Riverine Flow-Through of Mine Pit Lakes: Improving both Mine Pit Lake and River Water Quality Values?

Clint McCullough[1] and Martin Schultze[2]

1. *Golder Associates/Mine Water and Environment Research Centre (MiWER), Edith Cowan University, Australia*
2. *UFZ Helmholtz Centre for Environmental Research, Department of Lake Research, Germany*

ABSTRACT

Coal mine pit lakes may form at mine closure when voids formed through mining extractions have extended below groundwater. Internationally, acid and metalliferous drainage (AMD) is a common problem for coal pit lake water quality. Even if not acidic, pit lake water quality may become degraded gradually through dissolution of contaminants and evapoconcentration.

Contaminated coal pit lake waters can present significant risk to both surrounding and regional communities and natural environments. Pit lake waters may discharge into surface and groundwater; or directly present risks to wildlife, stock and human end users.

Riverine flow-through is increasingly being proposed to mitigate pit lake water contamination. This paper presents the motivation for, and key processes and considerations regarding a flow-through final lake hydrology. International case studies as precedent and lessons for future application are also described from a review of literature describing pit lakes that use or propose surface water inflows and discharge as key components of their closure and pit lake management designs.

Chemical and biological processes such as dilution, absorption and flocculation and sedimentation reduce solute loads from river and lake. We conclude that riverine lake flow-through may often be a valid mine closure strategy for pit lakes with poor water quality. Although, we caution that maintenance of existing riverine system values must be maintained first and foremost, we further suggest that decant river water quality may, in some circumstances, be improved; notably in examples of meso-eutrophic river waters flowing through slightly acidic pit lakes.

Flow-through closure proposals for coal pit lakes must be scientifically justifiable and follow a risk assessment approach. Due to the high-uncertainty, biotic and physico-chemical attributes of both upper and lower river and lake should be well monitored. Monitoring should directly feed into an adaptive management framework approved by key stakeholders.

Keywords: pit lake, mine closure, flow-through, AMD, salinity

INTRODUCTION

Due to operational and regulatory practicalities, coal pit lakes will continue to be common legacies of many mine lease relinquishments. Weathering of potentially acid forming (PAF) 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 rivers and pit lakes (Younger, 2002). AMD-degraded water quality in pit lakes may reduce regional environmental values and may present practically perpetual risks to surrounding communities and environmental values (McCullough & Lund, 2006; Hinwood *et al*., 2012). As a result, mine closure guidelines and regulations increasingly require low risk long-term to surrounding ecological and social environments for closure practices to be acceptable (McCullough *et al*., 2009a). Many currently operating or planned mines do not have available options for AMD avoidance (e.g. Wisotzky (2013) in place for a variety of historical and contemporary socio-economic and regulatory reasons (Hilson & Haselip, 2004).

Increasingly, beneficial end uses are also required for pit lakes either through regulatory requirements, or through other stakeholder aspirations such as communities, or interest or non-governmental organisations (NGOs) (Swanson, 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 & Lund, 2006). Such management may be very costly and difficult to achieve in remote mining regions (Kumar *et al*., 2011).

The hydrological setting of lakes is well known as a key factor for water quality (Straskraba, 1999; Kratz *et al*., 2006). Furthermore, lakes are usually storage elements in river networks, reactors transforming many of water constituents and sinks for particles and dissolved water constituents, but may act temporarily also as source. Accordingly, design and management of the connection of pit lakes to river systems and to the groundwater have been applied as management approach for controlling water quality both in pit lakes and in rivers e.g., (Schultze *et al.* (2011)).

This review presents the findings of a search for literature describing coal pit lakes that used surface water inflows and discharge as key components of their closure and pit lake management designs. The experiences documented in the found literature are summarised, evaluated and generalised.

PIT LAKE HYDROLOGY

The pit lake equilibrium water balance and final depth is defined by the net effect of all its hydrologic components. For example, groundwater intrusion and seepage, catchment and direct surface water inputs and evaporative losses (McCullough *et al.*, 2013b). This net effect will determine whether the final pit lake water balance is terminal as an evaporative sink (Figure 1a), source (surcharged) (Figure 1b) and perched above local groundwater levels or flow-through (Figure 1c,d) and directly to ground and surface waters. Terminal hydrology is most common for pit lakes in net negative rainfall areas due to their constrained catchment size relative to natural lakes (Niccoli, 2009) and surcharge or flow-through for lakes in net positive areas. However, in climates of marked rainfall seasonality, pit lakes may even demonstrate a combination of terminal and flow-through system depending on season.

Flow-through pit lakes distinctly show discharge of water to the greater catchment. These pit lakes have a relatively net nil water balance where water entering them exits as either a through-flow groundwater (Figure 1c) hydrogeology (may or may not be expressed as surface water down-gradient) or a flow-through surface water hydrology (Figure 1d).

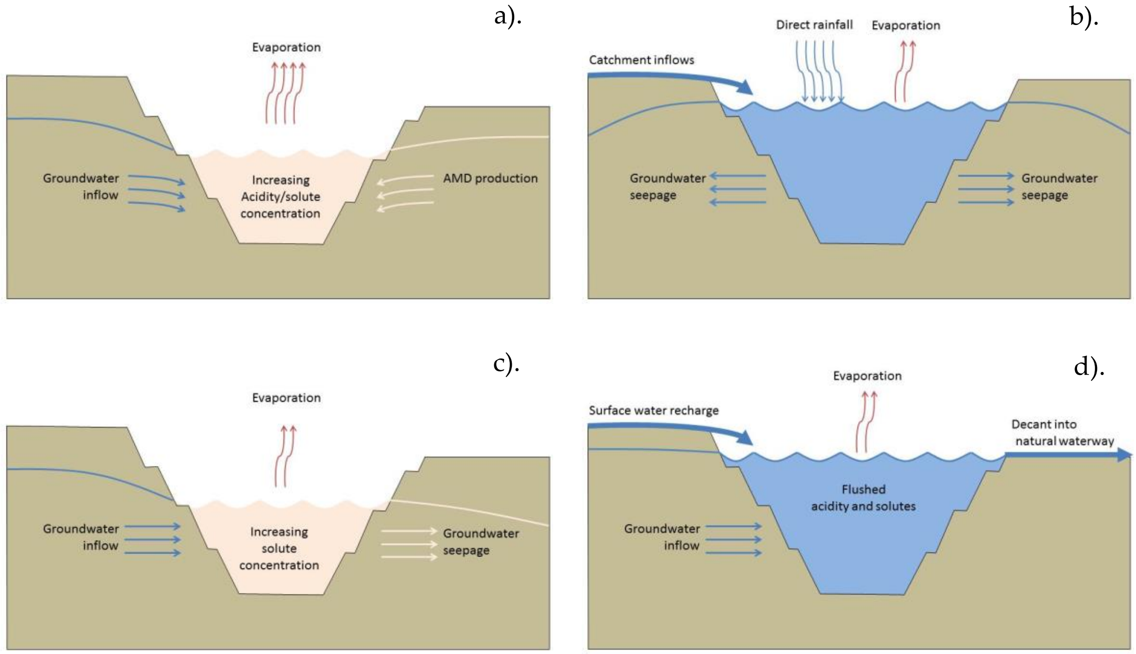

Figure 1: Conceptual equilibrium hydrogeological regimes for pit lakes. a) evaporative terminal sink, b) surcharged lake, c) groundwater through-flow system, d) surface water flow-through system

ENGINEERED PIT LAKE FLOW-THROUGH

There are a number of reasons for engineering a permanent diversion of river or other surface water into a pit lake, mostly related to maintaining or improving pit lake water quality:

a) because a surface drainage system was originally diverted around the pit void location and it is desirable that the system is diverted back into its 'natural' channel for mine closure for cultural or similar motivations;

b) the pit lake is proposed as a water reservoir, or for retaining and buffering high flows as flood protection for downstream;

c) higher quality (e.g., less acidic, lower salinity) river water is required to maintain a minimum pit lake water level or minimum water quality, or, conversely;

d) the pit lake is proposed as a treatment facility to improve water quality of the river.

Surface water flow-through processes

Pit lake water balance largely determines whether lake water quality reach equilibrium or continues to evolve over time. A pit lake water balance with evaporation as the primary water loss function will typically lead to increases in solute concentrations compared to a flow-through system where incoming water can continue to replenish and dilute and solute concentration effects that are occurring/have occurred in previous dryer seasons (Niccoli, 2009).

For lakes affected by AMD, lake acidification can continue after initial rapid filling and neutralisation of acidity by alkaline waters e.g., from a river diversion. The major sources of both acidity and alkalinity are surface and, groundwater inflows, biogeochemical alkalinity generation inside the pit lake including its sediment and elution of side walls and shore material and final pH will reflect the net result of all geochemical contributions (Müller *et al*., 2011).

Solute and acidity concentrations are usually higher in pit lakes containing AMD (Banks *et al.*, 1997) than in river waters (Meybeck, 2005). Consequently, flow-through by river water typically will result in dilution (likely to be insignificant for acidity, but potentially significant for salinity) and acidity neutralisation (which may be significant).

The reaction of river water bicarbonate with pit lake acidity is the most important chemical reaction removing lake acidification. It is accompanied by the precipitation of dissolved iron and aluminium as the main contributors to acidity. The success of metal removal may be limited since some metals require pH above 8 for removal (e.g., manganese, zinc). However, co-precipitation with iron and aluminium are also important mechanisms of the removal of substances from the lake water during neutralisation and in particular phosphorus and trace metals (Lee *et al.*, 2002; Kopacek *et al.*, 2005).

Acid pit lakes with high phosphorus loadings show increased algal biomass which may then lead to improvements in water quality through phytoremediation (Fyson *et al.*, 2006) and sulfate reduction of decaying organic algal cells (Wendt-Potthoff *et al*., 2012). However, Totsche *et al.* (2006) demonstrated that artificial eutrophication, through stimulation of primary production, is limited by phosphorus fixation to iron minerals in the lake sediment. Although Schultze *et al.* (2011) considered the contribution of rapid river filling to phytoremediation to be small, in the case of ongoing lake flushing with river water, the contribution of primary production may become a much more important alkalinity-generating process over longer time scales.

In conclusion, flow-through pit lakes systems can contribute a number of important processes to improve and maintain pit lakes water quality over long-term scales (Table 1).

Table 1: Benefits and risks of flow-through pit lake closure strategy for pit lakes

Pit lake advantages	Limitations / Risks
Dilution of elevated solute concentrations in lake waters e.g., salinity, contaminants	Incoming flows may contribute solutes to the pit lake
Neutralisation of lake acidity by river water alkalinity	
Chelation and sorption of lake metals by river nutrients such as C and P (Fyson *et al.*, 2006; Neil *et al*., 2009)	River water may introduce contaminants such as nutrients, organic pollutants and/or toxic metals (Klemm *et al.*, 2005)
Import of aquatic organisms through inflowing waters accelerating pit lake colonisation and establishment of a representative aquatic biotic community (Peterka *et al.*, 2011)	Aquatic communities may be riverine species and not representative of proposed lake ecosystems. Pest species may be established in pit lakes due to connectivity (Stich *et al.*, 2009; Kosík *et al.*, 2011)

River water can contribute much needed organic carbon and phosphorus to foodwebs of new pit lakes and especially for acid pit lakes (McCullough *et al.*, 2009b)	Lakes may become eutrophic following excess nutrient imports through river water (Hupfer *et al.*, 1998)
Acidity generation by interaction between lake water and lake sediment may be limited due to a fast accumulation of benthic sediment (Dessouki *et al.*, 2005)	Nutrients may be buried under inorganic sediments or in a monimolimnion and become unavailable (von Sperling & Grandchamp, 2008; McNaughton & Lee, 2010)
Provides nutrients stimulating primary production as an approach for pit lake neutralisation (Tittel & Kamjunke, 2004)	Only likely to be important over longer terms due to phosphorus fixation to iron and aluminium in water column and lake sediments (Kleeberg & Grüneberg, 2005; Kopacek *et al.*, 2005)
Inflows may provide a source of organic material which contributes organic carbon as a substrate for sulphate reduction in the lakes' sediment (Salmon *et al.*, 2008)	Only likely to be important over longer terms as sulfate reduction is a relatively weak alkalinity-generating process (Wendt-Potthoff *et al.*, 2012)
Meromixis may be stabilized (Boehrer & Schultze, 2006) allowing for save burial of hazardous mine waste and treatment of AMD (Pelletier *et al.*, 2009)	Meromixis may result in enrichment of hazardous substances (metals, H_2S, CO_2, methane) in the monimolimnion affecting the entire lake water body in the case of limnic eruption or other reasons for long-term instability of chemical stratification (Sanchez-España *et al.*, 2014)

Since diversion of river water is a substantial impact for the river, respective aspects have to be considered. Beside legal, economic and social aspects (e.g. existing rights for water use) there are also ecological advantages and risks as shown in Table 2.

Table 2: Benefits and risks of flow-through pit lake closure strategy to rivers

Advantages to rivers	Limitations/risks to rivers
Decreased suspended and dissolved contaminant loads, especially nutrients (McCullough *et al.*, 2013a)	Decreased pH and alkalinity. Increased solute contaminants such as heavy metals, ammoniacal nitrogen (McCullough *et al.*, 2012)
Extends riverine aquatic habitat	May form physical or chemical migration barrier to movements of aquatic life
Reduced flood incidence and extended base flow duration	Altered hydrological regime reducing flood peaks required for biology and for scouring and shaping river channels
	Reduced overall river flow volume as a result of greater seepage and evaporation

Although water quality in a river may benefit from diversion through pit lakes (Table 2), there may also be substantial risks for the river. They should be avoided by adequate management. Typically, impacts resulting from acidification of pit lakes will not affect the downstream river if flow-through is established following acidic pit lake water neutralisation and the precipitation/co-precipitation of metals. The amount of water diverted from a river into a pit lake can often be best managed by limiting diverted flow to the pit lake. This will depend on the hydrological situation in the river and should be directed to maintaining hydrological patterns downstream as necessary for sustaining river end uses. The barrier function of a pit lake for migrating organisms can be mitigated by connecting the pit lake via bypasses to the river. This strategy may therefore allow for relatively simple management of flow-through, and, in this way, for balancing positive and negative effects of the flow through approach.

Lowest risk for downstream rivers will be presented when the river is already degraded. For instance, we do not recommend flow-through as leading practice for pit lake closures with high downstream river water quality and end uses. The strategy has worked particularly well in the Lake Kepwari pit lake situation (see EXAMPLES,) as the river channel was able to be maintained in its historical course and river water quality was already degraded (McCullough *et al.*, 2012; McCullough *et al.*, 2013a). This reduced risk of AMD on downstream river values. Similarly, the monitoring period has validated the closure approach.

Poor water quality could affect both the ecological communities that might come into contact with the surface water of the pit lake and the down-gradient groundwater system at flow-through pit lakes (McCullough *et al.*, 2013b). River flow timing such as hydroperiod of when water flow is elevated (or even available in seasonal/ephemeral rivers) may also be important for triggering biological responses such as fish spawning events.

Effects of climate change on flow-through hydrology

Climate is the single most important factor on the hydrologic processes associated with a pit lake (Niccoli, 2009). Changes in climate (e.g., temperature, rainfall, wind, precipitation amount and distribution) will affect the individual hydrologic components over a short period of time whilst ground water inflow responses are generally and ultimately generated from precipitation recharge. Pit lakes with significant interaction with a groundwater system will tend to be buffered against short-term climatic changes, however, long-term climatic changes will still be reflected in ground water inflows over the long-term.

The water balance may be affected so grossly in a dryer climate that reduced pit lake water levels lead to cessation of flow through and lakes then become terminal sinks. In comparison, a wetter climate will most likely result in elevated pit lake water levels leading previously terminal pit lakes to become flow-through to either ground or surface waters. However, it is difficult to make broad statements about how climate changes will affect the status of a pit lake (i.e., if it will change from a flow-through to a terminal pit lake or vice-versa) because climate changes will affect all the components of the hydrologic system. Because of this, the effect on water balance for each pit lake resulting from climate change must be evaluated on a case-by-case basis.

EXAMPLES

There are examples for beneficial application of pit-lake flow-through strategy in different countries. Lake Senftenberg (Germany) was neutralised and kept neutral (Werner *et al.*, 2001). Flushing of pit lakes will be the future strategy for many German pit lakes (Luckner *et al.*, 2013). To reach this goal, the connection of naturally separated river basins is already in practice and is discussed to be extended in Germany in future (Koch *et al.*, 2009). The Muldereservoir, a pit lake in Germany, traps considerable amounts of toxic trace elements (ranging from 16% for zinc to 90% for cadmium) from Elbe River and its tributaries into the North Sea (Zerling *et al.*, 2001; Klemm *et al.*, 2005). Moser and Weisser (2011) reported the successful neutralisation of a pit lake in Austria by diversion of river water. Lake Kepwari and Collie River (Western Australia) form a further example for the successful application of the flow-through strategy (McCullough *et al.*, 2012; McCullough *et al.*, 2013a).

CONCLUSIONS

Flushing with river water has proved to be a very useful strategy for management of some pit lakes internationally. A fundamental prerequisite for the use of river water and mine water for filling and management of pit lakes is the water availability. Water scarcity may be a limiting factor for flow-through solutions to pit lakes that currently function as terminal lakes due to regional water availability. That is, the applicability of filling and flushing of pit lakes with river water and mine water strongly depends on the climate and the intensity of the use of water downstream the pit lakes. In the case of limited water availability, floods may be the only options for the filling of pit lakes under such arid conditions and this method may be evaluated similar to the practices in Germany. However, the ecological needs of the river system downstream the pit lakes have to be kept in mind, including the flow magnitude and variability of the flow rate under such conditions.

The water quality of the used river water also has to suit the requirements of the planned use of the pit lakes. Otherwise, treatment of the river water, the mine water or the pit lake may be necessary. Of more importance, priority should be given to river water quality and end uses and the maintenance, or improvement, of existing water values (McCullough & Pearce, 2014). River water quality should generally not be presented with risk of degradation by pit lake flow-through, which will limit opportunities to this strategy to pit lakes of early better water quality and/or rivers of relatively lower water quality. Ideally, hydrological and geochemical modelling will precede a trial period of flow-through which then validates the model expectations to stakeholders' satisfaction.

Some pit lakes can also be used as reactors under certain conditions for instance, removing nutrients from river water and in turn precipitating metals from lake water. Nonetheless, hydro-chemical processes will vary between operations and sites based on the specific geological, hydrological and climate characteristic of each lake and its inflow/outflow characteristics. Developing flow-through systems must be based upon reliable data and accurate predictions of water balance and water quality e.g., from deterministic models. Nevertheless, abatement of acidification and salinisation as the import of alkalinity and freshwater, is typically the key driver to use flow-through as a closure strategy for pit lakes.

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