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Appendix D – Pit Lake Closure with Strategic Riverine Connectivity

Mine Lakes
CONSULTING

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INDUSTRY PRACTICE REVIEW

Pit lake closure with strategic riverine connectivity

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EXECUTIVE SUMMARY

Mine pit lakes may develop at mine closure when voids formed through mining extractions extending below groundwater levels fill with water. Internationally, acid and metalliferous drainage (AMD) is a common problem for mine pit lake water quality. Even if not acidic, pit lake water quality may be degraded through weathering of catchment geologies and evapoconcentration.

Such contaminated pit lake waters can present significant risk to both surrounding and regional communities and natural environments. Contaminated pit lake waters also limit beneficial end use opportunities. Pit lake waters may discharge into surface and groundwater; or directly present risks to wildlife, stock and human end users. Abatement of acidification and salinisation is typically the key driver to use flow-through as a closure strategy for pit lakes.

Riverine flow-through is increasingly proposed to mitigate or remediate pit lake water contamination using catchment scale processes. This paper presents the motivation for, and key processes and considerations regarding a flow-through final lake hydrology closure strategy. International case studies as precedent and lessons for future application are also described from pit lakes that use or propose flow-through as a key component of their mine closure design.

Chemical and biological processes such as dilution, absorption and flocculation and sedimentation can sustainably reduce pit lake contaminant concentrations to acceptable levels for risk and to enable end use opportunities to be realised. We conclude that riverine lake flow-through may often be a valid mine closure strategy for pit lakes with poor water quality. However, we caution that maintenance of existing riverine system values must be the first and foremost consideration. 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 strategies must be scientifically justifiable and follow a risk assessment approach for both lake and river and receptors potentially affected by surface and groundwater transport. Due to the high uncertainty often associated with this complex strategy, biotic and physico-chemical attributes of both inflow and decant river reaches as well as the lake should be well monitored. Monitoring should directly feed into an adaptive management framework discussed with key stakeholders with validation of flow-through as a sustainable strategy required before mine relinquishment is made.

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APPENDIX A
Limitations

1.0 BACKGROUND

Mine Lakes Consulting (MLC) was contracted by McArthur River Mine, Glencore (MRM) to provide advice for mine closure planning of the pit lake proposed to form in the project's open cut void.

The objective of this review was to provide learnings and a summary of national and international examples of pit lake closure for pit lake flow-through at mine closure that demonstrate precedent of riverine connectivity to pit lakes as a leading practice closure strategy.

2.0 SCOPE OF WORK

A review of the national and international grey (e.g. reports) and peer-reviewed (e.g. conference proceedings, books and industry and academic journal papers) literature was undertaken with a focus on flow-through as either a deliberate or incidental closure strategy for mine closure of projects involving mine voids that had already or would form pit lakes.

The review aimed to discover and describe leading industry practice of completely filled lakes with flow-through from regional river systems; the challenges, lessons learned and knowledge gaps remaining.

Special attention was given to the previous and current approaches of collaborative mining company pit void flow-through development by the German mining lake districts e.g., the Lusatian region of 370 lakes (south of Berlin) and of the Collie Lake District (200 km south of Perth).

The differences (risks and opportunities) between partial lakes with no river interconnection and full lakes with river connections were also explored.

3.0 INTRODUCTION

Due to operational and regulatory practicalities, pit lakes are significant legacies of many mine lease relinquishments (Castro & Moore, 2000; Younger, 2002). Weathering of potentially acid forming (PAF) materials in pit lake catchments, such as pit wall rock, waste rock dumps, and tailings storage facilities, may result in acid and metalliferous drainage (AMD) forming in pit lakes (Castro & Moore, 2000). Even in non-sulfidic host geologies, mobilised contaminants such as salinity (Eary, 1998; McCullough *et al.*, 2013b) may accumulate in pit lakes from the broader mining-disturbed catchment (McNeill *et al.*, 2012). AMD-degraded water quality in pit lakes may then reduce regional environmental values and present practically perpetual risks c.f. Nieto et al. (2013) to surrounding communities and environmental values (McCullough & Lund, 2006; Hinwood *et al.*, 2012). As a result, mine closure guidelines and regulations increasingly require long-term assessment of pit lake risk to surrounding ecological and social environments (McCullough *et al.*, 2009a; McCullough, 2016a).

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 pit lake water body on regional ground and surface water resources (Williams, 2009; DIIS, 2016). 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. Pit lake closure requirements and expectation are therefore typically closely oriented to water quality criteria (Jones & McCullough, 2011; Vandenberg *et al.*, 2015). However, there remain few options for closure management and limited research is being undertaken to resolve the increasing scale globally of issues with poor pit lake water quality (McCullough, 2016b).

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) (McCullough *et al.*, 2009a; Swanson, 2011). Such 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).

The hydrological setting of lakes is well known as a key factor for determining pit lake water quality (Straskraba, 1999; Kratz *et al.*, 2006; Sawatsky *et al.*, 2011). Lakes are usually storage elements in river networks, reactors transforming many of the water constituents and sinks for particles and dissolved water constituents, but a lake may also act as a source. Thus, lakes may strongly influence the water quality and the colonization by aquatic organisms of the entire river system (e.g. Liermann et al. 2012). Accordingly, consideration, design and management of the connection of pit lakes to surface and groundwater have been applied as a management approach for controlling water quality both in pit lakes and in surface waters (e.g., Schultze *et al.* (2011). However, opportunities for and values of both types of water bodies, lakes and surface waters, have to be considered when choosing such management approaches.

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

- because a surface drainage system was originally diverted around the mine. Thus, it is desirable that the system is diverted back into its 'natural' channel at mine closure for cultural reasons or to reduce channel maintenance liability or failure risk;
- the pit lake is specified as a water reservoir, or for retaining and buffering high flows as flood protection for downstream;
- higher quality (e.g., less acidic, lower salinity) river water is required to maintain a minimum pit lake water level or minimum water quality to meet certain criteria, or
- the pit lake is proposed as a treatment facility to improve water quality of the river during passage through the lake.

In this paper, we discuss river flow through as an option for water quality improvement in both pit lakes and rivers. Basic hydrological and biogeochemical processes are evaluated and pit lake flow-through examples presented. Conclusions are drawn regarding the applicability of river flow through as a management option for pit lakes at mine closure.

3.1 Pit lake hydrology and flow-through

The pit lake equilibrium water balance and final depth is defined by the net effect of all its hydrologic components. This would include, 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) contributing directly to ground and surface waters through seepage and/or decant, respectively. Terminal hydrology is most common for pit lakes in net negative rainfall areas (that is, evaporation exceeds rainfall) 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.

Non-terminal pit lakes have a 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 as flow-through surface water hydrology (Figure 1d).

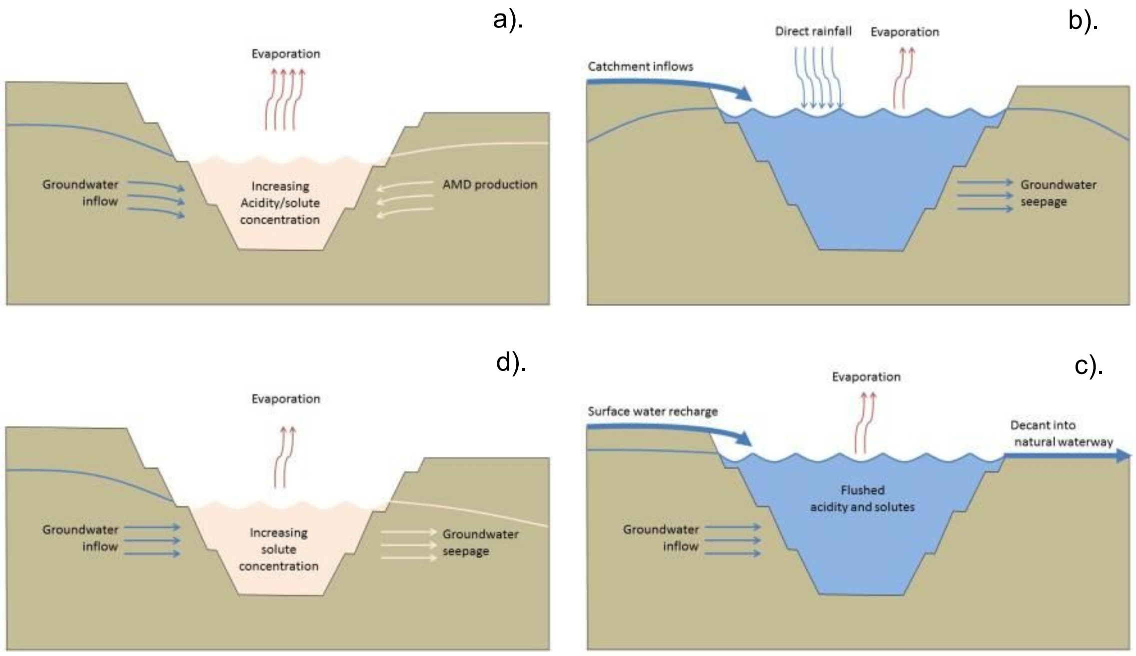

Figure 1. Conceptual equilibrium hydrogeological regimes for pit lakes. a). evaporative terminal sink, b). surcharged lake, c). groundwater through-flow, and d). surface water flow-through.

Flow-through pit lakes may occur in areas where precipitation rates exceed evaporation rates; even occasionally. This could occur, for example when heavy rainfall events and larger catchments result in relatively high volumes of water inflowing to the pit void (Connolly & Hodgkin, 2003). Pit lakes which are used as reservoirs or for flood protection, as is the case, for example, for several pit lakes in Germany (Schultze *et al.*, 2013), are generally (even though only temporarily) river flow-through systems.

3.2 Key flow-through bio-geochemical processes

Solute concentrations are usually higher in pit lakes receiving AMD (Banks *et al.*, 1997) than in many river waters (Meybeck, 2005). Consequently, flow-through by river water typically will result in dilution of pit lake water solutes which is particularly relevant for the concentrations of major ions, i.e. salinity. In turn, the effluent from pit lakes may increase solute concentrations in receiving rivers.

As for lakes and reservoirs in general, also pit lakes act usually as sinks for the particulate load from rivers entering them. This is the consequence of much lower flow velocities in the lakes and the resulting sedimentation of mineral particles, detritus and plankton. Plankton, which is well adapted to turbulence in rivers, is often not able to survive in lakes due to excessively high sedimentation losses and is replaced by organisms better adapted to the hydrodynamic conditions in lakes (e.g. Kimmel and Groeger, 1984; Reynolds at al., 1994; Bridgeman et al., 2012; Hanson et al., 2015; Maavara et al., 2015; Powers et al., 2014). Growth of lake plankton and its eventual death and sedimentation often additionally contributes to the role of lakes as nutrient sinks in river networks e.g., Bowling (1994). However, some lake plankton may also be flushed into the river downstream and influence the plankton development in this system (e.g., Prygiel and Leitao, 1994; Bahnwart et al. 1998; Yu et al. 2017)

Nutrients imported by river water into pit lakes may stimulate primary production in the lake, even under acidic conditions e.g., Woelfl (2000). This eutrophication may enhance the removal of trace contaminants originating from mining as well as from the catchment of the river. Such phytoremediation by intentional addition of nutrients, i.e., intended eutrophication of pit lakes, has been successfully tested and applied in lakes (McNee *et al.*, 2003; Fyson *et al.*, 2006; Wen *et al.*, 2015; Kumar *et al.*, 2016).

Sedimentation and consequent bacterial decomposition of organic matter (detritus, plankton) in the lake may lead to physico-chemical conditions conducive to microbially-mediated reductive processes in the lake sediment such as reduction of nitrate, manganese, iron and sulphate. Of particular importance to acidic lakes, sulphate reduction is accompanied by alkalinity production and may contribute to neutralization of AMD present in the pit lake or entering it via groundwater or catchment runoff. Such biological processes are usually acting slowly but may become important in the long term (McCullough, 2008; Schultze, 2012; Kumar *et al.*, 2013; Schäfer *et al.*, 2016; Opitz *et al.*, 2017).

A further aspect of manganese, iron and sulphate reduction is their potential to cause re-dissolution of phosphorus from the sediment and respective internal load resulting in eutrophication e.g., Wang and Jiang, 2016; Caraco et al., 1989; Roden and Edmonds, 1997). However, this is only a potential long-term consideration since phosphorus is usually well fixed in the sediment of pit lakes due to the typically high concentrations of iron and aluminium in pit lake sediments e.g., Kleeberg and Grüneberg (2005), Herzsprung et al., 2010; Grüneberg and Kleeberg, 2013.

The inflow of iron-rich groundwater is also a typical issue for pit lakes. The iron is oxidized in the lake water and phosphate as well as other trace chemicals is co-precipitated as iron (oxy)hydroxide. As long as the lake environment oxic and there remains sufficient surplus of iron reagents in the sediment, the internal load of phosphorus will not present a eutrophication risk in pit lakes, (Herzsprung et al., 2010). Indeed, a relatively thick iron-deficient surface layer in the benthos sediment must form before the high amounts of sedimentary iron are no longer relevant for the fixation of phosphorus contributed to the lake's nutrient budget by riverine inputs (Lewandowski *et al.*, 2003).

Seepage of iron-rich groundwater to the pit lake is also a source of acidity for the water. A further source of acidity may be the elution of side walls of the former mine void shell, or of mine waste deposited in the catchment of the pit lake (Opitz *et al.*, 2017). This may cause continued acidification of a pit lake or a re-acidification if the pit lake where it had been initially neutralized by measures like filling with river water or liming (Geller and Schultze 2013). Import of bicarbonate, i.e. alkalinity, by river water and its reaction with present or entering acidity is the main neutralizing process when using riverine flow-through as a management option for pit lakes. Already neutralized pit lakes can therefore also be kept neutral in this way (see example Lake Senftenberg below; Werner et al., 2001a, (Werner *et al.*, 2001).

If pit lake water is still acidic or contains elevated metal concentrations when it discharges into the river it may consume river alkalinity or even acidify the receiving river environment. Elevated concentrations of metals (and in case of blasting during mining, also ammonia and nitrate) may also affect aquatic life in the receiving river environment. Export of large loads of iron (dissolved or particulate) may cause iron hydroxide deposition on the river bed. These bedded sediments can impact riverine benthic communities as demonstrated also by rivers receiving groundwater rich in iron in former mining areas (Bilek *et al.*, 2017). If the flow-through pit lake acts as a sink for nutrients and organic material, primary production and contamination of the river water may be lower in the river reaches downstream, than in the river reaches upstream of the pit lake.

Although there are a range of potential risks to both pit lake and river from a flow-through closure strategy, the greatest risk is poor water quality in the downstream river and/or presenting as groundwater surface expressions (McCullough *et al.*, 2013a). If present, degraded water conditions can lead to reduced water values which must be considered in light of benefits gained from the strategy.

3.3 Riverine flow-through of pit lakes; processes and effects

Table 1 lists some key benefits and risks for pit lakes resulting from riverine flow-through. There are diverse benefits but also considerable risks, both requiring careful evaluation for each individual pit lake. The cost-benefit analysis may need to be checked regularly since conditions or requirements may change during mine life.

Since diversion of river water is a substantial alteration for the river's morphological and chemical condition, similarly cost-benefit aspects must be considered to the river as a receiving system. There are also significant advantages and risks to the river besides legal, economic and social aspects e.g., existing rights for water use as shown in **Table** 2.

Table **1. Potential benefits and risks of flow-through pit lake closure strategy for pit lakes.**

Benefits to pit lake	Risks to pit lake
Dilution of elevated solute concentrations in lake waters e.g., salinity, contaminants	Incoming flows may contribute solutes to the pit lake such as salinity under particular conditions (e.g. (McCullough, 2015)
Neutralisation of lake acidity by river water alkalinity	
Sorption and precipitation of lake metals by river nutrients such as carbon and phosphorus (Fyson *et al.*, 2006; Neil *et al.*, 2009)	River water may introduce contaminants such as nutrients, organic pollutants and 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 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 carbon and phosphorus to foodwebs of new pit lakes and especially for acid pit lakes (McCullough *et al.*, 2009b; Kumar *et al.*, 2016)	Lakes may become eutrophic following excess river nutrient imports (Axler *et al.*, 1996; 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)
Nutrients stimulate primary production assisting neutralisation (Tittel & Kamjunke, 2004)	Nutrients only available over longer terms due to phosphorus fixation to iron and aluminium in water column and lake sediments (Kopacek *et al.*, 2000; Kleeberg & Grüneberg, 2005)
Inflows provide a source of organic material as a substrate for sulfate reduction in the lakes' sediment (Salmon *et al.*, 2008)	Only important over longer terms as a relatively weak alkalinity-generating process (Wendt-Potthoff *et al.*, 2012)
Meromixis may be stabilized (Boehrer & Schultze, 2006; Santofimia & López-Pamo, 2010) allowing for safe 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 presenting risk in case of erosion of the chemocline (Boehrer *et al.*, 2014), chemical stratification becomes unstable or even limnic eruption (Murphy, 1997; Sanchez-España *et al.*, 2014)

Table **2. Benefits and risks of flow-through pit lake management strategy to rivers.**

Benefits to river	Risks to river
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	Physical or chemical migration barrier to movements of aquatic life
Reduced flood incidence and extended base flow volume and duration	Altered hydrological regime reducing flood peaks required for biological cues and for channel morphology
	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. These risks should be avoided by early, well- informed and 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 e.g., only during storm or other high flow events when any impact to the river downstream is relatively less significant. This will depend on the hydrological situation in the river and the strategy should be directed to maintaining hydrological patterns downstream required to sustain river end uses. Any 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 river reaches will be present when the river is already significantly 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, however, worked particularly well in the Lake Kepwari pit lake situation (see Section 4.7) as the river channel was able to be maintained in its historical course and river water quality was already degraded by anthropogenic catchment activities (McCullough *et al.*, 2012; McCullough *et al.*, 2013a). These reduced values lessened the reduced risk of decant on downstream river values.

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.*, 2013a). River flow timing such as hydroperiods 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.

3.4 Effects of climate change on flow-through hydrology

Climate is the single most important factor accounting for a pit lake water balance (Niccoli, 2009). Changes in climate will affect individual hydrological components over a short period of time whilst groundwater inflow responses are generally generated from precipitation recharge over longer periods of time. 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 groundwater inflows over the long-term.

There is a high probability that mean earth surface temperatures will continue to increase into the future (IPCC, 2007). This increase in temperature will affect surface hydrologic processes differently in different parts of the world. For example, in southern Australia most areas will become net drier due to decreased rainfall and increased evaporation, whilst areas in northern Australia will become wetter due to increased rainfall and decreased evaporation (Hobday & Lough, 2011). The water balance may be affected in a drier climate with reduced pit lake water levels leading to cessation of flow-through and lakes becoming terminal sinks (Kumar *et al.*, 2009). In comparison, a wetter climate will most likely result in elevated pit lake water levels leading to previously terminal pit lakes becoming 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 the water balance for each pit lake resulting from climate change must be evaluated case-by-case based on predictive modelling. Regular updates of the models and the simulations including the use of collected monitoring data should also be made (Castendyk *et al.*, 2015a; Castendyk *et al.*, 2015b).

4.0 EXAMPLES

Existing examples of flow-through pit lakes both offer demonstration of the level of success of this management strategy as well as an opportunity to learn from these case studies to avoid their mistakes as well as to refine these strategies further. Published literature provides a number of examples of riverine flow-through in pit lakes. We focus of examples well known to the authors and, therefore, mainly located in Australia and Germany. Further examples from elsewhere have been reported by Moser and Weisse (2011; Austria), Juncosa et al. (2016), and Halí and Žižka (2008; Czech Republic).

4.1 Lusation Mining District (Germany)

The Lusatian Lignite Mining District is a region in eastern Germany strongly impacted by surface mining for lignite in the last approximately 100 years. Many pit lakes have been created and the water balance of the rivers is characterized by a complex, artificial management (Koch *et al.*, 2005). A management system was established for the entire Lusatia and the Spree River down to Berlin. This large system comprises pit lakes, reservoirs, operating mines and mine water treatment plants and connects three river systems: Neisse River, Spree River and Schwarze Elster River (from east to west) which were naturally separated (for more details see (Koch *et al.*, 2005; Geller & Schultze, 2013; Schultze *et al.*, 2013). In order to manage potential future phases of water scarcity in the mentioned rivers caused by climate change, diversion of water from the larger Elbe and Oder rivers is also under discussion (Koch *et al.*, 2009). Figure 4 shows the central part of the Lusatian Lignite Mining District. The lakes Senftenberg, Knappenrode, Lohsa I, Lohsa II, Dreiweibern, Bernsteinsee and Baerwalde (numbers 2, 12, 15, 17, 16, 14, 18 in Figure 4) are managed as reservoirs and can also be used for flood protection.

Figure 2. Schwarze Elster River at channel between Lakes Geierswald and Senftenberg (Photo courtesy of Martin Schultze, Helmhotz Institute).

Figure 3. Outflow from Lake Dreiweibern (Photo courtesy of Martin Schultze, Helmhotz Institute).

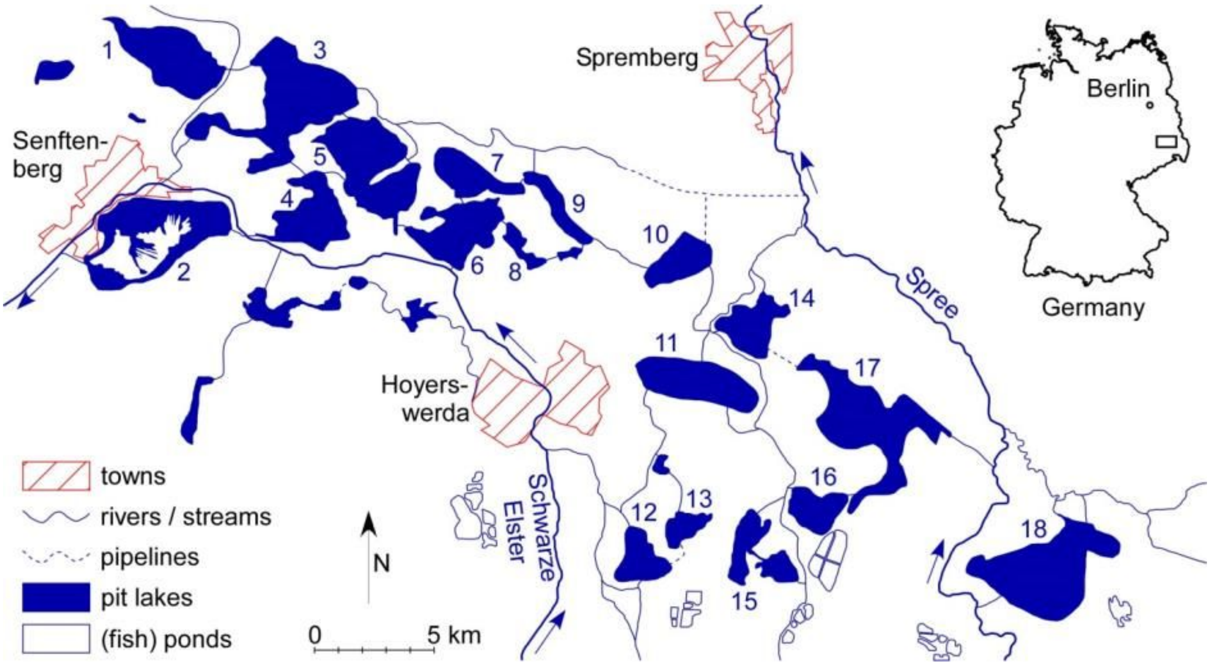

Figure 4. Lausitzer Seenland", the central part of the Lusatian lignite mining district. Lakes: 1 Lake Großraeschen, 2 Lake Senftenberg, 3 Lake Sedlitz, 4 Lake Geierswald, 5 Lake Partwitz, 6 Lake Neuwiese, 7 Lake Bluno, 8 Lake Bergen, 9 Lake Sabrodt, 10 Lake Spreetal, 11 Lake Scheibe, 12 Lake Knappenrode, 13 Lake Graureihersee, 14 Lake Bernsteinsee, 15 Lake Lohsa I, 16 Lake Dreiweibern, 17 Lake Lohsa II, 18 Lake Baerwalde. Only selected towns are shown for orientation (McCullough & Schultze, in prep)

The lakes Knappenrode, Lohsa I and Senftenberg are selected for detailed presentation below since they have already been in operation for decades (McCullough & Schultze, in prep). The presented data on water quality and hydrology were provided by the regional environmental authorities (Landesamt für Umwelt, Landwirtschaft und Geologie des Freistaates Sachsen (LfULG) for lakes Knappenrode and Lohsa I and Landesamt für Umwelt Brandenburg (LfU) for Lake Senftenberg). Table 3 summarizes the morphometric data and the years of commissioning of the three lakes, which are used as reservoirs.

Five consecutive years were selected for which monitoring data comprising hydrology and water quality have minimal gaps. For diverse reasons, the selected years differ for the lakes. Concentrations of sulphate, iron, phosphorus, ammonia nitrogen and nitrate-nitrogen, and pH were selected to characterize water quality: pH, sulphate and iron as typically mining influenced and phosphorus and nitrogen as drivers of eutrophication and representative of water pollution from non-mining anthropogenic activities in the river catchment.

Table 3. Morphometric data and year of commissioning as reservoir (LTV 2007; (Nixdorf et al., 2001); Schultze et al. 2013; LTV personal communication) (McCullough & Schultze, in prep).

Lake	Lake measurements			Managed upper layer		Year commissioned
	Volume (GL)	Surface area (ha)	Maximum depth (m)	Volume (GL)	Thickness (m)	
Knappenrode	18.1	286	11	6.38	2.4	1953
Lohsa I	23.3	342	22	5.8	1.8	1972
Senftenberg	102.5	1300	23	20.5	1.7	1973

The lakes Knappenrode and Lohsa I are located quite close to each other (Figure 4, Figure 5) but belong to two different river systems: Lake Knappenrode to Schwarze Elster River and Lake Lohsa I to Spree River. Both lakes are connected to the river in a by-pass position and mark the upstream border of the mined area. Figure 5 shows the details of the connection between the lakes and the local streams as well as the locations of the considered sampling sites.

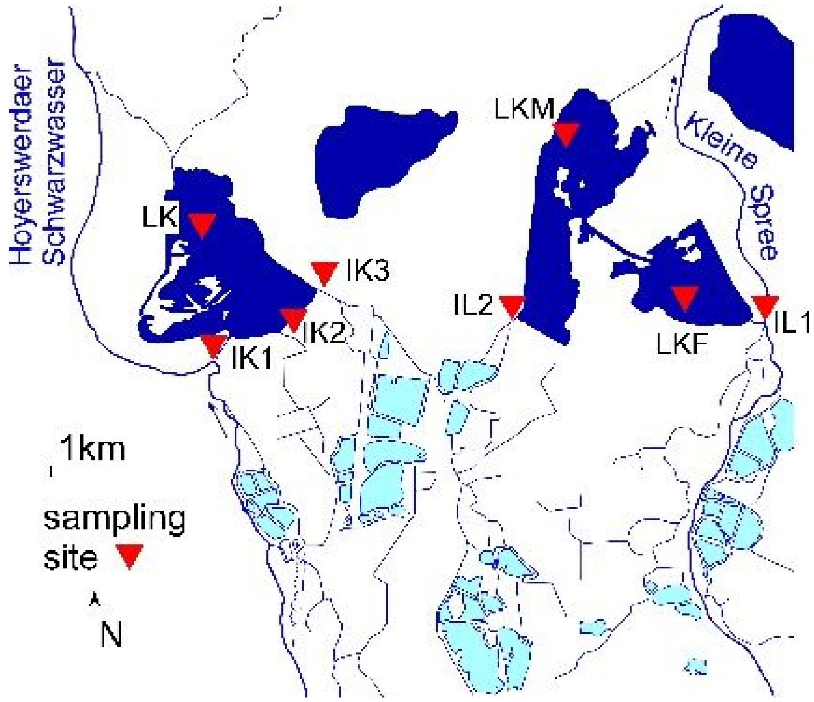

Figure 5. Location of sampling sites used for Lake Knappenrode (number 12 in Fig. 2) and Lake Lohsa I (number 15 in Fig. 2). LK – Lake Knappenrode; IK1-IK3 – inflows into Lake Knappenrode; LLM – Basin Mortka of Lake Lohsa I; LLF – Basin Friedersdorf of Lake Lohsa I; IL2, IL2 – inflows into Lake Lohsa I (McCullough & Schultze, in prep).

For both lakes, only the connection to the main local stream, Hoyerswerdaer Schwarzwasser in the case of Lake Knappenrode and Kleine Spree in the case of Lake Lohsa I, can be controlled. That means, the inflows IK2, IK3 and IL2 are permanent and uncontrolled inflows. The hydrological data indicate an intensive management system is in place to provide water for purposes downstream in periods of low flow (summer and autumn) in the rivers and also for flood protection. The slightly higher sulphate concentrations in the lake water point to inflow of mining impacted groundwater into the lakes. Despite such groundwater inflow, the lakes act as sinks for iron. They also trap phosphorus and nitrogen. Growth of phytoplankton and photosynthetic activity suggests alkalinity-generation is a likely reason why the pH in the lake water is slightly higher than in the river water. The flow-through of river water reduces the nutrient load of the river water and does not affect water quality in lakes Knappenrode and Lohsa I.

Lake Senftenberg (lake 2 in Figure 4) is an example for pit lakes filled and permanently flushed with river water (Werner *et al.*, 2001), Werner et al. 2001a,b). Lake Senftenberg forms a bypass to the river (Figure 5 and Figure 6) and is intensively managed and used for flood protection. Furthermore, flood water retention permits secure minimal flow downstream during regularly occurring low-flow periods in summer and autumn. The water balance of Lake Senftenberg has been positive since 2010 due to increasing groundwater levels and filling of pit lakes in the north of Lake Senftenberg (Uhlmann *et al.*, 2016). The outflow from the lake represents about 39% of the total flow in Schwarze Elster River at the Bielen gauge downstream of Lake Senftenberg while the mean annual inflow from Rainitza Stream is in the range of 0.08 to 1.0 m^3/s.

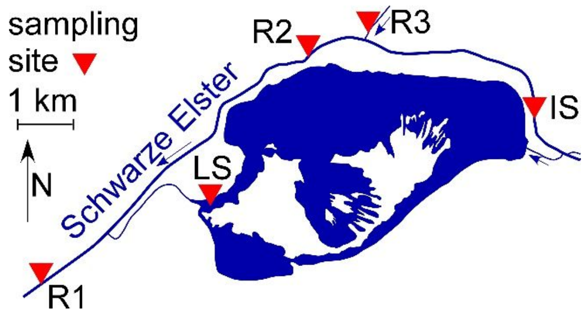

Figure 6. Location of sampling sites used for Lake Senftenberg (number 2 in Figure 4). LS – Lake Senftenberg; IS – sampling site at Schwarze Elster River representative for inflows into Lake Senftenberg; R1 – Schwarze Elster River downstream of Lake Senftenberg at gauge Bielen, R2 – Schwarze Elster River at sampling site Senftenberg Amtsmühle, R3 – Rainitza Stream

The river water neutralised the initially acidic water originating from groundwater rebound and also kept the main (northern) basin of the lake neutral. The south-western basin is generally sheltered from flow-through and, therefore, has remained acidic. An interruption in the diversion of river water resulted in a temporary pH decrease from >7 to 5 in the main basin in 1995 (Werner *et al.*, 2001), Werner et al., 2001a,b). This pH decrease demonstrated the importance of the river water for maintaining lake water quality. By collecting and neutralising acidic groundwater, Lake Senftenberg is operating as a reactor and deposition site avoiding adverse impacts on the ecosystem of the Schwarze Elster River (inflow of acidity and precipitation of ochreous material). The role of Lake Senftenberg is also as a trap for phosphorus and nitrogen. Although the sulphate concentration in Lake Senftenberg is higher that of Schwarze Elster River, the upstream Rainitza River is the main sulphate adding source for Schwarze Elster River in the vicinity of Lake Senftenberg. The sulphate concentration of Schwarze Elster River was already elevated before the water from the lake enters the river.

Based on successful rehabilitation experiences at lakes Senftenberg, Knappenrode and Lohsa I, riverine flow through will be the future main strategy to sustain acceptable water quality in the pit lakes as well as in the rivers in the Lusatian lignite mining district (Luckner *et al.*, 2013). A regionally important example is a chain of pit lakes (with volumes in brackets) comprising from east to west the lakes Spreetal ($97×10^6$ m^3), Sabrodt ($27×10^6$ m^3), Bergen ($3×10^6$ m^3), Bluno ($64×10^6$ m^3), Neuwiese ($56×10^6$ m^3), Partwitz ($133×10^6$ m^3), and Sedlitz ($212×10^6$ m^3) (lakes 10, 9, 8, 7, 6, 5, 3 in Figure 4, respectively). The water for flow-through will be diverted from the Spree River in the east. The Schwarze Elster River will receive the outflow in the west. The purpose of the riverine flow through is:

- to keep the water of the lakes neutral and its iron and sulphate concentrations below the thresholds for discharge into Schwarze Elster River; and,
- to maintain the water quality of the lakes suitable for planned use for recreation and nature protection.

Initial acidic pit lake water neutralization will be achieved by filling the pit lakes with river water and neutralized mine water and by liming to protect the downstream rivers Rainitza and Schwarze Elster. If necessary, liming will be continued or repeated once the flow through system is in operation. Outflow of water from the chain of pit lakes into the downstream rivers is permitted only for neutral water (Luckner *et al.*, 2013; Benthaus *et al.*, 2014).

4.2 Central German Mining District

The lakes Zwenkau, Stöhna, Witznitz and Borna are used for flood protection in the southern part of the Central German lignite mining district. They replace the flood retention capacity of mined areas in the former flood plains. Substantial stretches of Weiße Elster and Pleiße Rivers have artificial river beds where mining occurred in the former flood plains (Schultze *et al.*, 2010). For example, in June 2013 an exceptional flood occurred in Central Europe. The aforementioned pit lakes retarded around 60×10^6 m^3 of flood waters (LfULG, 2013; LMBV, 2013). This was almost three times the volume retarded by reservoirs and other storage facilities constructed for flood protection in the same river basin, that of Weisse Elster River (LfULG, 2013) (). The city of Leipzig was well protected by the mine lakes acting as flood structures.

Lake Borna (Figure 8) was selected as the first example from the Central German Lignite Mining District to be presented in detail since it has been connected to the Pleiße River only in case of needed flood protection. The lake is connected to the river as a bypass. In order to have a large storage capacity for flood protection ($46.1\text{x}10^6$ m^3), a dike (6.5 km long) was constructed around almost the entire pit lake. The lake was commissioned in 1970 and has a total volume of $105.5\text{x}10^6$ m^3 in case of use of the full storage capacity. Under this condition, the lake surface area is 5.7 km^2 (LTV 2007).

There were only two short periods with inflow from the river for the entire period 2011 to 2015: $7\text{x}10^6$ m^3 within 3 days in January 2011 and about $30\text{x}10^6$ m^3 within 5 days in June 2013. The latter coincided with the aforementioned flood event occurring in Central Europe. The frequent small outflow (on average 0.39 m^3/s for 2011–2015) results from groundwater entering Lake Borna giving the lake a slightly positive water balance.

Lake Borna acts as source of sulphate and iron for Pleiße River. However, this influence is not very important because of the infrequent occurrence of considerable volumes of outflow from the lake into the river and the high inputs of sulphate and iron by groundwater entering Pleiße River directly from the overburden dump of the former Witznitz mine further downstream. The difference in pH between lake water and river water is probably caused by the higher photosynthetic activity of phytoplankton in the lake. For phosphorus and nitrogen, Lake Borna acts as a sink. The pulses of nutrients entering Lake Borna during diversion of flood waters into the lake cause temporary increases in nutrient concentrations in the lake water and subsequent growth of phytoplankton. The sedimentation of the dead plankton and the fixation of phosphorus in the lake sediment by iron originating from groundwater results in a gradual recovery of lake water quality after a flood event. In the case of the 2013 flood event, the pre-flood conditions were again observed basically in autumn 2015 as indicated by concentrations of TP at the lake bottom (data not shown). This shows the high potential of the lake to capture nutrients but also the limitation of this capacity.

The Muldereservoir (110×10^6 m^3) (Figure 9) in the northern part of the Central German lignite mining district) is a second example from the Central German Mining District. The Muldereservoir was initially filled with river water from Mulde River over the period 1975–1976; the Mulde River still permanently flows through it. Flow-through of the Muldereservoir demonstrates significant benefit for both the Elbe River and the North Sea (Klemm *et al.*, 2005). The upper catchment of Mulde River was the subject of metal mining and metallurgy for about 800 years. Substantial fractions of the resulting load of heavy metals and arsenic of Mulde River are trapped in the Muldereservoir. The comparison between the total load of Elbe River into the North Sea and the large load trapped in the lake sediment of the Muldereservoir shows the importance of this pit lake for the river system downstream (Table 4).

Figure 7. The channeled Weisse Elster River (Photo courtesy of Martin Schultze, Helmhotz Institute).

Figure 8. Lake Borna (Photo courtesy of Martin Schultze, Helmhotz Institute).

Figure 9. Inflow structure into the Muldereservoir (Photo courtesy of Martin Schultze, Helmhotz Institute).

Figure 10. Flood inflow structure into Lake Zwenkau (Photo courtesy of Martin Schultze, Helmhotz Institute).

Table 4: Trapped load as both t yr-1 and as percent (%) of the total load of Elbe River into the North Sea (average values from 1993 to 1997 (Zerling et al., 2001)

	As	Cr	Cd	Pb	Zn	Cu
Load t yr^{-1}	21.6	14.6	5	43	243	26.4
Percent (%)	27.0	20.6	90.3	50.8	15.8	22.8

4.3 Upper Pit Lake, Canada

Suncor's DDA3 (Upper Pit Lake) is planned to contain in-pit tailings with a water cover that will be in place for some time before discharge to the receiving environment occurs (Suncor Energy, 2016).

DDA3 is planned to be filled with water beginning in 2043. Tailings will be treated with coagulant to reduce the mobility of constituents of potential concern (COPCs) and flocculant to dewater the fluid tailings. Once all the tailings have been treated and deposited in DDA3, placement of the aquatic cover will begin. The majority of water expressed from the deposit will be recycled during operations. This pit lake will be filled while Suncor is on site operating the mine, which affords the following opportunities:

- Outflow water can be recycled to operations if necessary while water quality is improving
- The pit lake filling and management period can be funded by concurrent operations
- Fixed and mobile equipment will be available for earthworks, pumping, etc.

The Upper Pit Lake will have a surface water filling period of a decade and a flow-through period which is expected to result in improved water quality compared to passively filling or not planning for flow-through. Suncor proposes to use a combination of Athabasca River water, run-off, and closure drainage water to establish a controlled rate of water release from the Upper Pit Lake to the Millennium End Pit Lake, which is released to the Athabasca River. Regular flushing of pit lake waters containing elevated COPCs by more dilute surface inputs has been shown to be a valid long-term management strategy to address the risk of initially elevated concentrations as well as long term accumulation of constituents (CEMA, 2012).

4.4 Sphinx Lake and Pit Lake CD, Canada

Reclamation on the Cardinal River and Gregg River coal mines includes the construction of mine pit lakes connected to stream environments (Miller *et al.*, 2013).

The Luscar Pit, mined from 1992 to 1999, is located in the Sphinx Creek drainage network. Prior to development, Sphinx Creek was diverted around the pit through a clean water diversion. When mining development was completed, overburden removed during mining was replaced and reshaped to backfill some of the pit, with the remainder being filled with water. Key reclamation steps included constructing an inlet and outlet channel for the lake, as well as a habitat suitable for aquatic plants and other biodiversity (Brinker *et al.*, 2011).

Stream water temperatures downstream of the lakes were significantly warmer than in inlet streams and streams without pit lakes. Aquatic communities including fish, invertebrates, zooplankton and aquatic plants were present in the pit lake ecologies. Athabasca rainbow trout (*Oncorhynchus mykiss*) populations are self-propagating (spawning at the outlets) with higher densities downstream than were there prior to lake reclamation.

However, the Sphinx Creek watershed now provides habitat for a substantial population of both resident and migratory native rainbow trout, as well as bull trout—both of which are listed as Species of Special Concern by Alberta's Endangered Species Conservation Committee (Teck Resources, 2010).

However, cortisol concentrations were greater in brook trout (*Salvelinus fontinalis*) and rainbow trout than in reference sites without coal mining disturbance (Miller *et al.*, 2009). Selenium concentrations in rainbow trout eggs taken from gravid pit lake fish were elevated above USEPA tissue guidelines (Miller *et al.*, 2013). Bull trout (*Salvelinus confluentus*) captured immediately downstream from coal mining activity in the region also had Se tissue concentrations that might impair recruitment (Palace *et al.*, 2004).

4.5 Enterprise Pit Lake, Australia

The Enterprise gold mine pit in the Northern Territory of Australia was closed in 1992 with Pine Creek, a local watercourse, diverted into the pit void (Fawcett & Sinclair, 1996). Rapid pit lake filling was used to reduce oxidation of sulfidic pit wall materials and consequently reduce rates of acid generation. The water level of the final lake was also designed so that the majority of acid forming minerals would be located below the (oxygenated) epilimnion. After the first wet season the lake was half full, and late in the second wet season it was about two thirds full.

The lake (see Figure 11) is now regarded as an off-stream storage recharged each wet season with diversion of Pine Creek peak flows into the lake (Boland & Padovan, 2002). Regular flushing offsets the slight acid production found at depth, resulting either from acidic groundwater seepage or due to PAF oxidation during deep mixing of oxygenated water (Jones *et al.*, 1997). However, the lake also serves as an aquatic habitat and as a water resource for the Pine Creek region.

Figure 11. Enterprise Pit Lake, Northern Territory, Australia.

4.6 Proposed Yandicoogina Pocket and Billiard South iron ore mine lakes, Australia

The proposed Yandicoogina Mine expansion in the Pilbara, Western Australia is exploring a preferred scenario to have flow-through pit lakes connected to the nearby Marillana and Weeli Wolli Creeks (Rio Tinto Iron Ore, 2011). This is primarily due to a lack of available material to backfill the pit voids following mining. Surface water flow in the region is typically ephemeral, with creek-flow only occurring following heavy or sustained rainfall events. Consequently, although geochemical testing has indicated low to nil AMD risk for pit lake waters, there is a risk of long-term pit lake salinization from net evaporative lake water loss.

The current mine plan assumes that the ore body is mined from several pits, from the west to the east (Inverarity *et al.*, 2012). The pits are separated where the orebody runs underneath or adjacent to ephemeral creek lines. The final landform configuration is proposed to involve diversion of creek lines to enable excavation of material from between the current pit shells, ultimately forming a single continuous 'channel' pit (Figure 12). Construction of engineered inlet and outlet structures will be required to mitigate erosion during pit lake filling and allow streamflow to enter and exit the channel pit lake i.e. main creeks and smaller tributaries. Construction of levees will also be used to prevent water discharging to the channel at uncontrolled locations.

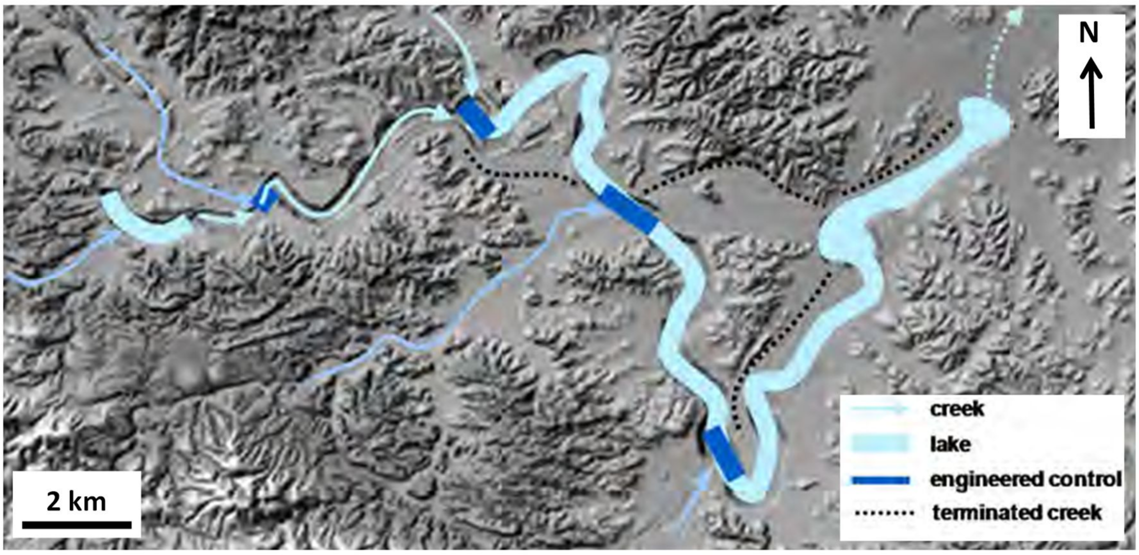

Figure 12. Closure landforms showing mine pit and flow-through pit lake (after Rio Tinto Iron Ore, 2011).

Whilst the proposed design has the potential to deliver a number of benefits, further studies and design refinements are expected to confirm viability and to mitigate negative impacts, particularly on downstream ecosystems, such as the environmentally-sensitive Fortescue Marsh. These include:

- studies to evaluate ecological limitations of the channel pit lake design including a suitable restoration target aquatic ecosystem (Van Etten *et al.*, 2011);
- options to restore the channel pit lake as a regionally representative water body (McCullough & Van Etten, 2011); and,
- habitat restoration priorities for keystone flora and fauna species (Lund & McCullough, 2011).

4.7 Lake Kepwari, Australia

Lake Kepwari is located in the Collie Coal Basin, in south-western Australia. The recreation and nature conservation values of the south-west are highly regarded with promotion for wildlife and recreation-based tourism by local business associations and government. The basin now has 13 pit lakes with a range of ages, size and water quality, yet all are acidic due to AMD. Further, much larger pit lakes are planned from ongoing mining in the region (Lund *et al.*, 2012).

Mining of the Lake Kepwari pit began with diversion of the seasonal Collie River South Branch (CRSB) around the western lake margin. Mining ceased in 1997 and reactive overburden dumps and exposed coal seams were then covered with waste rock, battered and revegetated with native plants.

To further reduce wall exposure and rates of resulting acid production, the lake was rapid-filled by a predominantly saline first-flush diversion from the CRSB during the winter periods from 2002–2008 following a low-flow year in 2001. Filling commenced under a licence requiring that all river pools downstream of the void were filled before water was diverted into the void.

The lake was flagged as a water-based community recreation resource for water skiing and swimming (Evans & Ashton, 2000; Evans *et al.*, 2003). However, although CRSB inflow initially raised the lake to above pH 5 and lake water met recreation guidelines during filling, a failure to identify and manage ongoing PAF acidity inputs adequately meant that water quality subsequently declined to below pH 4 (Salmon *et al.*, 2008). Although the relatively good water quality of the pit lake still lent itself to a range of potential end uses, low pH and elevated metal concentrations degraded water quality (Lund & McCullough, 2009). Consequently, as closure criteria have not been met, the lease remains unrelinquished and proposed end uses are not yet realised.

During August 2011, heavy rainfall in the upstream catchment led to the CRSB flowing into the lake and decanting downstream. During this time, although the decant was uncontrolled, CRSB water quality end use values were not significantly impaired (McCullough *et al.*, 2013a) and lake water quality was significantly improved (McCullough *et al.*, 2012).

An engineered lake river flow-through was trialled from 2012–2014 (McCullough & Harkin, 2015) (see Figure 13) with the lake becoming neutral by early 2014 and becoming fresher over time (McCullough, 2015) (see Figure 14). Concomitant decreases in metal concentrations and increases in organic carbon and phosphorus concentrations have also occurred resulting in an increase in aquatic biotic diversity and abundance. During flow-through there has been no degradation of downstream values, as defined by water quality guidelines for aesthetics and recreation, livestock drinking or aquatic ecosystem protection. Decreases in nutrient concentrations in the eutrophic river have also occurred. Similarly, recreational, stock drinking and ecosystem values have increased in the lake over this period (DIIS, 2016).

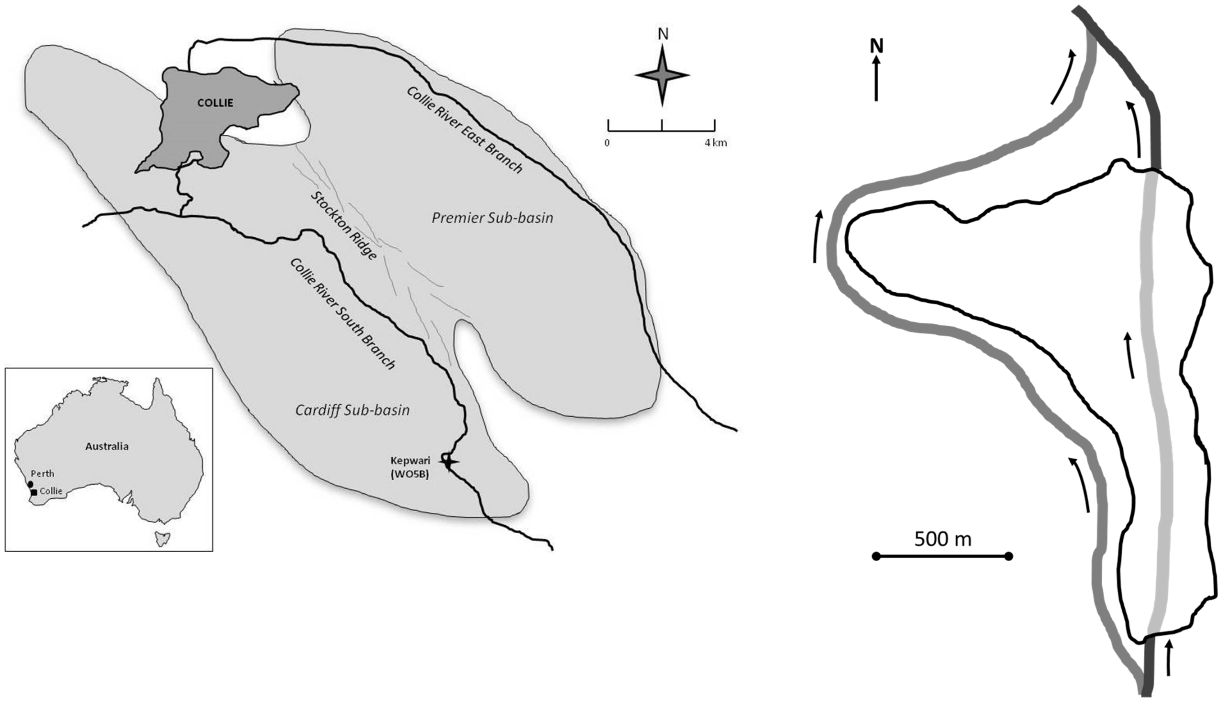

Figure 13. A/. Location of Lake Kepwari in Western Australia. B/. Lake Kepwari flow-through design showing historical CRSB channel in black, previous river diversion in dark grey and presumed lake passage in light grey.

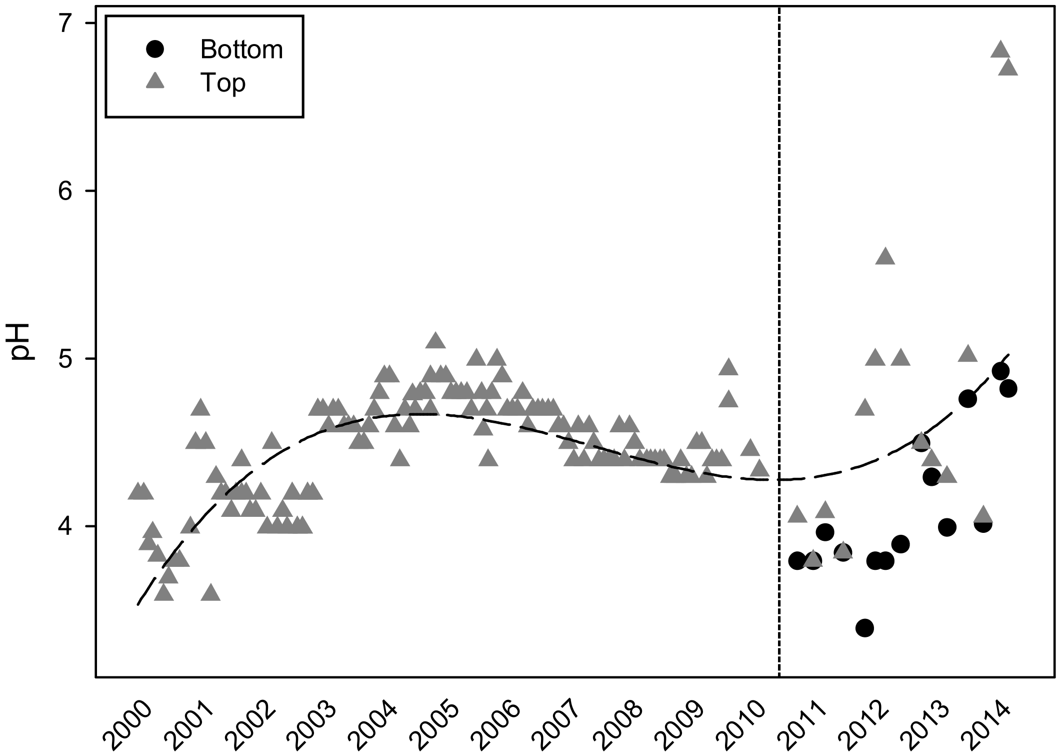

Figure 14. Time-series graph of Lake Kepwari pH historically, during and after flow-through began (after (McCullough et al., 2010; McCullough, 2015; McCullough & Harkin, 2015)). Dashed regression line indicates surface water pH trend over time. Dotted vertical line indicates date of breach and flow-through.

5.0 CONCLUSIONS

Flushing pit lakes with river water has proved internationally to be a very useful strategy for mine pit lake closure planning and management. A fundamental prerequisite for the use of river water for pit lake flow-through is water availability. Consequently, the applicability of flow-throughs strongly depends on the current and future climate and the existing and likely future use of water downstream of the associated pit lake. In the case of limited water availability, floods may be the only options for the filling and flow-through of pit lakes. Moreover, existing and likely future values of the river system downstream must be considered carefully. If substantial decline of river water quality is expected other methods of pit lake management may have to be used, possibly in combination with riverine flow-through.

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 or the pit lake may be necessary with little commensurate benefit for the cost or risk of the approach. However, pit lakes can also be used as biogeochemical reactors under certain conditions such as, for example, removing nutrients from river water and in turn precipitating metals from lake water.

Hydro-chemical processes will vary between operations and sites based on the specific geological, hydrological and climatic characteristics of each lake and its inflow/outflow characteristics. As a result, application of general scientific principles will be required in concert with site considerations. Developing flow-through systems must always be evidence-based using reliable data and accurate predictions of water balance and water quality e.g., from deterministic models.

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APPENDIX A

Limitations

Disclaimer and Statement of Limitations