Pit Lakes: Liability or Legacy?

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Abstract

WA currently has more than 2,000 mine voids of which more than half have potential to form pit lakes following cessation of mining. Mining companies are reluctant to backfill with waste rock or tailings because of very high costs and the risk of sterilising remaining resources.

In 2003, the former Water and Rivers Commission (now Department of Water), published *Mine Void Water Resource Issues In Western Australia*, to provide guidance on understanding environmental issues associated with mining below the water table and managing potential impacts as part of mine closure planning. The importance of managing pit lakes as part of mine closure planning has been reinforced in the *Guidelines for Preparing Mine Closure Plans* (DMP & EPA 2012) and the *Mining Rehabilitation Fund Act 2012* (and associated Regulations), which recognise pits as a liability requiring payment of a levy until appropriately rehabilitated.

The two main features required to assess whether a pit lake is likely to become a liability or a legacy after closure are pit water levels and water quality. Predicting final water levels requires a sound understanding of hydrogeological and climatic conditions. The time required to attain a stable water level may vary from several to hundreds of years. Water quality and chemistry are much more difficult to predict and may take thousands of years to equilibrate with pit and aquifer geology.

This paper will outline tools available to hydrologists and geochemists for predicting final pit lake levels and water quality parameters including salinity, acidity, alkalinity and concentrations of toxicants. A recent assessment of an existing pit at the Nifty Copper Operation in the Eastern Pilbara region of Western Australia will be used as a case study. In this example, hydrological, hydrogeological and geochemical modelling was used in concert to predict pit lake water quality 300 years subsequent to mine closure. The study concluded that final pit water quality would be controlled by the relative contributions of two diverse water sources; well buffered alkaline water from the Nifty Carbonate Member aquifer and acidic and metalliferous drainage (AMD) from a pyritic black shale hanging wall exposed in the pit. Water and solute balance modelling predicted formation of a saline (30,500 to 42,000 mg/L TDS) pit lake with a freeboard of 43 m (depth below lowest point on the pit perimeter) and drawdown of 24 m (depth below ambient groundwater levels). Geochemical modelling indicated low risk of developing an acidic pit lake, despite significant inputs of AMD. Risk assessment indicated a very low risk of the pit lake affecting groundwater quality in local aquifers at Nifty. In this example, formation of the pit lake significantly reduced the risk associated with potentially acidic drainage from rehabilitated waste rock dumps and heap leach facilities and this structure will actually play an important role in successful closure of the Nifty mine site.

Introduction

Developments in deep open pit mining methods and efficient extraction and utilisation of mine dewater over the past 50 years have led to proliferation of large pits operating below the groundwater table. Once mining and therefore dewatering cease, water levels recover and a blend of groundwater, rainwater and surface runoff can accumulate in the void.

There are currently more than 2,000 mine voids and more than 150 mines operating below the water table in Western Australia (WA). Many are located in the Pilbara and Goldfields regions, both of which experience semi-arid to arid climates where protection of groundwater resources is essential to surrounding pastoral enterprises. Unless managed appropriately, the liability of mine voids is likely to be a long-term concern for WA. Potential impacts of poorly managed pit lakes include:

- Contamination of both local and regionally significant surface or groundwater bodies located hydrogeologically down gradient from a pit lake.
- Poor vegetation health in the vicinity of, or down gradient from a pit lake.
- Adverse impacts on fauna that may use a pit lake as a source of drinking water, particularly avifauna.
- Adverse impacts on subterranean fauna in the vicinity of, or down gradient from a pit lake.

However, careful planning and management can result in a pit lake providing significant operational benefits and environmental value, such that it becomes a legacy. Examples of such benefits and values include:

- Backfilling a pit with highly sulfidic (potentially acid forming) waste rock or tailings, whilst maintaining a permanent water cover to reduce the risk of acid and metalliferous drainage (AMD) formation.
- Provision of a reliable storage for process water for mineral processing of ore from associated underground operations and satellite pits.
- Storage for human or livestock drinking water.
- A site for recreational purposes such as swimming or water sports.
- Wildlife habitat.
- A water source for aquaculture.

One of the first stages in determining whether a pit lake could provide benefits or value following closure, or at the very least ensure that it does not become a liability, is to predict pit water levels and quality. It is important to have an understanding of these properties and how they are likely to change during operations (in response to activities such as backfilling with waste rock or tailings), at closure and beyond.

Pit Lake Assessment Process

A pit lake model utilises relevant baseline information to provide quantitative data sets for impact assessment. The degree of complexity required for both the model and impact assessment is largely driven by potential contaminants of concern and the receiving environment. For example a pit lake formed within the highly weathered zone of non-acid forming, benign waste in the Goldfields could be adequately assessed via several modelling scenarios and a relatively simple impact assessment. However, assessment of a pit lake formed within the mineralised zone of potentially acid-forming waste and adjacent to a regional water reserve would need to be more rigorous, considering several hundred model scenarios and a substantial impact assessment.

Figure 1 summarises how hydrogeological and geochemical modelling of a pit lake can assist with the environmental assessment process.

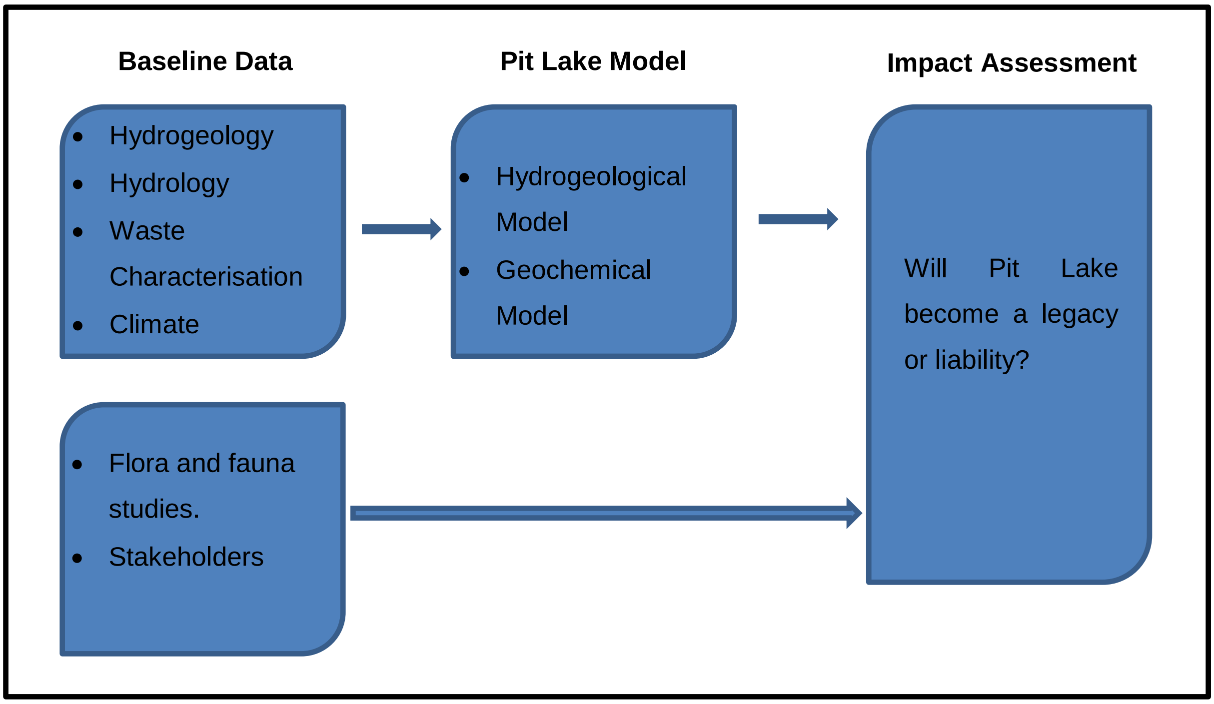


Figure 1: Schematic of Pit Lake Assessment Process

Typical questions targeted by a pit lake modelling process include:

- Will a pit lake form and if so, how long will it take?
- Will hydrogeological processes result in the pit becoming a hydraulic sink or a throughflow feature?
- What will be the final volume of the pit lake and will this be subject to seasonal variations or significant changes over time?

- Will there be sufficient freeboard to prevent overtopping or flow into surface water systems following extreme rainfall events?
- What will the quality of pit lake water be in terms of salinity, acidity, soluble metals and nutrients?

Typical questions targeted by impact assessment include:

- Is this water quality acceptable, given the receiving environment?
- If the pit lake water is of acceptable quality, is there potential for beneficial use post closure (legacy)?
- If the pit lake will contain water of poor quality, what is the risk of it impacting sensitive receptors? How can any risks be managed (liability)?

Pit Lake Modelling

Final pit lake levels and water quality are a result of a complex range of variables such as rainfall, evaporation, hydrology, hydrogeology, pit geology and pit geometry. These variables can also take many years to equilibrate, meaning that water quality fifty years post-mining could be quite different 300 years later. To account for the complex range of interactions, a staged approach first using hydrogeological and then geochemical modelling is often applied.

Hydrogeological Component

In the context of this paper hydrogeological modelling of a pit lake aims to address whether a pit lake will form, what volume of water is likely to result in the pit and likely solute concentrations. Such modelling requires a detailed understanding of the following:

- Long term rainfall data.
- Evaporation losses.
- Pit geometry and surface area.
- Pit catchment area.
- Local and regional hydrogeology (number and position of aquifers, transmissivity, flow direction).

Depending on the accuracy of the aquifer hydraulic properties, reliable predictions of pit lake volume over time can be provided using a range of water balance modelling software. Groundwater Resource Management (GRM) currently uses the ‘GoldSim’ software package for this application. Rainfall, rainfall runoff inflows and evaporation are estimated using climate data. Groundwater interaction is calculated using a standard groundwater flow equation, based upon set flow path lengths and hydraulic conductivities, and variable differences in hydraulic head, estimated from modelled pit lake volumes. Separate flow rates are estimated for different hydrogeological units present and can be verified against peak pit dewatering rates (if available).

The solute accounting aspect of the model uses analyte concentrations assigned to the initial pit lake volume, and inflows and outflows. These analyte concentrations are provided by geochemical modelling (see below). Sensitivity analysis is also carried out on these parameters to assess possible effects of variation in water chemistry.

For pit lake modelling studies, GoldSim predicts pit water levels and solute concentrations as a function of time. Sensitivity analysis is conducted to assess possible effects of variation in water chemistry, rainfall and hydraulic connection between the pit lake and surrounding groundwater system. The output of the program then becomes a series of 'scenario runs' predicting water levels and solute concentrations over time, under varying hydrological, hydrogeological and chemical conditions.

Geochemical Component

A geochemical model utilises baseline data and hydrogeological model outputs to predict pit lake water chemistry as a function of time. Typical contaminants of concern include acidity (pH <3), alkalinity (pH >10), salinity, arsenic, copper, zinc, nickel, manganese, fluoride and nutrients. Table 2 summarises water quality for a series of existing pit lakes. In all of these cases, reliable water quality data for the pit lake can be gathered now via direct sampling. However, as closure planning for these sites progresses, it will become increasingly important to understand if and how this water quality will change over the next 10, 50 or 500 years.

Table 1: Examples of Pit Lake Water Quality and Concerns

Site Location	Ore Type	Major Influences	Pit Water Quality	Potential Impact on Receiving Environment
Northwest Queensland, Australia	Copper (massive sulfide orebody)	• Sub-tropical climate with distinct wet season. Site experiences isolated, high rainfall events. • Pit wall geology – highly mineralised and sulfidic	• Highly acidic. • Moderate salinity. • Very high copper concentrations. • Elevated aluminium, manganese, cobalt, nickel and zinc concentrations.	• Contamination of local or regional groundwater via seepage, flowthrough or overtopping. • Contamination of local or regional surface water bodies via seepage, flowthrough or overtopping. • Vegetation health in the vicinity of or downstream from pit lake. • Subterranean fauna in the vicinity or hydrogeologically down gradient from pit lake. • Fauna (especially birds) in the vicinity of or downstream from pit lake. • Aesthetics.
Goldfields, Western Australia	Nickel	• Semi-arid climate with low, but variable rainfall and high evaporation. • Saline groundwater quality	• Circum-neutral pH. • High salinity. • High nitrate concentrations. • Low metal concentrations.	
Goldfields, Western Australia	Gold	• Semi-arid climate with low, but variable rainfall and high evaporation. • Saline groundwater quality	• Slightly alkaline. • Moderate salinity. • Elevated arsenic. • Low metal concentrations.	
Indonesia	Gold	• Tropical climate with high rainfall year round). • Pit wall geology -highly sulfidic, but with limited mineralisation.	• Highly acidic. • Low salinity. • Very low heavy metals. • Slightly elevated manganese concentrations.	
Southwest Western Australia	Coal	• Mediterranean climate with moderate winter rainfall. • Pit wall geology includes some sulfides. • Alkaline local groundwater chemistry.	• Slightly acidic. • Low salinity and metal concentrations.	

Site Location	Ore Type	Major Influences	Pit Water Quality	Potential Impact on Receiving Environment
Southwest Western Australia	Silica Sand	• Mediterranean climate with moderate winter rainfall. • Regional geology and groundwater chemistry – limited alkalinity and presence of ASS.	• Variable, but can become slightly acidic due to poor buffering capacity. • Very low salinity. • Very low heavy metals.	

Processes Affecting Water Chemistry

Before rushing to apply geochemical modelling software, it is important to understand competing equilibrium processes that may occur within a pit lake as these will influence how the model is established. The most prevalent equilibrium processes are salinisation and acidification.

Salinisation

Many pit lakes in the semi-arid regions of Western Australia are characterised by high salinity. This is a result of very high evaporation rates compared to rainfall and surface runoff inflows, moderate to very high salinity levels in groundwater and generally low groundwater flows because of the lack of high permeability sedimentary aquifers. Disused pits therefore behave as a 'sump' for low groundwater flows and most of this water is lost to the atmosphere via evaporation.

The major constituents of saline groundwater (sodium, chloride, magnesium and sulfate ions) are considered as **conservative ions**, because they are not chemically reactive and remain in solution rather than participating in processes such as precipitation and surface adsorption. As a result, pit lake salinities can reach very high levels under conditions of very low rainfall, high evaporation rates and very low groundwater flow through. The solubility of sodium chloride (NaCl, halite) at 30ºC is 360,000 mg/L, which can be achieved in concentrated pit lake brines in the eastern Goldfields.

Prediction of pit lake salinity is a relatively straight forward exercise once the pit lake volume and recovery time have been determined by accurate water and solute balance modelling. By considering the solutes as conservative ions, salinity can be calculated as the ratio between solute mass and water volume at any particular time during pit lake development.

Figure 2 shows a conceptual model of water and solute inputs for conservative ions in a typical WA Goldfields pit lake.

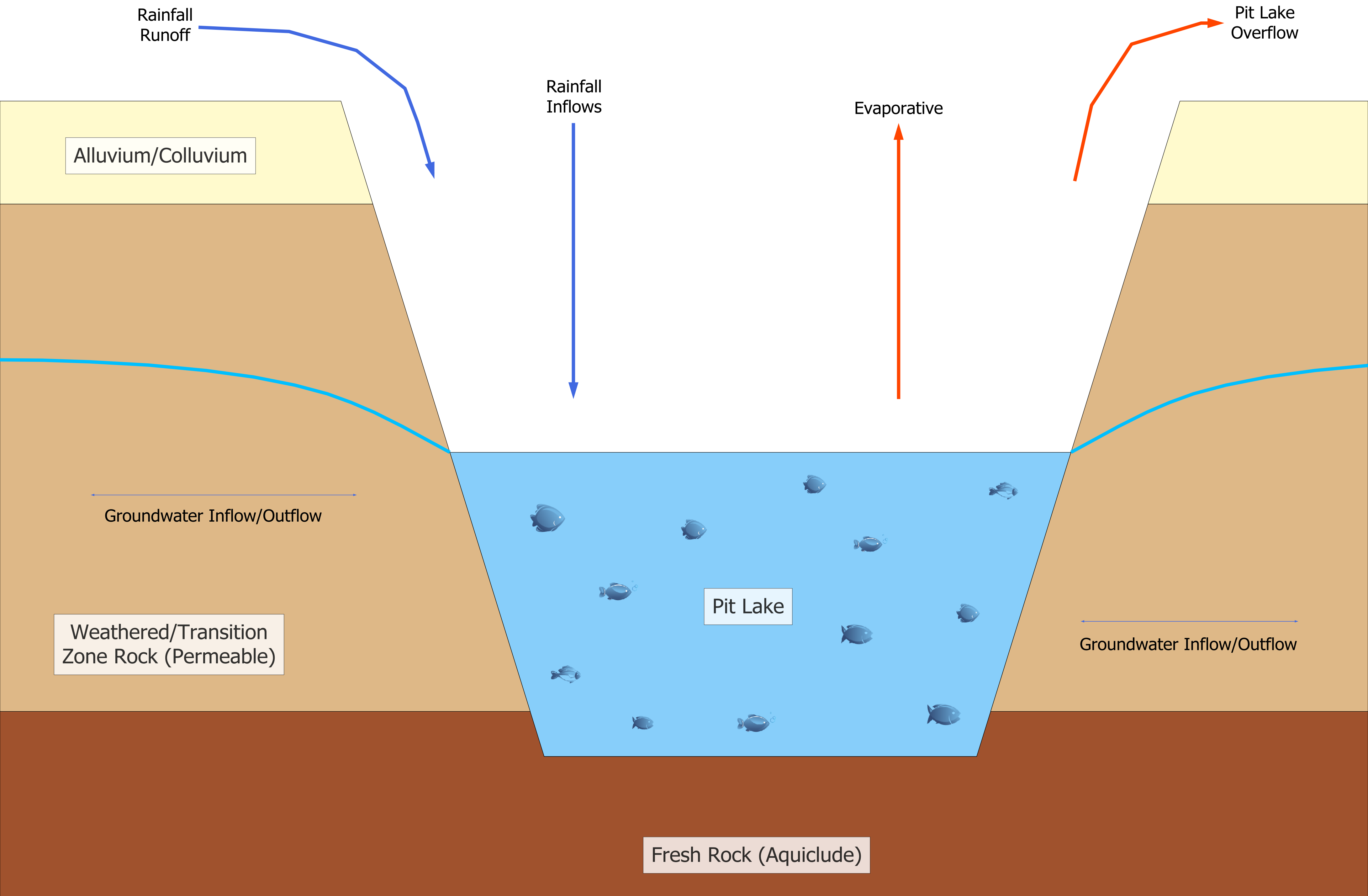


Figure 2: Conceptual Model of Water and Solute Balance in Pit Lakes

Acidification

The presence of sulfides in pit walls can result in acidic and metalliferous drainage (AMD) collecting within the pit lake. Prediction of water quality in a pit lake affected by AMD is difficult because many solutes associated with AMD are **non-conservative ions,** capable of chemical reaction, surface adsorption and precipitation, depending on which form they take. Critical to acid pit lake quality prediction is estimation of pH, as it is a major determinant of solubility of metals and metalloids associated with AMD, notably aluminium, iron, manganese, copper, nickel and zinc. Most metals are almost insoluble at circum-neutral to slightly alkaline conditions, but increase in concentration as pH decreases. For example, copper, nickel and manganese form insoluble oxide and hydroxide minerals under circum-neutral and alkaline pH conditions. Under acidic conditions, these minerals dissolve, thereby liberating the metal as hydrated cations. Other elements such as molybdenum, vanadium and uranium also form insoluble oxide and hydroxide minerals under circum-neutral pH conditions, but soluble oxy-anions as pH increases (alkaline conditions).

Other Factors

The fate of dissolved metals and metalloids is also influenced by other geochemical conditions in addition to pH including:

- Redox potential (e.g. iron and manganese are more soluble under reducing (low dissolved oxygen) conditions).
- Ability to form complex ions with other solutes (e.g. the solubility of copper and cobalt increases in the presence of cyanide or high concentrations of chloride ions in hypersaline water).
- Adsorption reactions with pit wall materials, pit lake sediments and dissolved organic matter (e.g. arsenic and selenium concentrations can be reduced by adsorption onto hydrous iron hydroxide sediments).

Figure 3 presents a conceptual model showing pathways controlling pit lake chemistry when an AMD component is included in the water and solute balance.

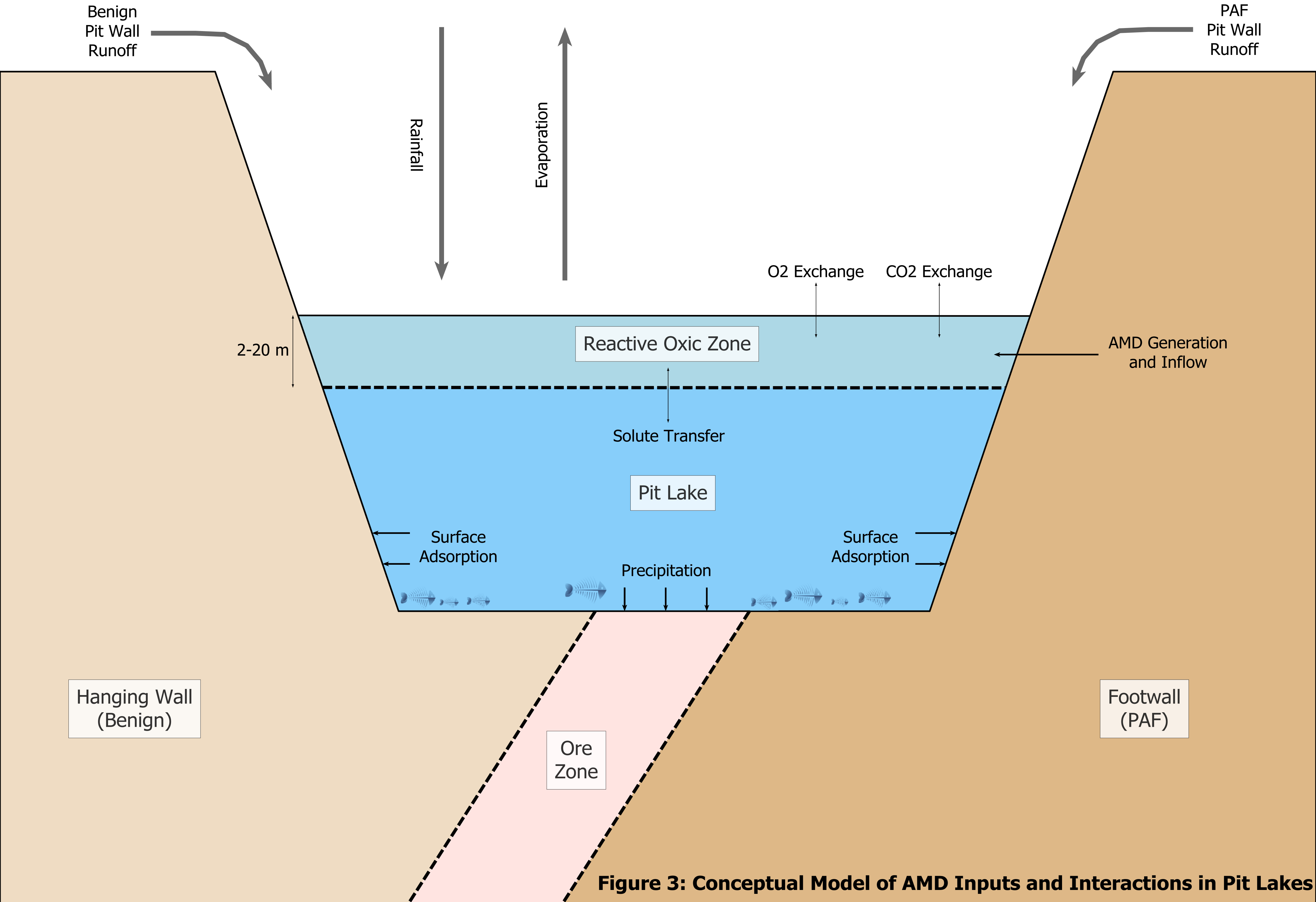


Figure 3: Conceptual Model of AMD Inputs and Interactions in Pit Lakes

Geochemical Modelling Software

Geochemical modelling software is applied to predict solution concentrations under competing chemical equilibrium and geochemical speciation conditions. A number of programs are available for this purpose; MBS Environmental (MBS) currently uses PHREEQC Version 3 which is a geochemical speciation model developed by the United States Geological Survey in 1995 (Parkhurst 1995). PHREEQC is a computer program written in the C and C++ programming languages that is designed to perform a wide variety of aqueous geochemical calculations with a user-friendly interface. PHREEQC implements several types of aqueous models including two ion-association, a Pitzer specific-ion-interaction and the Specific ion Interaction Theory (SIT) aqueous model. Using any of these aqueous models, PHREEQC has capabilities for:

- Ionic speciation and saturation-index calculations.
- Batch reaction and one-dimensional (1D) transport calculations with reversible and irreversible reactions, which include aqueous, mineral phase, gas, solid-solution, surface-adsorption, and ion-exchange equilibria, and specified mole transfers of reactants, kinetically controlled reactions, mixing of solutions, and pressure and temperature changes.
- Inverse modelling, which identifies sets of mineral and gas mole transfers that account for differences in composition between waters within specified compositional uncertainty limits.

PHREEQC can produce a broad range of outputs under different scenarios to assist with prediction of pit lake water quality including prediction of species present, species complexation and saturation states, interaction with solid phases (such as pit walls or sediments) and equilibrium under different atmospheric conditions (to account for varying elevations). Such outputs can then feed into the impact assessment process.

Pit Lake Modelling Limitations

As with any modelling software, GoldSim and PHREEQC contain a number of inherent assumptions and approximations relating to factors such as thermodynamic activity, transport modelling and surface complexation. Furthermore, the reliability of results is dependent on the quality of input data. Baseline data is often subject to uncertainty and the significance of fluctuations in this data needs to be understood when interpreting results. As discussed previously, some uncertainties can be accounted for by providing a number of different ‘scenario runs’ under varying hydrogeological, hydrological and chemical conditions. The likelihood of these scenarios can then be addressed at the impact assessment stage.

Case Study – Nifty Copper Operations

Project Description

Birla Nifty Pty Ltd (BNPL), a wholly-owned subsidiary of Aditya Birla Minerals Limited (ABML), operates the Nifty Copper Operation (NCO), located about 65 km southwest of Telfer in the Eastern Pilbara region of Western Australia.

The operation includes an open pit (no longer being mined) and underground workings below. The base of the pit is well below the natural water table and is currently subject to dewatering to allow underground operations to continue. The pit is predicted to form a pit lake after mine closure.

BNPL is currently developing a closure plan according to recent changes to the *Mining Act 1978* (Mining Act), which require all operating mines in Western Australia to submit a Mine Closure Plan to the Department of Mines and Petroleum (DMP) by 2014. Mine closure guidelines (DMP & EPA 2011) require mine operators to achieve a safe and stable landform that does not pollute the surrounding environment. BNPL recognised that if poor water quality was to form within the pit, this could adversely affect the surrounding environment or compromise the quality of groundwater for future land users such as pastoralists. Therefore, as part of the closure planning process, longer term pit water levels and geochemistry were modelled and potential impacts assessed.

Pit Lake Modelling Methodology

Hydrogeological modelling work was undertaken by GRM using the 'GoldSim' software package. Geochemical modelling was undertaken by MBS by applying the PHREEQC speciation model to 'GoldSim' output concentration data to calculate pH values and refine heavy metal concentrations by considering precipitation of stable mineral phases. An arbitrary period of 300 years subsequent to mine closure was adopted for the modelling work.

The main groundwater inflows to the Nifty pit are from the Nifty Carbonate Member (NCM). The Hanging Wall Shales (HWS) and Footwall Shales (FWS) are generally aquitards, but can provide minor inflow. Current dewatering rates for the pit were estimated using a site water balance which indicated a peak dewatering rate of approximately 5,500 m^3/day.

The water balance model comprised the stored lake volume, and inflows and outflows associated with:

- Rainfall and rainfall runoff from the pit catchment.
- Groundwater interaction (seepage in or out of the pit lake).
- Evaporation losses from the pit lake surface.

Direct rainfall, inflow from rainfall runoff and evaporation were estimated using climate data, comprising a synthetic daily rainfall data set estimated from the Bureau of Meteorology records for Nifty and nearby Telfer mine sites and long term average evaporation rates from Telfer adjusted for pan to lake and salinity effects. A sensitivity run was conducted using monthly median rainfall rates.

Groundwater interaction was calculated by the water balance using a standard groundwater flow equation, based upon set flow path lengths and hydraulic conductivities, and variable differences in hydraulic head, estimated from modelled pit lake volumes. Separate flow rates were estimated for three hydrogeological units (NCM, HWS and FWS), and verified against the peak pit dewatering rate. Sensitivity analysis was carried out to assess possible effects of variation in the hydraulic connection between the pit lake and surrounding groundwater system by adjusting the groundwater flow path length.

Solute Accounting Inputs

The solute accounting aspect of the model used analyte concentrations assigned to the initial pit lake volume, and inflows and outflows. Solute input data were provided from the following sources:

- Rainfall. Rainwater composition was sourced from a reputable aquatic chemistry textbook (Morel and Hering 1993) and an inland rainwater composition data set (Root *et al*. 2004).
- Pit wall runoff. Pit water runoff composition data was based upon water leachate data from an earlier waste characterisation (MBS 2007). For the purpose of considering a worst case scenario, the NCM and FWS rocks were considered to be non-reactive and the HWS rocks were considered to be reactive (generating an acidic leachate). HWS rock represents a total of 37% of the total exposed pit wall rock surface. Pit wall runoff composition was characterised by brackish salinity provided by conservative ions (calcium, magnesium, sodium, sulfate and chloride), no bicarbonate alkalinity, elevated concentrations of iron and aluminium (up to 2,300 and 3,600 mg/L respectively) from pyrite oxidation acidity and slightly elevated concentrations of manganese, copper, nickel and zinc.
- Groundwater composition data was based upon the following:
  - Water quality of the NCM for the worst case scenario was based upon recent data associated with a review of mine dewatering water quality (MBS 2012).
  - Water quality of the NCM for the expected case scenario was based upon a statistical interpretation of likely natural groundwater quality (URS 2008).
  - Water quality of FWS and HWS for both the worst and expected case scenarios was based upon baseline groundwater data (MBS 2004).

  Groundwater quality was characterised by moderate levels of alkalinity, slightly brackish salinity (close to the livestock drinking water guideline of 5,000 mg/L) and low concentrations of dissolved metals.

- Release from reactive pit wall lithologies. The reactive wall data was based upon calculated pyrite oxidation rates derived from kinetic testing of black shale waste rock (RGS 2012). Worst and expected case scenarios were based upon the production of sulfate at a rate of 8.58 kg/m^3/a and 3.38 kg/m^3/a from the oxidation of pyrite (FeS_2). Solute release rates from this source are presented in Table 3.

Table 2: Reactive HWS Wall Data

Analyte	Concentration (kg/m^2/yr)	
	Worst Case	Expected Case
Calcium	1.7	0.68
Potassium	0.03	0.01
Magnesium	11	4.3
Sodium	0.34	0.13
Chloride	0.55	0.22
Nitrate	0.12	0.05
[1]Sulfate	8.6	3.4
Aluminium	1.4	0.53
Arsenic	0.0002	0.0001
Cadmium	0.001	0.0004
Copper	9.6	3.8
[1]Iron	2.5	0.98
Nickel	0.25	0.10
[2]Lead	0.00	0.00
Zinc	0.22	0.09

Notes:

[1]Iron and sulfate loads are representative of sulfide oxidation.

[2]Load is based upon predicted below detection levels of lead when the HWS material is exposed to oxidising conditions (RGS 2012).

Geochemical Scenarios

The following two geochemical scenarios were considered for the purpose of exploring the sensitivity of the solute accounting undertaken using GoldSim:

- A <u>worst case scenario</u> that can be generally described by:
  - Very high loads of mineral acidity and solutes from pit wall run off.
  - Very high loads of mineral acidity and solutes in leachate originating from the pyritic HWS pit lake wall.
  - Lower than expected loads of bicarbonate alkalinity in NCM groundwater.

- An <u>expected case scenario</u> that can be generally described by:
  - Expected loads of acidity and solutes from pit wall run off.
  - Expected loads of acidity and solutes in leachate originating from the pyritic HWS pit lake wall.
  - Expected loads of bicarbonate alkalinity in NCM groundwater.

A total of fifteen model runs (scenarios) were undertaken, with details summarised in Table 4.

Table 3: Solute Accounting Sensitivity Analysis Runs

GoldSim Run	Geochemical Scenario	Groundwater Flow Conditions	Rainfall Input	Reactive Oxygen Rich Depth
1	Worst Case	Expected Inflow	Synthetic Daily Rainfall	0 m
2	Expected Case	Expected Inflow	Synthetic Daily Rainfall	0 m
3	Expected Case	Expected Inflow	Nil	0 m
4	Worst Case	Expected Inflow	Synthetic Daily Rainfall	10 m
5	Expected Case	Expected Inflow	Synthetic Daily Rainfall	2 m
6	Worst Case	Low Inflow	Synthetic Daily Rainfall	10 m
7	Expected Case	Low Inflow	Synthetic Daily Rainfall	2 m
8	Worst Case	High Inflow	Synthetic Daily Rainfall	10 m
9	Expected Case	High Inflow	Synthetic Daily Rainfall	2 m
10	Worst Case	Expected Inflow	Monthly Median Rainfall	10 m
#11	Expected Case	Expected Inflow	Synthetic Daily Rainfall	10 m
12	Worst Case	Expected Inflow	Synthetic Daily Rainfall	20 m
13	Worst Case	Low Inflow	Synthetic Daily Rainfall	20 m
14	Worst Case	High Inflow	Synthetic Daily Rainfall	20 m
15	Worst Case	Expected Inflow	Monthly Median Rainfall	20 m

Notes: #The expected base case.

An evaporation factor of 0.7 was used for all runs.

A runoff co-efficient of 0.9 was used for all runs

Results

Hydrogeological Aspects

Key findings from the GoldSim water balance and pit lake volume modelling are summarised as follows:

- Equilibrium conditions (where annual inflows are balanced by annual outflows) were established after about 50 years.

- The peak groundwater inflow rate, which occurs immediately after closure, for the base case was approximately 5,600 m^3/day, which is similar to the peak pit dewatering rate. This demonstrates the model realistically captured the hydraulic connection between the pit lake and groundwater system.

- Long-term inflow rates range between 1,300 and 1,880 m^3/day, with a base case rate of approximately 1,630 m^3/day.

- The long-term pit water level for the base case is estimated at 255 mAHD, which equates to a freeboard of 43 m (depth below lowest point on the pit perimeter) and drawdown of 24 m (depth below ambient groundwater levels). Sensitivity analysis indicates the long-term lake level may range from 241 to 267 mAHD (Figure 4).

- The predicted long-term pit lake volume is approximately 18.9 GL, compared to the pit's maximum capacity of 44.3 GL. Upper and lower bound results range from 14.7 to 21.7 GL.

- The most hydraulically conductive aquifer associated with the pit lake is the NCM aquifer.

- Pit lake levels are unlikely to exceed the ambient groundwater level and thus the pit lake will effectively become a groundwater sink.

- There is no direct hydraulic link between the NCM aquifer and the Nifty Paleochannel aquifer.

- The predicted long term pit lake drawdown (24 m) suggests there is reasonable likelihood that the post closure cone of depression in the NCM aquifer will extend under the heap leach pad. The NCM aquifer directly underlies areas beyond the west of the pit and thus there may be significant hydraulic linkage between seepage water from the heap leach pad and the pit lake.

- The FWS aquitard underlies areas to the north of the pit lake and as such there is not likely to be significant hydraulic linkage between seepage water from the waste rock dump and TSF and the deeper aquifer. Shallow subsurface seepage can occur in the upper weathered horizon.

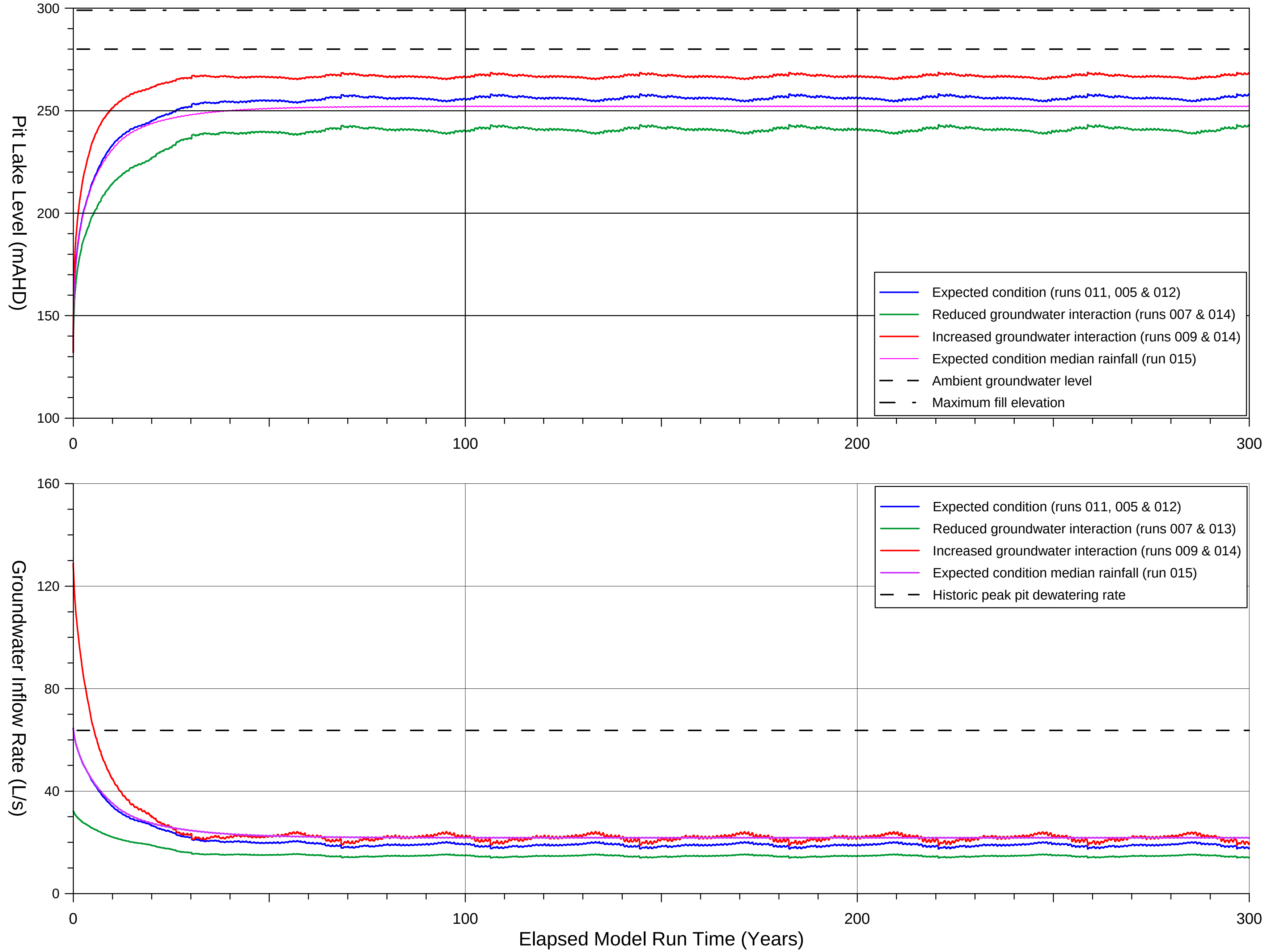
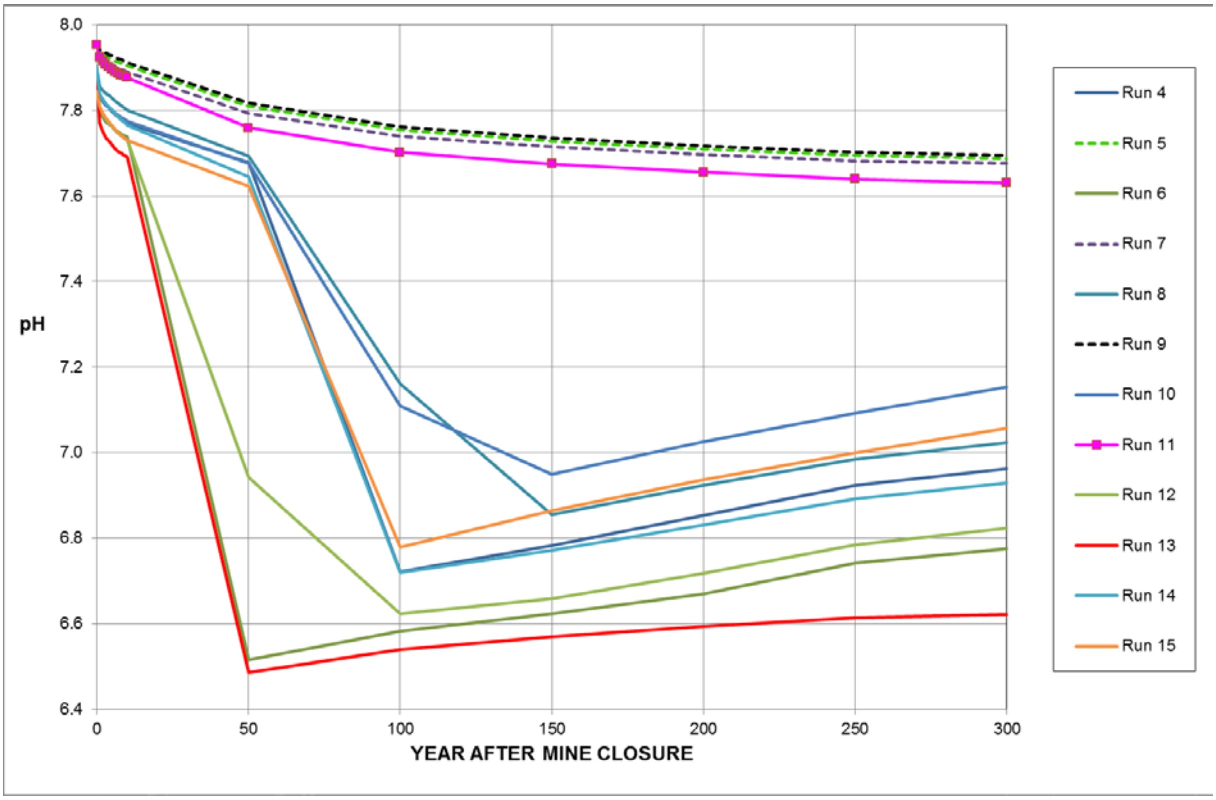


Figure 4: Predicted Pit Lake Levels and Groundwater Inflow Rates

Geochemical Aspects

Figure 5 shows the potential variation in equilibrium pH with time for Runs 4 to 15. These results represent the pH in the pit lake after equilibrium has been reached with the atmosphere, solid solution mineral phases and FWS and NCM reactive mineral materials. Results for the expected base case (Run 11) are highlighted with a fluorescent pink line and data markers.

Figure 5: Predicted pH Values



These results indicate a low risk of development of an acidic pit lake. The expected case (Run 11) indicates a gradual decrease in pH from 7.9 to 7.65 over a 300 year period. The lowest predicted pH was 6.49 achieved under Run 13, which is based on a worst case geochemical scenario, low groundwater inflows and a 20 m reactive zone (versus the conventionally accepted 10 m zone).

As a result of very high evaporation rates and the inherent assumption of the modelling work that no transport of solutes away from the pit lake occurs, salinity levels are predicted to increase. Expected conditions (Run 11) suggest the final salinity of the pit lake will be 30,500 mg/L, which is slightly less than typical seawater, 34,500 mg/L (Lenntech 2012). The mass proportion of sulfate ions is expected to be similar to chloride ions and the mass proportion of sodium ions is expected to be 2.9 times the mass proportion of magnesium ions.

Worst case conditions (Run 13) suggest the final salinity of the pit lake will be 42,000 mg/L, which is slightly higher than typical seawater. The mass proportion of sulfate ions and magnesium ions is significantly higher than expected conditions. The additional sulfate and magnesium is primarily as a result of higher inputs of leachate originating from the pyritic HWS pit wall.

Predicted metal ion concentrations were low for most metals as a result of circum-neutral to slightly alkaline pH conditions. Solid solution formation and mineral dissolution, which is primarily determined by pH and the relative abundance of pairing anions (such as SO_4^{2-}, OH^-, CO_3^{2-} and Cl^-), controlled the final total soluble concentrations. Saturation indices for key copper hydroxide minerals (antlerite, atacamite, brochantite, malachite, tenorite and $Cu(OH)_{2(s)}$) were predicted to increase over the 300 years subsequent to closure and it is this process which drives the precipitation of copper and other metals. The predicted final total copper concentrations of 0.06 mg/L in the expected case (Run 11) and 0.91 mg/L in the worst case (Run 13) represents less than 0.01% of the total input of soluble copper into the pit lake. Elevated concentrations of manganese may be present in the final pit lake, with modelling predictions of 87 mg/L and 178 mg/L in the expected case (Run 11) and worst case (Run 13) scenarios respectively. However, the modelling approach did not consider free exchange of the pit lake with oxygen in the atmosphere. High concentrations of dissolved oxygen would be expected to precipitate manganese and mixed trivalent and tetravalent hydrous oxides, which would result in much lower concentrations of soluble manganese.

Conclusions

Modelling of recovery times and salinity levels within a pit lake is a relatively straightforward exercise if the hydrogeology and groundwater quality of the site have been adequately characterised. Many pits in the eastern and northern Goldfields of Western Australia that have been mined below the natural groundwater table are expected to form moderately saline to hypersaline pit lakes.

Whether or not flows of AMD from sulfidic waste rock or pit walls mixes with circum-neutral or slightly alkaline groundwater to form an acidic pit lake is much more difficult to predict. In addition to accurate water and solute balance modelling, prediction of final pH, acidity and dissolved metal concentrations requires use of sophisticated geochemical speciation software to elucidate the relative contributions of complex competing geochemical reaction pathways.

In the case study presented, pyritic black shales in the Nifty pit walls were expected contribute volumes of highly acidic and metalliferous drainage to the pit lake. However hydrogeological and geochemical modelling predicted the resultant pit lake water quality will remain circum-neutral to slightly alkaline over the 300 year post-mine closure period in response to relatively high flows of alkaline groundwater from the NCM aquifer. Dissolved copper concentrations were also predicted to remain below the livestock drinking water guideline of 1 mg/L due to precipitation of common copper hydroxide/oxide/carbonate minerals. Water quality in the lake is unlikely to be a risk to animals such as migratory birds because elevated salinity levels make it unsuitable for drinking. Circum-neutral conditions and low concentrations of soluble metals are also unlikely to result in health issues arising from dermal contact.

Risk assessment indicated a very low risk of the pit lake affecting groundwater quality in local aquifers near Nifty, particularly shallow aquifers that provide water of livestock drinking quality. Formation of the pit lake significantly reduces the risk of potential impacts from AMD draining from rehabilitated waste rock dumps and heap leach facilities into the lake where it will be neutralised by the lake's alkalinity. The pit lake will play an important role in successful closure of the Nifty Copper Operation, thereby providing BNPL with a legacy and not a liability.

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