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## Pit lakes as evaporative 'terminal' sinks: an approach to best available practice mine closure

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### Abstract

Pit lakes may form when open cut mining operations extend below groundwater level and then fill at cessation of mining and associated dewatering operations by ground and surface water influx. Pit lake hydrogeology may function as an evaporative "sink" when pit lake water evaporation rates exceed influx rates. Although not ideal closure, management of local surface and groundwaters contaminated by Acid and Metalliferous Drainage (AMD) through entrainment toward an evaporative terminal pit lake may provide a best-case scenario for protection of regional water resources required by typical mine closure time scales of hundreds to thousands of years.

We present two case studies from Western Australia; the first where closure of above ground landforms such as waste dumps by covers would arguably not be successful over long terms (1,000 years or more) and another where Potentially Acid Forming waste (PAF) management is limited by current waste rock dump location and suitable cover materials.

Pit lake water balance modelling indicates both case study pit lakes will function as hydraulic sinks if they are not backfilled above their equilibrium water levels. A best closure outcome for these pit lakes may be to be backfilled with PAF encapsulated with alkaline/neutral waste and then filled as rapidly as possible to minimise PAF oxidation and ensure an evaporative sink pit lake is formed.

**Keywords:** backfill, groundwater sink, closure, pit lake, AMD, through-flow, evaporative sink

### Introduction

Due to operational and regulatory practicalities, pit lakes will continue to be common legacies of mine lease relinquishments. Pit lake water quality is often degraded by Acid and Metalliferous Drainage (AMD) which may lead to acidic water with elevated metal concentrations (McCullough 2008). Degraded water quality reduces pit lake environmental values and may present risks to surrounding communities and environmental values (McCullough and Lund 2006). Mine closure guidelines and standards increasingly require chemical safety and low risk to surrounding ecosystems for long-terms for closure practices to be acceptable (ANZMEC/MCA 2000; ICMM 2008; DMP/EPA 2011).

Unplanned or inappropriate management of these novel geographical features 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 (Doupé and Lymbery 2005).

Nevertheless, most developed jurisdictions are consistent in their requirement for mining companies to plan and/or rehabilitate to minimise or prevent entirely any potential deleterious effects of the pit lake water body on regional ground and surface resources (Jones and McCullough 2011). The focus of most general or *ad hoc* pit lake regulation is given to protecting human and ecological communities from effects of the pit lake. For example, in Australasia, closure guidelines are based on ANZECC/ARMCANZ (2000) criteria; generally for ecosystem protection requirements. 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). AMD treatment may be very costly and difficult to achieve in many remote mining regions. 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).

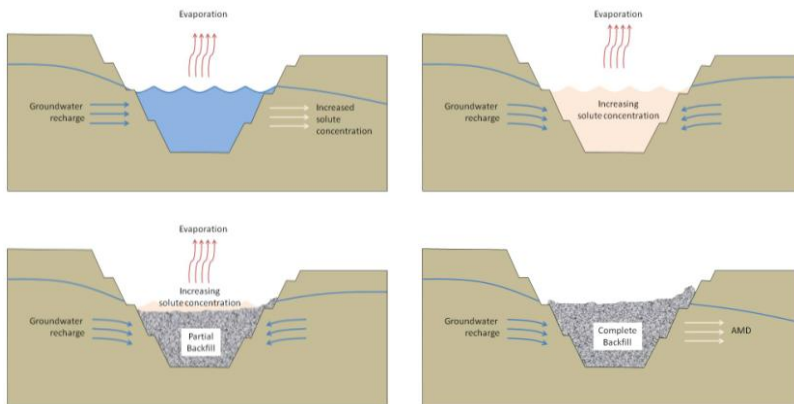
### **Pit lake water balance in an arid climate**

Climate is the single most important factor on the hydrologic processes associated with a pit lake (Castendyk 2009). Changes in climate (e.g. temperature, rainfall, wind, precipitation amount and distribution) will affect the individual hydrologic components differently. In general, surface hydrologic processes (e.g. direct precipitation, evaporation, surface water runoff) are defined by regional climate. 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 over the long-term. Modelling of 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” lakes or “evaporative sinks” (Niccoli 2009). Evaporative sinks may occur in arid climates where the evaporation potential is higher than average rainfall runoff. During groundwater cone-of-depression rebound and pit void filling, the pit lake water level rises to a level where inflows (rainfall, 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 is not released to the environment (Figure 1). The water quality of evaporative sink lakes is expected to show increases in acidity, metals and salt concentrations over time through accumulation of solutes introduced through groundwater inflows, surface catchment run-off and direct rainfall to the developing lake’s surface.

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 lake walls (Puhlovich and Coghill 2011). If backfill volumes and distributions are small enough to permit accumulation of water above the backfill, then this use of the pit void as a waste rock or otherwise dump will remove these waste materials

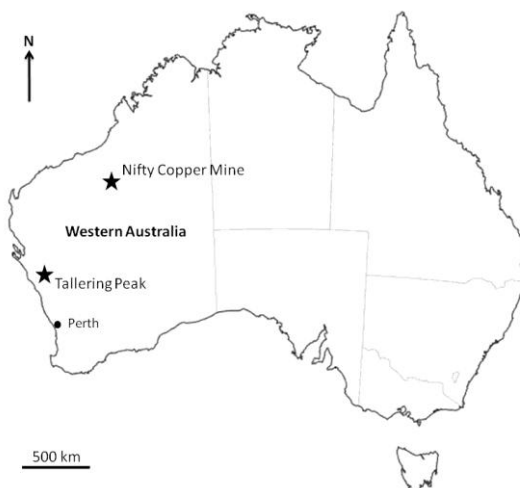
from the typically higher rates of weathering and transport encountered when placed above ground. However, the pit backfill volumes and/or placement will cause pit lake surface area reductions and alter the pit lake hydrological balance. Decreased net evaporation may then lead to the pit lake changing from an evaporative 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 environment through seepage into the regional groundwater system.



**Figure 1** Generalised potential hydrogeological regimes for pit lakes in an arid region.

## Case studies

Although there are many examples for 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 will be relevant to many other arid/semi-arid parts of the mining world e.g., south-west US, South Africa, etc. (Figure 2). Both operations are currently working towards development of detailed mine closure plans but face difficulties with Potentially Acid Forming waste (PAF) management in above ground waste landforms where armouring and waterproof waste cover materials are lacking in their regional environments which instead primarily consist of highly dispersive clays and sand. Geochemical testing indicates both pit lakes are likely to develop AMD affected water quality over time.



**Figure 2** Location of case studies in arid Western Australia.

Both operations' pits are expected to fill with water naturally when pit dewatering ceases at closure due to the accumulation of groundwater inflow and rainfall, however, the equilibrium lake elevations depend on the hydrogeology setting and the long-term climatic characteristics in the region. Total inflows into the pit lakes are expected to gradually decrease as the open pits fill while total outflows are expected to increase due to increased evaporation from an increasing lake area. At some stage, total inflows would approximate total outflows and the water level in each open pit will reach equilibrium, albeit responding dynamically to changes seasonal precipitation and evaporation rates. Water level fluctuations are expected as a result of occasional cyclones.

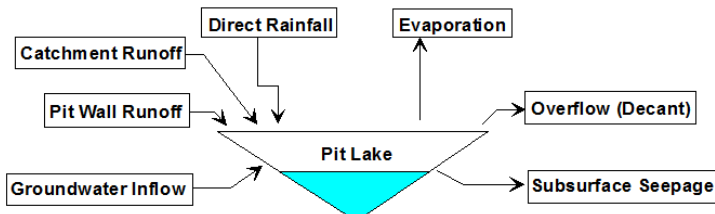
If the steady-state pit lake elevation remained lower than the surrounding groundwater surface, the pit lakes will remain an evaporative sink within the confines of the open pit with no water release into the environment through groundwater decant. However if the final pit lake elevations reach the surrounding groundwater level, the pit lakes would turn into a through-flow system with water release to the environment through groundwater seepage which could then spread potential contaminant plumes to environmental receptors.

### *Modelling*

A water balance model for each of the closure scenarios was then modelled using the GoldSim Monte Carlo simulation software package. Golder assessed three post-closure scenarios for both of the case-study open pits: pit not backfilled and a pit lake forming, pit partially backfilled to below pre-mining groundwater levels with consequently shallower pit lake forming; and, pit backfilled to above water table, no pit lake forming.

Pit lake hydrological inflows were defined as direct rainfall, groundwater inflow and run-off (catchment and pit walls). Outflows were defined as evaporation from

lake surface, groundwater seepage (if any), and overflow (if any) and climate change predictions were accounted for (**Figure 3**).



**Figure 3** Conceptual pit lake process flow diagram.

#### *Nifty Copper Operation, Aditya Birla*

Nifty is located in the Pilbara region of Western Australia approximately 1,200 km nor-north-east of Perth (Figure 2). The Pilbara experiences an arid climate with two distinct rainfall patterns. In summer, rainfall occurs from either tropical cyclones or thunderstorms, while the winter rainfall is typically from low pressure trough systems. Average annual rainfall is low and varies in the region from 200 mm to 420 mm (Kumar et al. 2011; Kumar et al. 2012).

The open pit scenario with no backfill was identified as an evaporative sinks. The partially backfilled scenario shows that the equilibrium water level would be more than 10 m higher than the elevation of the backfill material which would then be submerged at pit lake water level equilibrium. The partially backfilled scenarios was identified as developing an evaporative sink. The fully backfilled scenario indicated that the pit would become a through-flow system with water contained in the pit will seep into the groundwater system. If the PAF material already contained in the pit leached chemicals harmful to the environment, this closure option may be present a significant risk at mine closure.

A partially backfilled option was based on the proposed volume of backfilled material provided by the mining company at the time which would reach an expected elevation. This model showed two main consequences to site AMD management at mine closure if the pit was backfilled above equilibrium groundwater level:

1. Reduction in evaporative losses from the absence of pit lake forming would likely lead to a through-flow scenario where groundwater quality would likely be strongly influenced by the geochemistry of pit backfilled material. As the proposed material was predominantly containing 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 through groundwater seepage, leading to increased risk of negative effects on local and possibly regional groundwaters.
2. If waste landforms are not provided with an effective cover system to reduce infiltration and if the pit lake did not form due to groundwater levels after cone rebound remaining below final pit void backfill surface levels, then this may

also affect the transport of contaminants arising from other above-ground waste landforms. In this scenario, AMD leachate from waste rock dumps containing PAF would enter the vadose zone (area of unsaturated ground above the water table) but would not be transported in the local groundwater plume toward the groundwater sink lake. Instead the AMD plume would be transported by the regional groundwater system and potentially surface water receptors such as groundwater dependant ecosystems of seasonal lakes, creeks and wetlands.

### *Tallering Peak Iron Ore Mine, Mount Gibson Mining*

Tallering Peak iron ore mine is located in the semi-arid Midwest mining region of Western Australia (Kumar et al. 2012), approximately 300 km north of Perth. The Tallering Peak Operation commenced production in 2004 and is predicted to continue operations until 2013.

A partially backfilled option for the T5 pit was based on a proposed volume of backfilled PAF material and assumed the backfill material would be placed in the bottom of the pit and not end dumping from the edge of the pit. After closure, the partially backfilled mine void is expected to fill mostly through groundwater inflows. The final pit lake would be above the backfill, 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 evaporative sink would also entrain AMD contaminated waters away from sensitive environmental receptors such as a nearby ephemeral creek which flows into the Greenough River.

Based on the results of the above analyses, the open pit with no backfill and the partially backfilled scenarios were identified as likely evaporative sinks. The fully backfilled scenario was predicted to be a through-flow system and would therefore be likely to introduce AMD into the groundwater system. While an evaporative sink is unlikely to introduce leachable compounds into local groundwater system, a through-flow system from up-gradient to down-gradient toward a seasonal creek line in the south-west is probably. Furthermore, there was only 5% chance after 35 years that the fully backfilled pit water level would rise high enough to decant to nearby surface waters.

## **Conclusions**

Mine closure is increasingly recognised as a whole-landscape development exercise which must take into account all closure landform elements and how they will interact over time (McCullough and Van Etten 2011). Both of these case studies present strong arguments that completely backfilled pit may not be the best solution to risks presented by pit lakes at mine closure, when long-term effects of climate and above ground closure landforms risks are also considered.

The water quality of evaporative sink lakes is expected to deteriorate over time through evaporation and the consequent entrapment of solutes. Although not desirable in itself, this water quality deterioration indicates that the pit lake is functioning as it should as an evaporative 'terminal' sink and protecting the surrounding environment from AMD (acid and metalliferous drainage) contaminated waters resulting from waste rock dumps.

In the long term, increasing solute concentrations in the evaporative sink pit lake may result in increasing water density. This concentration change may cause density-driven flow into the surrounding groundwater under certain hydrogeological conditions and should be investigated as part of the risk assessment process for this closure 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 be a key consideration in the use of pit lakes 'sacrificially' as evaporative sinks. For example, an increasingly wet climate may lead evaporative sink pit lakes to become through-flow or decant to the environment through other means such as over flow. Similarly, even though mean net precipitation may not change or even decrease in a predicted drying climate, an increase in intense rainfall events such as cyclone frequencies may lead to mobilisation of degraded pit lake waters to the surrounding regional groundwaters following such events.

In conclusion, although proposed as best practice by a number of regulatory and sustainability organisations, fully or partially backfilled pit may sometimes potentially lead to poorer closure outcomes than retaining a pit lake. This example demonstrates both the need for mine closure planning to be considered site-specific and on a case-by-case basis as well as for closure strategies to be founded on good empirical evidence of which water balance and geochemical modelling will be key considerations.

## Acknowledgements

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