6	6	2.44	
Magnesium	104	7.55	4.33	
Manganese	0.08	0.08	0.012	
Sodium	88	88	4.6	0.24
Selenium	0.014	0.014	0.0012	
Vanadium	0.002	0.002	0.016	
Zinc	0.024	0.024	0.0414	

These source terms were then used in the GoldSim model to mix and predict the chemistry in the pit. The initial results of this mixing were then altered using other geochemical processes relating (amongst others) to the potential for layer formation in the pit lake.

---

[3] World Data Centre for Precipitation Chemistry. http://www.wdcpc.org/content/global-assessment-data-sets from data collected at Mali, Niger, Benin, Cote D'Avoire and Cameroon

2.3.5 Geochemical modelling of layers

The initial mixtures assume a homogenised lake water will form and layers can develop. The source terms when mixed form a bulk water chemistry which is modelled geochemically and follows a well-established approach (e.g. Eary, L.E. 1999).

1. Layer 2 water chemistry is calculated from the bulk chemistry of the source terms mixture using Goldsim, which is speciated using PHREEQC, allowing specific mineral phases to precipitate if they become oversaturated and are thermodynamically favoured.
2. The Layer 1 chemistry is calculated using the Layer 2 chemistry by equilibration with atmospheric carbon dioxide (partial pressure = 0.00033 bar or $10^{-3.5}$ atm) and oxygen gas (partial pressure = 0.21 bar or $10^{-0.68}$ atm). The equilibration may also result in specific mineral phases becoming oversaturated and these were also allowed to precipitate, if thermodynamically favourable.
3. Uncontaminated natural waters typically have neutral to alkaline pH, where calcium and alkalinity concentrations are affected by the solubility of calcite [$CaCO_3$]. In pit lakes, the values of saturation indices (SI) for calcite show an increase over the pH range of 6.8 to ±9. Pit lakes with a pH>7 generally have calcite SI values>0, which indicate oversaturation conditions are typical. The apparent oversaturation with calcite is common in natural aqueous systems and is often attributed to slow precipitation kinetics in pit lakes.
4. The degree of calcite oversaturation is also related to the solubility of CO_2(g) in solution and the rate of CO_2(g) loss or gain by the solution. Calculations based on measured pH and alkalinity values, show that most pit lakes are oversaturated with CO_2(g) compared to the atmospheric level of $10^{-3.5}$ atm, ranging up to levels of $10^{-2.0}$ atm.
5. Other studies into pit lake predictive chemical modelling indicate that gypsum is included in the geochemical model as a mineral phase allowed to precipitate.

The specific mineral phases which will be allowed to precipitate have been taken from a review (Eary L.E. and W.M Schafer, 2009) of solubility controls in 24 No. existing hard-rock pit lakes and 66 No. existing coal mine pit lakes and are shown below. This has been supplemented by other plausible minerals controlling the major ion in the pit lake as the layering develops.

Table 3 Mineral phases allowed to precipitate in the PHREEQ model

Phase Name	**Equations Used in Modelling**
Ferrihydrite	$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 2H^+$
Manganite	$Mn^{3+} + 2H_2O \rightarrow MnO(OH) + 3H^+$
Amorphous gibbsite	$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$
Barite	$Ba^{2+} + SO_4^{2-} \rightarrow BaSO_4$

2.4 Results: water quality prediction

The results also indicate the following:

- Steady state is likely to form after +150 years, and hence geochemical modelling was terminated at 200 years.
- The lower boundary of TDS suitable for certain livestock is also exceeded after 100 years, although it is lower than the 3000mg/l threshold indicating the water will be suitable for some livestock.

- The local nitrogen concentrations in the groundwater meant that the nitrogen compounds in the pit lake may be elevated over time.
- After 200 years the nitrogen concentration (as nitrate) and selenium (marginally) exceed the livestock drinking water standards.

The results of the assessment have been incorporated into a bespoke dashboard which can be defined and used for any site that requires pit lake modelling. An example of the dashboard is presented below in Figure 3. This allows for various input parameters to be changed if, as the pit evolves, key variables need to be updated.

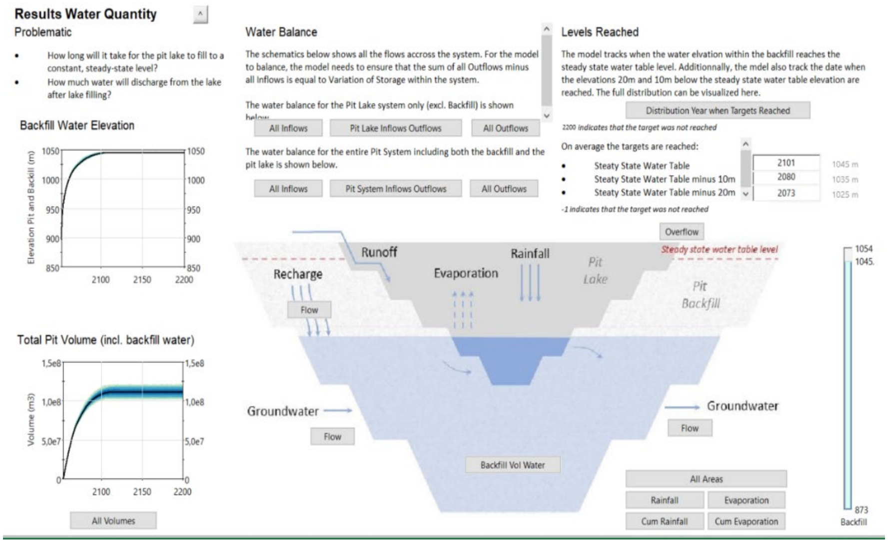
3 Passive treatment feasibility

Passive treatment systems (PTS) employ the same science identified in natural wetlands, but they are designed to optimize the competing microbial environments and processes occurring naturally in a wetland ecosystem. To paraphrase Gusek (2002):

> *Passive treatment is a process of sequentially removing contaminants and/or acidity in a natural-looking, man-made bio-system that capitalizes on ecological, and/or geochemical reactions coupled with physical sequestration. The process does not require power or chemicals after construction and lasts for decades (or longer) with minimal human help.*

3.1 Passive treatment methodology

When considering the treatment of nitrogen in water using passive wetland type systems, a fundamental principle which will need to be considered in the outline design is that passive systems should not dry out completely for significant lengths of time. There are two options which might be viable namely a surface water flow aerobic system and a floating wetland. For reference to readers unfamiliar with PTS terminology the term “aerobic wetland” is akin to the traditional “reed beds” used in sewage treatment systems.



Results Water Quantity

Problematic

- How long will it take for the pit lake to fill to a constant, steady-state level?
- How much water will discharge from the lake after lake filling?

Water Balance

The schematics below shows all the flows accross the system. For the model to balance, the model needs to ensure that the sum of all Outflows minus all Inflows is equal to Variation of Storage within the system.

The water balance for the Pit Lake system only (excl. Backfill) is shown below.

The water balance for the entire Pit System including both the backfill and the pit lake is shown below.

Levels Reached

The model tracks when the water elvation within the backfill reaches the steady state water table level. Additionnally, the mdel also track the date when the elevations 20m and 10m below the steady state water table elevation are reached. The full distribution can be visualized here.

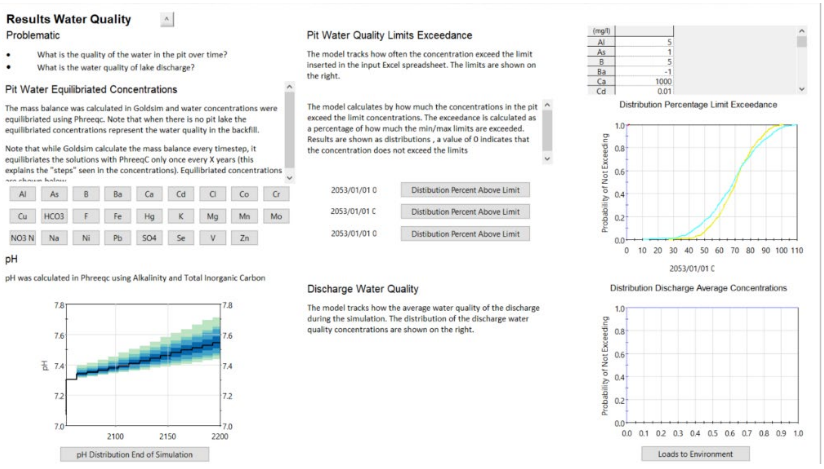
2200 indicates that the target was not reached

On average the targets are reached:

Steaty State Water Table	2101	1045 m
Steaty State Water Table minus 10m	2080	1035 m
Steaty State Water Table minus 20m	2073	1025 m

-1 indicates that the target was not reached

(a) Pit Lake Water Quantity



Results Water Quality

Problematic

- What is the quality of the water in the pit over time?
- What is the water quality of lake discharge?

Pit Water Equilibriated Concentrations

The mass balance was calculated in Goldsim and water concentrations were equilibriated using Phreeqc. Note that when there is no pit lake the equilibriated concentrations represent the water quality in the backfill.

Note that while Goldsim calculate the mass balance every timestep, it equilibriates the solutions with PhreeqC only once every X years (this explains the "steps" seen in the concentrations). Equilibriated concentrations are shown below:

pH

pH was calculated in Phreeqc using Alkalinity and Total Inorganic Carbon

Pit Water Quality Limits Exceedance

The model tracks how often the concentration exceed the limit inserted in the input Excel spreadsheet. The limits are shown on the right.

The model calculates by how much the concentrations in the pit exceed the limit concentrations. The exceedance is calculated as a percentage of how much the min/max limits are exceeded. Results are shown as distributions , a value of 0 indicates that the concentration does not exceed the limits

Discharge Water Quality

The model tracks how the average water quality of the discharge during the simulation. The distribution of the discharge water quality concentrations are shown on the right.

(mg/l)	
Al	5
As	1
B	5
Ba	-1
Ca	1000
Cd	0.01

(b) Pit Lake Water Quality

Figure 4 Result dashboard for predicted (a) quantity and (b) quality of pit lake water

A surface flow wetland system could be constructed on the mine terraces as the pit lake develops. Assuming a constant water level in the wetland, the inflow and meteorological data are used to compute the wetland outflows:

Table 4 Water balance used for passive treatment system (Kadlec R.H and Knight,1996)

$$\mathbf{Qo} = \mathbf{Qi} + \mathbf{A}\,.\,(\mathbf{P} - \mathbf{ET} - \mathbf{I})$$

Where

A = Wetland area, m^2

ET = Evapotranspiration rate (m/d)

I = Infiltration rate (m/d)

P = precipitation rate (m/d)

Q = flow rate (m^3/d)

Best practice dictates the pollutant mass balance for this wetland will use a cell-by-cell basis in accordance with the following (Kadlec R.H and Wallace S, 2009).· In this model the concentrations (C_I) enter a cell at a flow rate (Q_I) with the effluent concentration being reduce by the removal mechanisms shown. The water balance results are distributed or apportioned according to the number of Tank In Series (TIS).

The TIS model established form the water balance uses a sequential treatment for each of the ‘tanks’. A first order model with a rate constant (k) is used with an associated background wetland concentration (C*). This follows the P-k-C* design model which has been used in several wetland designs. The concentration exiting the first of the tanks in series is given (assuming no rainfall pollution) by:

Table 5 Prediction of treated concentration in a wetland

$C1 = \dfrac{Qi\,.\,Cin + (k\,.\,A1\,.\,C\,*)}{Q1 + \left((\alpha ET)A1\right) + \ (I\,.\,A1) + \ (k\,.\,A1)}$	C_1	Concentration
	C_{in}	Input concentration
	C*	Background concentration
	K	First Order Rate coefficient
	ά	Transpiration fraction
	A_1	Area of tank

There is an interconnection between the biotransformation of the nitrogen species and a further integration of the P-k-C* is required. The wetland degradation can produce ammonium and therefore this needs to be accommodated in the design. The mass balance for these become linked such that production terms for ammonification in the ammonia balance and nitrification in the oxidised nitrogen balance are included. The outlet concentration of the nitrogen species is therefore dictated by:

Table 6 Prediction of treated nitrogen concentration in a wetland

Co = $\dfrac{Qin\ Coin + kA1Co*}{Q1 + (\alpha ET)A1 + IA1 + koA1}$	C_o	organic N concentration, mg/l
Ca = $\dfrac{Qin\ CAin + Ka\ A1\ Ca* + ko(Co1 - Co*)}{Q1 + (\alpha ET)A1 + IA1 + KaA1}$	C_a	ammonium concentration, mg/l
Cn = $\dfrac{Qin\ Cnin + Ka\ A1\ Cn* + ka(Ca1 - Ca*)}{Q1 + (\alpha ET)A1 + IA1 + KnA1}$	C_n	oxidised N concentration, mg/l
	k_o	organic N rate coefficient, m/d
	k_a	ammonium rate coefficient, m/d
	k_n	oxidised N rate coefficient, m/d

The above equations are there solved sequentially to account for the potential ammonium production within the wetland. This preliminary analysis uses rate coefficients which have been calculated from the fitting of annual data from existing wetlands by Kadlec and Wallace (2009). The data has been selected from frequency distribution of the fitted k-value using the 50 percentiles of the distribution (median). The selected rate coefficients are shown below.

Table 7 Rate coefficients examples used in wetland sizing

Parameter	Rate Coefficient (m/yr)
Organic Nitrogen	17.3
Ammoniacal Nitrogen	14.7

The use of floating wetland treatment systems can be very effective in treating nitrogen compounds[4]. Given the transient nature of the lake infilling, this might be a viable option, depending on the rate of infill. As opposed to surface flow systems, the rates used for floating wetlands are based on substance removed per unit area. For floating systems, the following is quoted[5]

Table 8 Removal rate used in floating wetland sizing (assuming anoxic shade)

Substance	**Removal Rate (US)** (**Lbs/ft^2/yr**)	**Removal Rate (metric)** (**mg /m^2/d**)
Ammonium	0.6	69
Nitrate	0.9	104
Total Nitrogen	1.7	197

Equivalent first order degradation coefficients are also available for metal and metalloids. These are not listed but can be obtained from reputable sources (such as Kadlec and Knight, 2006). Using these assumptions, the following reduction in nitrogen might be realised following integration of the water budget into the sizing equation. This preliminary assessment used site data estimates and examined the area of wetland that might be required to reduce the nitrogen compound in the pit lake as it evolves.

Table 9 Wetland sizing based on different flows

Wetland Type	**Size Based (hectares)**		
Flow Rate (m^3/d)	86	430	860
Surface Flow	0.5	1.5	2
Floating	2.4	4.8	7.2

The likely area of the surface water in the pit will be between 420 000 and 1 400 000 m^2 at maximum extent which indicates the fraction of wetland treatment area will be relatively small assuming the flow rates used are realistic. The presence of vegetation retards evaporation in surface flow wetlands. This is to be expected due to shading, increased humidity, and reduction of the wind at the surface. The presence of a litter layer can also create a mulching effect that reduces open water evaporation.

This does not necessarily mean that the wetland conserves water, because wetland plant transpiration can offset this reduction. With plant transpiration offsetting reductions in open water evaporation, large surface flow wetland evapotranspiration and lake evaporation are roughly equal. Some studies report (Roulet N.T and Woo M.K.,1986) this equality for a low arctic site, and a review of swamps/bogs (Linacre E.T.,1976) transpiration concluded rough equality with lakes is probably the most reasonable assumption. Studies by Jiménez-Rodríguez et al, 2019; Bois et al, 2021 and Kiniry, 2023) have indicated that when comparing with open water evaporation, the plant type is important as some promote higher evapotranspiration than open water evaporation and some are equivalent.

3.1 Passive Treatment Results

It is not likely that the inclusion of a wetland will dramatically change the modelling of evaporation. It is clear from the literature that the impact on evaporation is plant type, and site specific and therefore it was recommended that a trial of wetland system is established prior to the pit lake has started to recover. The predictive modelling results indicate that the use of wetland treatment may well have a positive impact on

---

[5] https://www.chesapeakewea.org/docs/Session_1G_-_FloatingWetlandsSolutions_CaseStudies.pdf

the water quality of the pit lake in the long term. The modelling indicates that up to 200 years all analytes are below the assessed relevant quality criteria for livestock in South Africa.

Table 10 Results of the assessment for pit lake water and passive treatment

Analyte	**Livestock**	**200 Years**		**200 Years**	
	DWS (SA)	**No Wetland**		**With Wetland**	
Layer		1	2	1	2
Al	**5**	$4.5E^{-04}$	$4.5E^{-04}$	$3.8E^{-04}$	$3.8E^{-04}$
As	**1**	0.025	0.025	0.003	0.003
Ca	**1000**	61	61	66	66
Cl	**1500**	872	872	780	780
Cu	**0.5**	0.003	0.003	0.001	0.001
Fe	**10**	0.03	0.03	0.03	0.03
F	**2**	1.36	1.36	1.25	1.25
Mg	**500**	32	32	15	15
Mn	**10**	$1.9E^{-05}$	$1.9E^{-05}$	$1.5E^{-05}$	$1.5E^{-05}$
Mo	**0.01**	0.008	0.008	0.007	0.007
Na	**2000**	360	360	323	323
NO_3	**100**	300	300	2.31	2.31
Pb	**0.1**	0.12	0.12	0.04	0.04
pH		9	7.22	8.9	7.13
Se	**0.05**	0.056	0.056	0.007	0.007
SO_4	**1000**	224	224	101	101
TDS	**1000** **2000**	2272	2382	1670	1778
V	**1**	0.46	0.46	0.37	0.37
Zn	**20**	0.11	0.11	0.037	0.037

There is limited information regarding water quality requirements for pomegranate fruit, however one study (Centofantic et al,2018) assessed the nutritional quality from 1-year-old pomegranate trees irrigated for 3 years with typical poor quality water containing high salinity (from 3 to 9 dS m^{-1}), Se (0.25 mg l^{-1}) and B (4 mg l^{-1}) in a micro-plot system where the root system was laterally confined.

This study showed that the young pomegranate trees tolerated irrigation with poor water quality containing high salinity, selenium and boron for 3 years. The fruit were smaller but contained higher concentrations of phenolic compounds than the same variety of pomegranates grown under unconfined root system and irrigated with good quality water. The juice produced from fruit collected from these trees contained Se (up to 0.24 mg l^{-1}) which has numerous human health benefits, as well as high concentrations of nutrients, including antioxidant phenolic compounds.

4 Conclusion

The results showed that incorporation of the passive treatment system would increase the viability of using the pit lake water for the livestock and for use in pomegranate farming for many years post-closure. Notwithstanding these results, mine closure is a whole-landscape development exercise which must consider all closure landform, engineering, and environmental elements and how they will interact over time not just the water quality and quantity. The water quality of a hydraulic sink lake, even with a wetland as mitigation for a 200-year period described herein, is still expected to deteriorate over time through evaporation and the consequent entrapment of solutes although before that happens, it can represent a valuable water resource of select post-closure land-uses.

5 Discussion

In developing the DMCS, the South African Regulators, note that rehabilitating land to its pre-mining state is not considered sustainable (complete backfilling). The DMCS emphasises the need for mines to consider economic diversification at closure with a focus on creating job opportunities during the post-closure phase.

The repurposing of the pit lake for post closure for agri-processing activities provides an opportunity to create 395 job opportunities, thereby allowing for economic diversification which aligns with the DMCS. Repurposing of the pit lake allows for the creation of job opportunities, thereby supporting future food security and well-being of people. Limited job opportunities and contribution to food security would be created post-closure if the open pit is completely backfilled, and the site rehabilitated to a pre-mining state of wilderness and grazing. In addition SLRs significant experience in planning and environmental studies sin South Africa has shown, agriculture is deemed a more sustainable land use than mining and is widely known and practised land use in South Africa.

Acknowledgments

SLR would like to thank Matt Goode (now of Rio Tinto) who originally conceived the modelling method with the lead author, and the fantastic One SLR team, based in South Africa, France, and the UK, who have been involved in the project and many others in the pit lake space. The team includes Brandon Stobart, Natasha Smyth, Paul Klimczak, Navika Erriah and Alex Pheiffer.

References

Bois P., D.L Childers, M Walaszek and A Wakno. 2021 Plant Transpiration in Constructed Treatment Wetland: Effects on water budget and management consequences. J of Env Man 295 113132

Carlino A.M., and C.D McCullough (2019) Modelling the long-term water balance of a pit lake with recreational end uses. Mine Closure 2019-AB Fouries & M Tibbet (eds) ISBN 978-0-9876389-3-9 doi:10.36487/ACG_rep/1915_110_Carlino

Centofanti T, Banueloa G and Wallis C.M. (2018) Fruit quality of pomegranate grown in arid environment and irrigated with saline water. Sustainable Water Resource Management 4(4)

Eary, L.E. 1999. Geochemical and equilibrium trends in mine pit lakes. Applied Geochemistry 14, 963-987.

Eary L.E. and W.M Schafer 2009 Approaches for Evaluating the Predictive Reliability of Pit Lake Numerical Models in Mine Lakes Characteristics, Predictive Modelling and Sustainability Volume 3 Ed D.N Castendyk and L.E Eary, Society for Mining, Metallurgy and Exploration 2009 Vol 15 pp 167 – 177

Gusek, J.J. 2002. “Sulfate-Reducing Bioreactor Design and Operating Issues: Is This the Passive Treatment Technology for Your Mine Drainage?” presented at the Nation Association of Abandoned Mine Land Programs, Park City, Utah, September 15-18.

Jiménez-Rodríguez C.D, C.Esquivel-Vargas, M.Coenders-Gerrits and M.Sasa-Marín (2019). Quantification of the Evaporation Rates from Six Types of Wetland Cover in Palo Verde National Park, Costa Rica. Water 2019, 11(4), 674

Kadlec R.H and Wallace, S (2009) Treatment Wetlands, Second Edition, CRC Press, Taylor and Francis Group, US.

Kadlec R.H and Knight (1996) Treatment Wetlands, First Edition, CRC Press, Taylor and Francis Group, US.

Kiniry J.R., A.S Willaims, L.M Reisner, J.L Hatfield and S Kim 2023. Effects of two categorically differing emergent wetland plants on evapotranspiration. Agrosystems, Geosciences and Environment Vol 6 Issue 1 e20331

Linacre E.T. (1976) Swamps. In: Vegetation and Atmosphere, Volume II: Case Studies, Monteith J.L. (ed.) Academic Press: London, United Kingdom, pp. 329–347.

Roulet N.T., Woo M.K. (1986) Wetland and lake evaporation in the low arctic. Arctic and Alpine Research 18: 195–200