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TECHNICAL ARTICLE

Mine Closure of Pit Lakes as Terminal Sinks: Best Available Practice When Options are Limited?

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Abstract In an arid climate, pit lake evaporation rates can exceed influx rates, causing the lake to function as a hydraulic terminal sink, with water levels in the pit remaining below surrounding groundwater levels. We present case studies from Western Australia for two mines nearing closure. At the first site, modelling indicates that waste dump covers for the potentially acid forming (PAF) material would not be successful over the long term (1,000 years or more). The second site is a case study where PAF management is limited by the current waste rock dump location and suitable cover materials. Pit lake water balance modelling using Goldsim software indicated that both pit lakes would function as hydraulic terminal sinks if not backfilled above long-term equilibrium water levels. Poor water quality will likely develop as evapo-concentration increases contaminant concentrations, providing a potential threat to local wildlife. Even so, the best current opportunity to limit the risk of contaminant migration and protect regional groundwater environments may be to limit backfill and intentionally produce a terminal sink pit lake.

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Introduction

Due to operational and regulatory practicalities, pit lakes will continue to be common legacies of many mine lease relinquishments. Weathering of potentially acid forming (PAF) waste materials in pit lake catchments, such as pit wall rock, waste rock dumps, and tailings storage facilities, may produce acid and metalliferous drainage (AMD) that reports to nearby rivers and lakes (Younger 2002). Although material geochemical characterisation and placement/storage strategies are often available to mitigate or contain AMD production, many currently operating or planned mines do not have these considerations in place for a variety of historical and contemporary socio-economic and regulatory reasons (Hilson and Haselip 2004; Botha 2012).

AMD-degraded water quality in pit lakes may reduce regional environmental values and may present risks to surrounding communities and environmental values (McCullough and Lund 2006; Hinwood et al. 2012). Mine closure guidelines and standards increasingly require chemical safety and long-term low risk to surrounding ecosystems for closure practices to be acceptable (ANZMEC/MCA 2000; ICMM 2008; DMP/EPA 2011). Unplanned or inappropriate management of pit lakes can lead to both short- and long-term liability to mining companies, local communities, the government, and the nearby environment during mining operations or after lease relinquishment (McCullough and Van Etten 2011).

As a consequence, most developed jurisdictions are consistent in their requirement for mining companies to plan and/or rehabilitate to minimise or prevent any potential deleterious effects of the pit lake water body on regional ground and surface water resources (Jones and McCullough 2011). The focus of most general or ad hoc pit lake regulation is to protect human and ecological communities from adverse effects of the pit lake. For example, in Australasia, closure guidelines are generally oriented to aquatic ecosystem protection, based on ANZECC/ARMCANZ (2000) criteria. Such guidelines generally emphasize either a demonstration of null-negative effects of the lake or require management to achieve the required level for compliance (Kuipers 2002). However, AMD treatment may be very costly and difficult to achieve in remote mining regions (Kumar et al. 2011). As a result, sustainable pit lake management aims to minimise short- and long-term pit lake liabilities and maximise short- and long-term pit lake opportunities (McCullough et al. 2009).

In an arid climate, pit lake evaporation rates can exceed water influx rates, causing the pit lake to function as a hydraulic 'terminal sink'. Mean water levels in these pit lake can remain below surrounding groundwater levels. This paper describes how a terminal lake approach was applied to meet regulatory concerns for mine closure planning to achieve better environmental outcomes for two mines in different highly active mining regions of Western Australia. Our study used simple but robust pit lake water balance modelling, incorporating both hydrogeological and meteorological variables to determine equilibrium pit lake heights relative to local groundwater levels. The resulting models indicated that the case study pit lakes would likely remain as mean terminal sinks long (at least hundreds of years) after closure.

Study Sites

There are many examples of successful dumping of mine waste under wet covers or at the bottom of pit lakes (Schultze et al. 2011). We present two case studies from semi-arid and arid Western Australia that are relevant to other arid regions with active mines, e.g. southwest US and South Africa. Both open-cut mining operations are remotely located hundreds to thousands of miles from population centres and regional services. Both are currently developing detailed mine closure plans and face difficulties with PAF materials management in above-ground waste landforms where potential cover materials in the regional environments primarily consist of highly dispersive clays and sand. Geochemical testing indicates both pit lake catchments are likely to develop AMD-degraded water quality over time (unpublished data).

We assumed that AMD runoff would be allowed to flow into the pit after closure, even though a safety bund (known in the US as a berm) might be constructed around the perimeter of the pit (DMP 2010). We assessed three post-closure scenarios for each of the open pits: pit not backfilled and a pit lake forming, pit partially backfilled to below pre-mining groundwater levels with pit lake forming; and pit fully backfilled.

Nifty Copper Operation, Aditya Birla

Nifty Copper Operation (Nifty) is located in the Pilbara region of Western Australia, approximately 1,200 km north-northeast of Perth (Carver 2004) (Fig. 1). The Nifty copper deposit is the most significant ore deposit in the Neoproterozoic Paterson region of Western Australia (Huston et al. 2005). The Pilbara has an arid climate with two distinct rainfall patterns: in summer, rainfall occurs from either tropical cyclones or thunderstorms, while winter rainfall is typically from low pressure trough systems. Average annual rainfall in this highly active mining region is low, ranging from 200 to 420 mm/year, while evaporation averages around 4,000 mm/year (Kumar et al. 2012). Monthly evaporation significantly exceeds rainfall throughout the year and seasonally ranges from around 150 to 200 mm per month from May to August (the dry season), up to 450 mm in December and January (the wet season; BOM 2012).

On a regional scale, the Nifty Copper Operation lies within the Paterson orogeny of the Paleoproterozic to Neoproterozoic era. The Nifty deposit itself is a structurally-controlled, chalcopyrite-quartz-dolomite placement of carbonaceous and dolomitic shale (Anderson et al. 2001). The Nifty mine pit lies in a syncline within shales of the

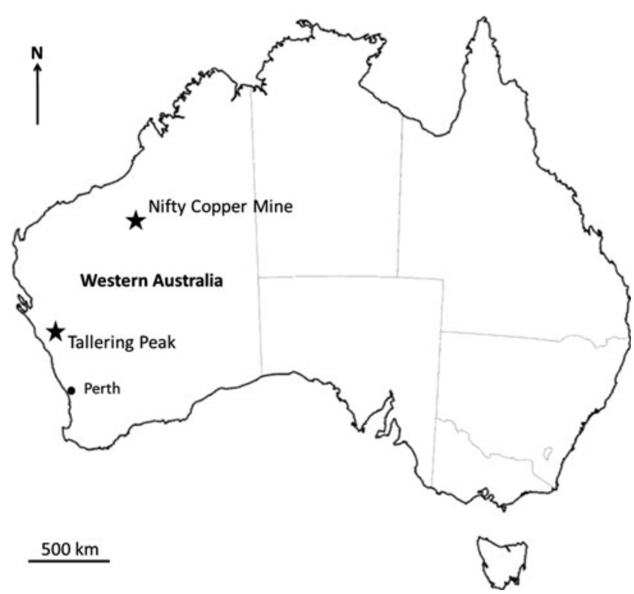


Fig. 1 Case study locations

upper Broadhurst Formation, which forms part of the Yeneena Supergroup. The folded shale of the Broadhurst Formation hosts the main copper ore body at Nifty Copper Operation and is strongly PAF. The mine stratigraphy consists of four units, the Foot Wall beds, the Nifty member, the Pyrite Marker bed and the Hanging Wall beds (Anderson et al. 2001).

Tallering Peak Iron Ore Mine, Mount Gibson Mining

Tallering Peak iron ore mine (Tallering Peak), which is owned and operated by Mount Gibson Mining (MGM), is located in the semi-arid midwest mining region of Western Australia (Kumar et al. 2012), approximately 300 km north of Perth (Fig. 1). Tallering Peak commenced production in 2004 and is predicted to continue operations until late 2013. Final landforms consist of mine pits T3, T4, T5, and T6A, and associated waste rock dumps. After closure, the partially backfilled mine void at T5, which is the largest pit, is expected to fill, mostly through groundwater inflow.

Arid Climate Conceptual Modelling of Pit Lake Water Balance and Water Quality

Climate is the most important factor of the hydrologic processes associated with a pit lake (Castendyk 2009). Changes in climate (e.g. temperature, rainfall, wind, precipitation amount, and distribution) affect individual hydrologic components differently. In general, surface hydrologic processes (e.g. direct precipitation, evaporation, and surface water runoff, including occasional stream or river inflows) are defined by regional climate to form a simple water balance budget for the pit lake (Fig. 2). Groundwater inflows are generated from precipitation recharge and tend to buffer short-term climatic changes, but long-term climatic changes will be reflected in groundwater inflows. Modelling of such groundwater and climate processes is often used to predict final water balances in pit lakes (Vandenberg 2011).

Post-closure pit lakes in an arid environment are typically classified as either ‘through-flow’ (Fig. 3a) lakes or terminal sinks (Johnson and Wright 2003). Terminal sinks may occur in arid climates where the evaporation potential is higher than average rainfall runoff (Niccoli 2009). During groundwater level rebound at the end of mining and pit void filling, the pit lake water level rises to a level where inflows (direct rainfall, catchment and pit wall runoff, and groundwater inflow) are in equilibrium with evaporation losses. Hence, pit lake water level does not rise to levels higher than adjacent groundwater levels and water does not seep into the groundwater system. The water quality of terminal sink lakes is expected to show increased acidity, metals, and salt concentrations over time as solutes introduced through groundwater inflow and pit wall runoff are concentrated by evaporation (Fig. 3b) (Miller et al. 1996).

Following groundwater rebound and dissolution of the cone of depression the pit lake begins to fill with water and groundwater influx into the pit initially increases as the influx area increases. Later, discharge slows as the change in head decreases (Gammons et al. 2009). As a result, total inflow into the pit lakes is expected to gradually decrease as the open pits fill, while total outflow is expected to increase due to increased evaporation from the greater lake area. At some stage, total inflow approximates total outflow and the water level in an open pit will reach equilibrium, albeit responding dynamically to changes in seasonal precipitation and evaporation rates. Water level fluctuations may occur, e.g. due to occasional cyclones.

If the steady-state pit lake elevation stabilizes below the surrounding pre-mining groundwater level, the pit lake becomes a terminal sink, with no water released into the environment through seepage into the groundwater system. However, if the final pit lake elevation reaches the

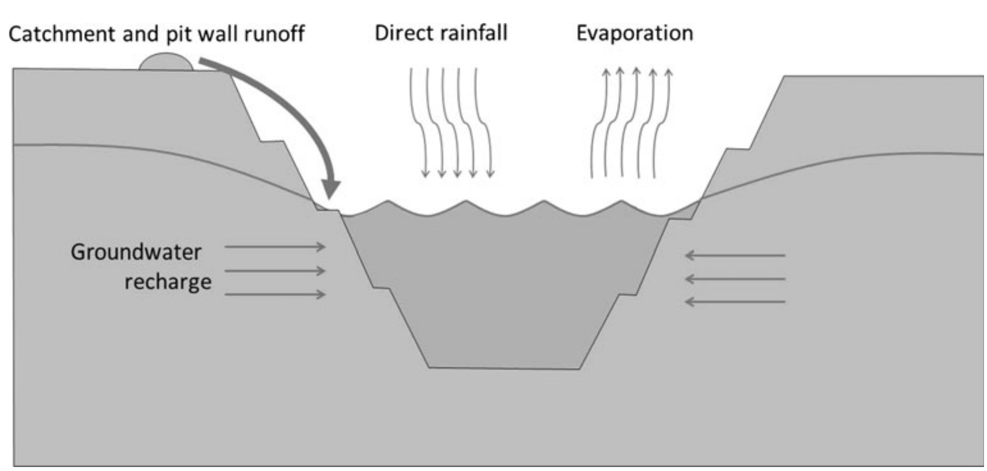


Fig. 2 Conceptual pit lake key water balance processes

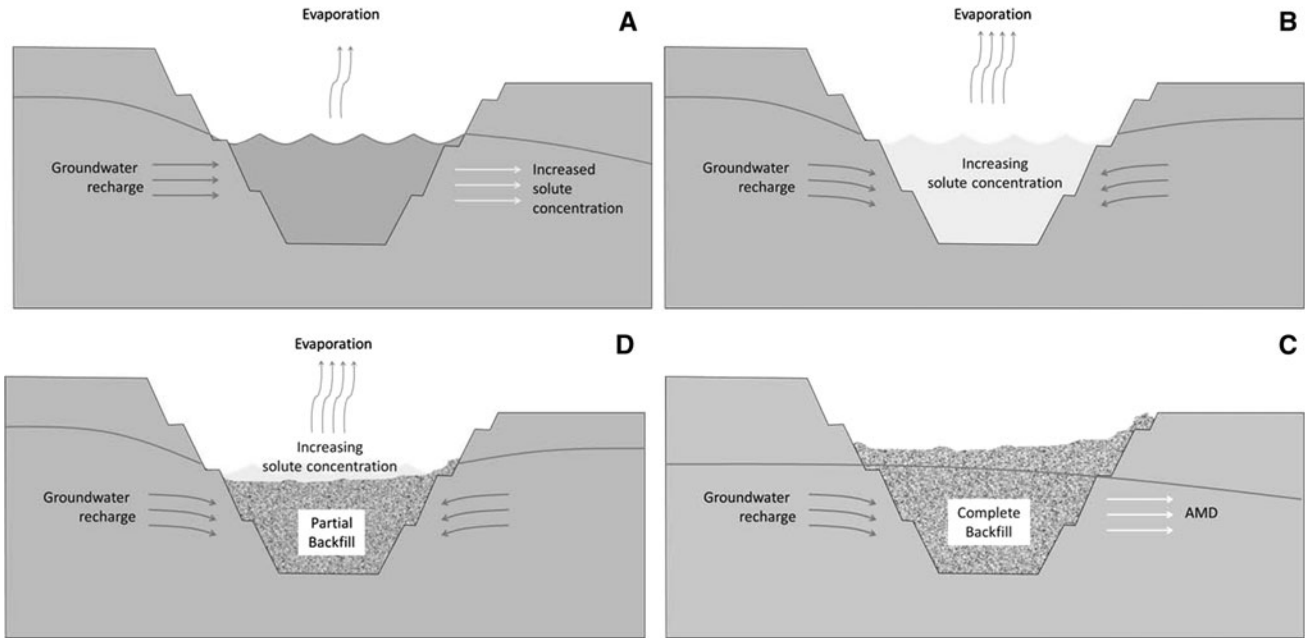


Fig. 3 Conceptual equilibrium hydrogeological regimes for an arid region pit lake. *Clockwise* from *top left* through-flow system, terminal sink, completely backfill through-flow system, partially backfill terminal sink

surrounding pre-mining groundwater level, the pit lake becomes a through-flow system with water being released to the environment through groundwater seepage, potentially spreading AMD plumes to environmental receptors.

Complete backfill is often recommended to avoid many issues associated with poor pit lake water quality developing from weathering of PAF material in the pit void and pit walls (Puhalovich and Coghill 2011) (Fig. 3c). If backfill volumes and distributions are small enough to permit accumulation of water above the backfill (Fig. 3d), then this use of the pit void will remove the mine waste from the typically higher rates of weathering and transport encountered when placed above ground. However, the pit backfill volumes and/or placement may also cause pit lake surface area reductions as waste is typically placed in the pit by tipping over the high wall. This change in surface area can thus alter the pit lake hydrological balance by decreasing net evaporation, which can change the pit lake from a terminal sink lake to a through-flow type. If the water quality in the pit lake is poor, this contaminated water may be released into the regional groundwater system.

Empirical Modelling

A water balance model for each of the closure scenarios was modelled using GoldSim software (Goldsim 2011). GoldSim is a Monte Carlo simulation software package for dynamically modelling complex systems. Monte Carlo simulations are a class of computational algorithms that rely on repeated random sampling of those components of the model with inherent uncertainty in their estimation when undertaking the simulations. Monte Carlo methods are especially useful for simulating systems with many coupled degrees of freedom, such as fluids. Pit lake hydrological inflows were defined as direct rainfall, runoff (catchment and pit wall), and groundwater inflow. Outflows were defined as evaporation from the lake surface, groundwater seepage (if any), and overflow (if any).

A GoldSim variation of a multi-state Markov chain model first developed by Srikanthan and McMahon (1985) was used to generate stochastic rainfall data from rainfall data from each mine site, with data gaps amended by correlation with publically available data from the nearest Bureau of Meteorology (BOM) weather station. In basic terms, the model generated a synthetic sequence of daily precipitation based on the probability of rainfall in one 'state' (states are essentially ranges in daily rainfall and are subject to user-defined limitations in terms of both their quantity and internal boundaries) being succeeded (on the following day) by rainfall in the same or another state. These probabilities were collated in a transition probability matrix (TPM). Seasonality was modelled by using 12 separate TPMs, one for each calendar month. The inputs required by GoldSim to generate stochastic data are the TPMs for each calendar month, the number of states and their boundaries, and distribution parameters derived for those days that exceed the adopted upper range of rainfall used to define the monthly TPMs.

The model was calibrated using the daily, monthly, and annual statistics of the observed data (which was the

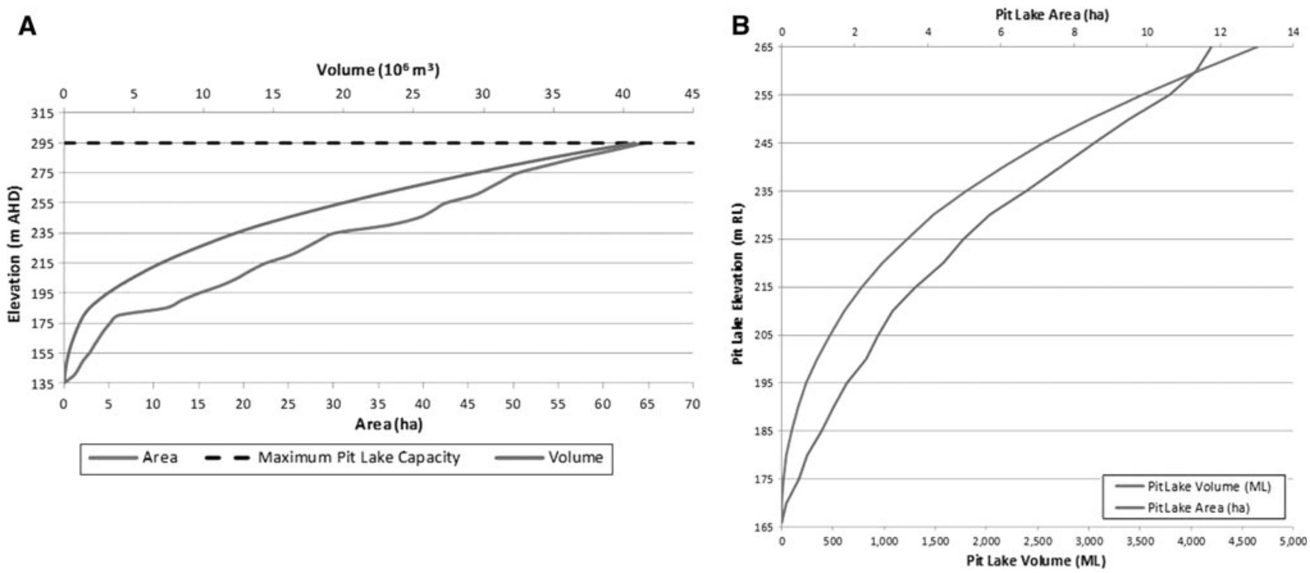


Fig. 4 Elevation-volume-area curve for (**a**) current Nifty Copper Operation and (**b**) current Tallering Peak open pits

primary input). This was achieved by iteratively (and manually) varying the limits of each state as well as the number of states to be considered in certain months. Following the calibration, 100 stochastic rainfall sequences were generated every 200 years in length to simulate the pit closure scenario models.

The volumes of rainfall onto the pit lakes were proportional to their associated surface areas (Fig. 4a, b). As the non-backfilled open pit filled with water, the lake surface increased and therefore, the volume of rainfall entering the lake increased. An elevation-volume-area curve developed for each pit design at closure was used to estimate the area of the pit lake as the water level rises. The curve was modified for the partially backfilled scenario based on the level of backfill, with 100 % of the direct rainfall first filling up the backfill void, based on the assumption that there was no pit outlet and that there was no evaporation during rainfall events. When the water level reached the backfilled elevation, the direct rainfall volume was based on the pit lake area above the backfill. In the case of the backfilled pit scenario, 50 % of the direct rainfall on the pit surface was expected to infiltrate directly into the footprint of the backfilled pit to fill backfill voids (Williams 2012).

Based upon site visits, pit wall rainfall runoff was assumed to mostly collect on mine benches or to evaporate before reaching the pit lake. However, for high rainfall periods, the runoff may then overflow the benches and flow into the pit lake; thus, a greater proportion of the runoff reaches the lake as rainfall increases. Also, if rainfall occurred on the previous day, ponds of water may still be present on the mine benches, coupled with higher antecedent moisture conditions; additional rainfall is therefore likely to overflow into the pit lake. Pit wall runoff coefficients were therefore applied to the rainfall to estimate runoff from the pit walls, based on the following empirical relationship:

$$\text{Runoff}_{\text{Pitwall}} = \text{Rainfall} \times \text{Runoff coefficient}_{\text{Pitwall}} \times (\text{Area}_{\text{Pitwall}} - \text{Area}_{\text{Pitlake}}) \quad (1)$$

The runoff coefficient was varied depending on the amount of rainfall and whether rainfall occurred on the previous day, based on regional site experience (Table 1). As the open pit fills with water, a portion of the pit walls are covered by water and the area of exposed pit wall is reduced, reducing the volume of pit wall runoff. In the partially backfilled scenario, the portion of the pit walls exposed stays constant until the pit lake water level rises above the backfilled level. In the fully backfilled scenario, the pit wall was not exposed and therefore there was no pit wall runoff.

The catchment area around each pit was estimated and it was assumed that up to 60 % of the runoff would occur during high rainfall events during cyclonic activity (BOM 2012) and that no runoff takes place during rainfall events less than 5 mm/day. Catchment runoff coefficients were applied to the rainfall to estimate runoff from catchments adjacent to the pit, based on empirical relationship (2). Runoff coefficients were assumed from calibrated values used in previous project experiences in the region which were within the range given published studies from Western Australia (Williams 2012). The catchment runoff coefficient for Nifty Copper Operation was assumed to vary depending on the amount of rainfall as shown in (Table 1).

Table 1 Tallering Peak pit wall runoff coefficients for pit void walls and catchment (after Williams 2012)

Daily rainfall (mm)	Previous day rainfall (mm)	Walls	Catchment
<5	N/A	0	0
<40	<20	0.30	0.15
<40	>20	0.65	0.40
≥40	N/A	0.65	0.40

Runoff coefficient is the rainfall fraction incident on the surface that does not infiltrate; *N/A* not applicable

$$\text{Runoff}_{\text{catchment}} = \text{Rainfall} \times \text{Runoff coefficient}_{\text{Catchment}} \times \text{Area}_{\text{Catchment}} \quad (2)$$

Nifty Copper Operation groundwater inflows (Q) were estimated using the Dupuit Equation for horizontal flow conditions as the main aquifer through the pit is an unconfined channel aquifer that the lake excises:

$$Q = K\left(\frac{h_1^2 - h_2^2}{L}\right) \quad (3)$$

where K is the average hydraulic conductivity of the rock mass, h_1 is the pre-mining groundwater elevation, h_2 is the pit lake elevation (which increases as the pit fills up with water), and L is the horizontal flow length from pre-mining water level to the pit lake surface (h_1 to h_2) (Fetter 1994).

Tallering Peak Iron Ore groundwater inflows were estimated using the Dupuit-Forchheimer equation for radial flow conditions for an unconfined aquifer:

$$Q = \pi K \frac{h_0^2 - h_w^2}{\ln \frac{R}{r_w}} \quad (4)$$

where K is the average hydraulic conductivity of the rock mass, h_0 is the pre-mining groundwater level, h_w is the pit lake level (which increases as the pit fills up with water), r_w is the pit diameter at the base, and R is the radius of Influence that can be expressed using the Cooper-Jacob equation (Cooper and Jacob 1946) as:

$$R = 1.5\sqrt{\frac{Kbt}{S_y}} \quad (5)$$

where b is the thickness of the aquifer, t is the time since the start of mining operations, and S_y is the specific yield of the aquifer. The equation indicates that groundwater inflows will decrease as the pits fill up with water and the radius of influence increases with time.

A partially backfilled option for the T5 pit was assessed on a proposed volume of backfilled PAF material. Based on the slope of the pit wall (32°), we assumed that the backfilled material would be disposed of in the bottom of the pit and not by end dumping from the edge of the pit.

MGM supplied Golder with the open pit shells for T5 at the end of mining, from which we created the elevation-volume-area relationship (Fig. 4b). Rainfall from the last 30 years was assumed to be representative of the current rainfall conditions on-site and was used to generate a stochastic rainfall distribution. The runoff coefficient for the pit wall was assumed to be 80 % from calibrated values used in previous project experiences in the region. The evaporation data applied in the model were obtained from the SILO Data Drill (http://www.nrm.qld.gov.au/silo). The Data Drill accesses grids of data interpolated from point observations by the Bureau of Meteorology. Interpolations are calculated by splining and kriging techniques. The data in the Data Drill were all estimated as there are no original meteorological station data available in the calculated grid fields. A monthly "Class A" lake to pan coefficient (BOM 2012) was used to estimate evaporation from the pit lake surface (Hoy 1977; Hoy and Stephens 1979).

Evaporation loss was not considered in the fully backfilled pit scenario; however, when the water level exceeded the backfilled elevation in the partially backfilled scenario, evaporation was simulated in the models. A reduction in evaporation rates was assumed as the depth of the lake surface below the adjacent ground level increased to reflect the influence of reduced wind across the lake surface.

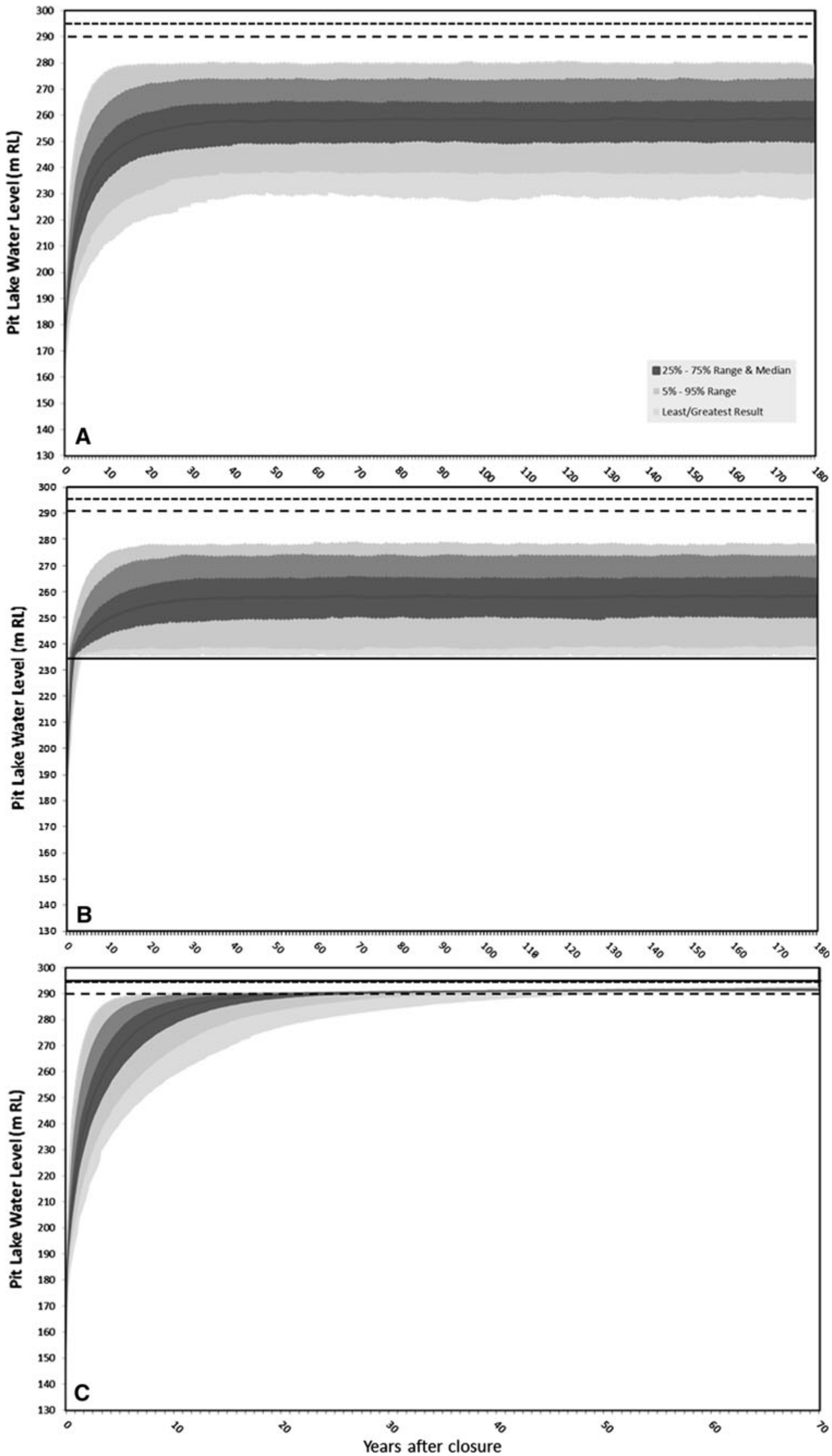
Groundwater seepage from the pit lake into the groundwater system will occur when the water level within the pit reaches a level greater than the surrounding groundwater level. Thus, groundwater seepage was estimated using Eq. (4) for radial flow conditions and an unconfined aquifer when h_w was greater than h_0.

Results

Nifty Copper Operation

The open pit scenario with no backfill was identified by modelling as an evaporative sink (Fig. 5a). Modelling of the partially backfilled scenario showed that the equilibrium pit lake water level would be more than 10 m above the elevation of the backfill, and was identified as a terminal sink due to the equilibrium pit lake water level being lower than the surrounding groundwater level (Fig. 5b). The fully backfilled scenario indicated that the pit would become a through-flow system with water contained in the backfilled pit seeping into the groundwater system (Fig. 5c). If the PAF material already contained in the pit leached chemicals harmful to the environment, this closure option may present a significant risk at mine closure.

Fig. 5 Nifty Copper Operation predicted pit lake levels for: **a** No backfill; **b** Most reactive waste partially backfilled, and: **c** Complete backfill. *Dotted black line* indicates pit lake overflow level, *dashed line* baseline groundwater level, *solid line* backfill level



A partially backfilled option model was developed based on the proposed volume of backfilled material provided by the mining company at the time. The model results indicate that the pit lake water level would stabilise after about 40 years to a median level of 259 m AHD (Australian hydraulic datum level that corresponds approximately to mean sea level). The results also show that there is a 95 % probability that the lake level will not exceed 275 m AHD and a 5 % probability that it will not exceed 239 m AHD. The latter would cover the deposited waste material with 4 m of water. A pit lake level of 275 m AHD is equivalent to 20 m of freeboard and an additional pit lake capacity (e.g. for buffering volume during heavy rain events) of approximately 11.5 million m^3.

The hydrogeological system is expected to remain a sink, with equilibrium groundwater levels below the pre-mining groundwater level of 290 m AHD. Furthermore, pit lake levels are expected to stay below the static groundwater levels of 285 m AHD in the adjacent Nifty Palaeochannel, indicating that there is little risk of pit lake water flowing into the palaeochannel system.

This model showed two main consequences to long-term AMD management at mine closure if the pit was backfilled above the surrounding groundwater level:

1. Reduction in evaporative losses would likely lead to a through-flow scenario. As the proposed material was predominantly PAF, it is therefore likely that water quality would be impacted by AMD as it flows through the pit waste backfill. Due to the through-flow nature of the backfilled pit, the water would then be released to the environment as seepage from the lake to groundwater (Fig. 6), leading to an increased risk of negative effects on local and possibly regional groundwaters, and any dependent ecosystems.
2. Waste landforms without effective cover systems to reduce infiltration may generate and transport AMD if the partially backfilled pit lake did not function as a terminal sink. In this scenario, AMD leachate from waste rock dumps containing PAF would enter the vadose zone (the area of unsaturated ground above the groundwater level), but would not be transported in the local groundwater plume toward the pit lake, since it would not be acting as a terminal sink. Instead the AMD plume would be transported by the regional groundwater system and potential surface water receptors, such as groundwater-dependant ecosystems of seasonal lakes, creeks, and wetlands.

Tallering Peak

In the no-backfill scenario, model results indicated that the open pit would fill gradually and eventually reach equilibrium seven years after closure (Fig. 7a). The equilibrium water level would then be around 231 m RL (project area relative level); lower than the pre-mining groundwater level (estimated at 238 m RL).

The partially backfilled option was based on the proposed volume of backfilled material provided by MGM. In this scenario, the model results indicate that the open pit would gradually fill with water and eventually reach equilibrium five years after closure (Fig. 7b) at around 236 m RL, i.e. below the pre-mining groundwater level. The final pit lake would be above the backfill level, covering the PAF material. Oxidation rates of the PAF material might then be significantly reduced because of the much lower oxygen diffusion rates through water. A final terminal sink would also entrain AMD contaminated waters away from sensitive environmental receptors such as a nearby ephemeral creek that flows into the Greenough River.

In the fully backfilled scenario, the model results indicate that the backfilled material voids would fill with water

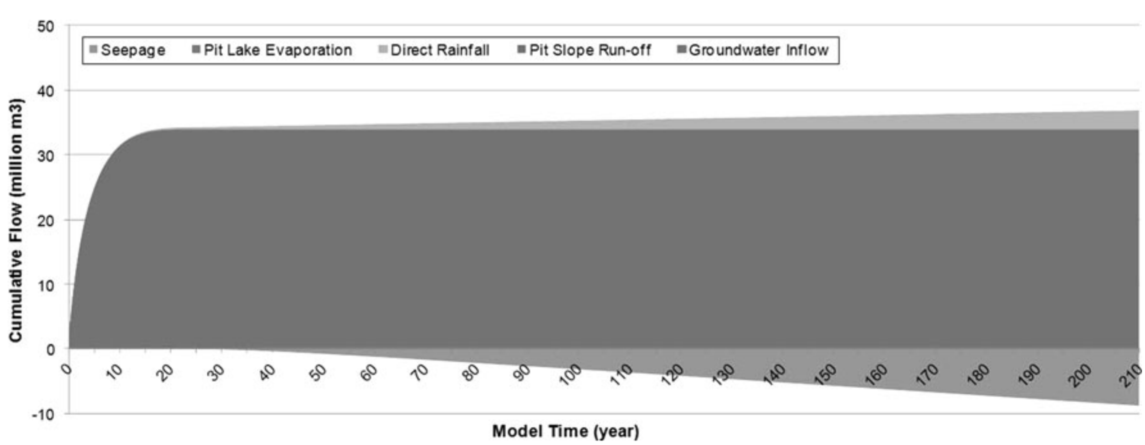


Fig. 6 Predicted cumulative flow for Nifty Copper Operation

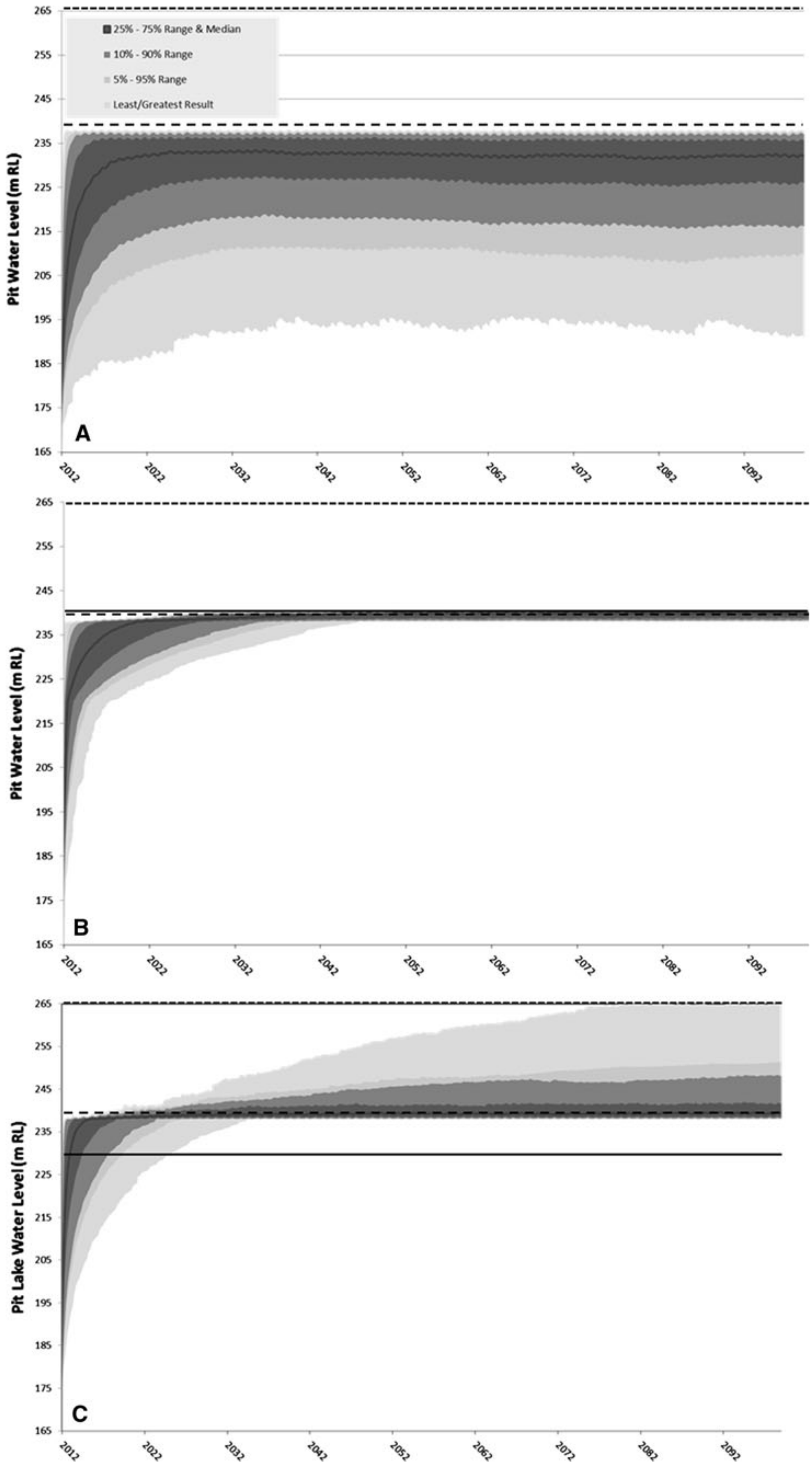


Fig. 7 Tallering Peak T5 predicted pit lake levels for **a** no backfill, **b** most reactive waste partially backfilled and **c** complete backfill. *Dotted black line* indicates pit lake overflow level, *dashed line* baseline groundwater level, *solid line* backfill level

(Fig. 7c). The water level within the backfilled pit would reach equilibrium three years after closure at around 238 m RL, about the same as the groundwater level in the area.

While a terminal sink is unlikely to introduce leachable compounds into the local groundwater system, a through-flow system toward a seasonal creek line in the southwest will most likely affect the groundwater system. Based on our analyses, the open pit with no backfill and the partially backfilled scenarios were identified as likely terminal sinks. In contrast, the fully backfilled scenario was predicted to be a through-flow system and likely to introduce AMD into the groundwater system. Furthermore, there was a 5 % probability that after 35 years, the fully backfilled pit water level would rise high enough to decant to nearby surface waters.

Discussion

Mine closure is increasingly recognised as a whole-landscape development exercise that must take into account all closure landform elements and how they will interact over time (Younger and Wolkersdorfer 2004; McCullough and Van Etten 2011). The catchment provides an ideal scale at which to holistically consider performance and interaction of these closure elements; often, the catchment will be artificially constrained such that the lowest part where water reports in the open pit becomes a pit lake.

Both of these case studies indicate that a partial backfilled pit and the formation of a terminal sink pit lake may pose less environmental risk than a completely backfilled pit where contaminants could be transported by seepage to the groundwater (MCA 1997).

Nevertheless, the water quality of terminal sink lakes is expected to deteriorate over time due to evaporation (Eary 1998), particularly in highly alkaline or acidic lakes (Eary 1999). Since such lakes are essentially abiotic, with little or no attenuation of contaminants occurring, this poor water quality is unlikely to be resolved naturally, even over long time scales (McCullough 2008). Poor water quality in such lakes may pose a threat to local wildlife and migratory waterfowl and will have limited options for post-mining use. Although not desirable in itself, this water quality deterioration indicates that the pit lake is functioning as a terminal sink and protecting the greater undisturbed regional environment off the project footprint from seepage of AMD-contaminated water resulting from exposed pit wall or in-pit disposal of waste rock.

In the long term, increasing solute concentrations in the terminal sink pit lake would increase water density. This concentration change may cause density-driven flow into the surrounding groundwater under certain hydrogeological conditions (Gvirtzman 2006) and should be investigated as part of a complete risk assessment process for development of a definitive phase mine closure plan strategy.

Stability of physical and chemical conditions inside the deposited waste and at its interface with the lake environment is the main prerequisite for successful long term storage of waste in a pit lake (Schultze et al. 2011). As such, climate change should also be a key consideration in the development of pit lakes used as terminal sinks for mine closure. For example, an increasingly wet climate may lead terminal sink pit lakes to become through-flow through seepage or even decant, i.e. overflow. Similarly, even though mean net precipitation may not change, an increase in intense rainfall events such as cyclone frequencies may still lead to similar mobilisation of degraded pit lake waters. Such inappropriate application of an terminal sink conceptual model to sites that fail, even infrequently, to behave as terminal sinks may present risk to downstream water resources (Bredehoft 2005). Consequently, although pit lakes as terminal sinks may greatly reduce risk of off-site water quality problems, conditions such as decanting (through high/seasonal rainfall events or filling to higher level than expected) (Commander et al. 1994), density- driven seepage caused by increased salinity, or the pit lake rising to heights above surrounding groundwater levels during high/seasonal rainfall events, should be explicitly considered as part of the conceptual model driving a closure plan incorporating terminal sinks as key design elements. Further important considerations will be the potential for resource sterilisation through any backfill activity and health and safety considerations for both human and wildlife populations associated with retaining an open pit as a final landform. The latter may require a formal environmental risk assessment of the effects of a terminal pit lake in the closure landscape.

Conclusions

Although often prescriptively proposed as best practice by a number of regulatory and sustainability organisations, fully or partially backfilled pit may sometimes lead to poorer regional closure outcomes than retaining a pit lake of some form, especially in arid and semi-arid regions. This demonstrates the need to consider mine closure planning on a case-by-case basis as well as for closure strategies to be founded on good empirical evidence, with water balance and geochemical modelling results frequently being key considerations. Furthermore, a good knowledge of premining conditions and groundwater system will almost always be mandatory to develop a reliable water balance model and predictive simulations of any pit closure scenarios.

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References

Anderson BR, Gemmell JB, Berry RF (2001) The geology of the Nifty copper deposit, Throssell Group, Western Australia: implications for ore genesis. Econ Geol 96:1535–1565

ANZECC/ARMCANZ, Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (2000) Australian and New Zealand guidelines for fresh and marine water quality. National Water Quality Management Strategy Paper 4, Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra, Australia

ANZMEC/MCA, Minerals Council of Australia (2000) Strategic framework for mine closure. ANZMEC/Minerals Council of Australia, Canberra

BOM, Bureau of Meteorology (2012) Telfer climate averages. http://www.bom.gov.au/climate/averages/tables/cw_009592.shtml. Accessed 18 Oct 2012

Botha PR (2012) The business case for mine closure planning and an overview of anglo American's mine closure toolbox approach. In: Proceedings of life-of-mine conference, Australasian institute of mining and metallurgy, Melbourne, Australia, pp 7–9

Bredehoft J (2005) The conceptualization problem—surprise. Hydrogeol J 13:37–46

Carver RN (2004) Nifty copper deposit, Great Sandy Desert, Western Australia. CRC LEME. http://crcleme.org.au/RegExpOre/Nifty.pdf

Castendyk D (2009) Conceptual models of pit lakes. In: Castendyk D, Eary T (eds) Mine pit lakes: characteristics, predictive modeling, and sustainability. Society for Mining Engineering (SME), Littleton

Commander DP, Mills CH, Waterhouse JD (1994) Salinisation of mined out pits in Western Australia. In: Proceedings of XXIV congress of the International Association of Hydrogeologists, Adelaide, SA, Australia, pp 527–532

Cooper HH, Jacob CE (1946) A generalized graphical method for evaluating formation constants and summarizing well field history. Am Geophys Union Trans 27:526–534

DMP, Dept of Mines and Petroleum (2010) DMP bond policy. Departmeny of Mines and Petroleum (DMP), Perth

DMP/EPA (2011) Guidelines for preparing mine closure plans. Western Australian DMP, Environmental Protection Authority of Western Australia (EPA), Perth

Eary LE (1998) Predicting the effects of evapoconcentration of water quality in pit lakes. Geochem Explor 64:223–236

Eary LE (1999) Geochemical and equilibrium trends in mine pit lakes. Appl Geochem 14:963–987

Fetter CW (1994) Applied hydrogeology, 3rd edn. University of Wisconsin, Oshkosh

Gammons CH, Harris LN, Castro JM, Cott PA, Hanna BW (2009) Creating lakes from open pit mines: processes and considerations, with emphasis on northern environments. Canadian Technical Report of Fisheries and Aquatic Sciences 2826, Ottawa, Canada

Goldsim (2011) GoldSim. GoldSim Technology Group, Washington DC, USA

Gvirtzman H (2006) Groundwater hydrology and paleohydrology at the Dead Sea rift valley. In: Enzel Y, Agnon A, Stein M (eds) New frontiers in Dead Sea paleoenvironmental research. GSA Book, Washington, DC, pp 95–111

Hilson G, Haselip J (2004) The environmental and socioeconomic performance of multinational mining companies in the developing world economy. Min Energ 19:25–47

Hinwood A, Heyworth J, Tanner H, McCullough CD (2012) Recreational use of acidic pit lakes—human health considerations for post closure planning. J Water Resour Protect 4:1061–1070

Hoy RD (1977) Pan and lake evaporation in northern Australia. In: Proceedings of hydrology symposium. Institute of Engineers, Brisbane, Australia, pp 57–61

Hoy RD, Stephens SK (1979) Field study of lake evaporation–analysis of data from phase 2 storages and a summary of phase 1 and phase 2. Technical Paper 41, Australian Water Resources Council, Canberra, Australia

Huston DL, Maas R, Czarnota K (2005) The age and genesis of the Nifty copper deposit: back to the future. Geoscience Australia, Canberra

ICMM, International Council on Mining and Metals (2008) Planning for integrated mine closure: toolkit. International Council on Mining and Metals, London, UK

Johnson SL, Wright AH (2003) Mine void water resource issues in Western Australia. Hydrogeological record series. Report HG 9, Water and Rivers Commission, Perth, Australia

Jones H, McCullough CD (2011) Regulator guidance and legislation relevant to pit lakes. In: McCullough CD (ed) Mine pit lakes: closure and management. Australian Centre for Geomechanics, Perth, pp 137–152

Kuipers JR (2002) Water treatment as a mitigation. Southwest Hydrol 1:18–19

Kumar NR, McCullough CD, Lund MA, Newport M (2011) Sourcing organic materials for pit lake remediation in remote mining regions. Mine Water Environ 30:296–301

Kumar RN, McCullough CD, Lund MA (2012) Pit lakes in Australia. In: Geller W, Schultze M, Kleinmann RLP, Wolkersdorfer C (eds) Acidic pit lakes—legacies of surface mining on coal and metal ores. Springer, Berlin, pp 342–361

MCA (1997) Minesite water management handbook. Minerals Council of Australia, Canberra

McCullough CD (2008) Approaches to remediation of acid mine drainage water in pit lakes. Int J Min Reclam Environ 22:105–119

McCullough CD, Lund MA (2006) Opportunities for sustainable mining pit lakes in Australia. Mine Water Environ 25:220–226

McCullough CD, Van Etten EJB (2011) Ecological restoration of novel lake districts: new approaches for new landscapes. Mine Water Environ 30:312–319

McCullough CD, Hunt D, Evans LH (2009) Sustainable development of open pit mines: creating beneficial end uses for pit lakes. In: Castendyk D, Eary T (eds) Mine pit lakes: characteristics, predictive modeling, and sustainability. SME, Littleton, pp 249–268

Miller GE, Lyons WB, Davis A (1996) Understanding the water quality of pit lakes. Environ Sci Technol 30:118A–123A

Niccoli WL (2009) Hydrologic characteristics and classifications of pit lakes. In: Castendyk D, Eary T (eds) Mine pit lakes: characteristics, predictive modeling, and sustainability. SME, Littleton, pp 33–43

Puhalovich AA, Coghill M (2011) Management of mine wastes using pit/underground void backfilling methods: current issues and approaches. In: McCullough CD (ed) Mine pit lakes: closure and management. Australian Centre for Geomechanics, Perth, pp 3–14

Schultze M, Boehrer B, Friese K, Koschorreck M, Stasik S, Wendt-Potthoff K (2011) Disposal of waste materials at the bottom of pit lakes. In: Fourie AB, Tibbett M, Beersing A (eds) In: Proceedings of 6th international conference on mine closure, Lake Louise, Canada, Australian Centre for Geomechanics, Perth, pp 555–564

Srikanthan R, McMahon TA (1985) Stochastic generation of rainfall and evaporation data. Technical Paper 84 Australian Water Resources Council, Canberra, Australia

Vandenberg J (2011) Use of water quality models for design and evaluation of pit lakes. In: McCullough CD (ed) Mine pit lakes: closure and management. Australian Centre for Geomechanics, Perth, pp 63–80

Williams DJ (2012) Some mining applications of unsaturated soil mechanics. Geotech Eng J SEAGS AGSSEA 43:83–98

Younger PL (2002) Mine waste or mine voids: which is the most important long-term source of polluted mine drainage? United Nations Environment Programme, Mineral Resources Forum: current feature paper

Younger PL, Wolkersdorfer C (2004) Mining impacts on the fresh water environment: technical and managerial guidelines for catchment scale management. Mine Water Environ 23:S2–S80