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Review

Engineered river flow-through to improve mine pit lake and river values

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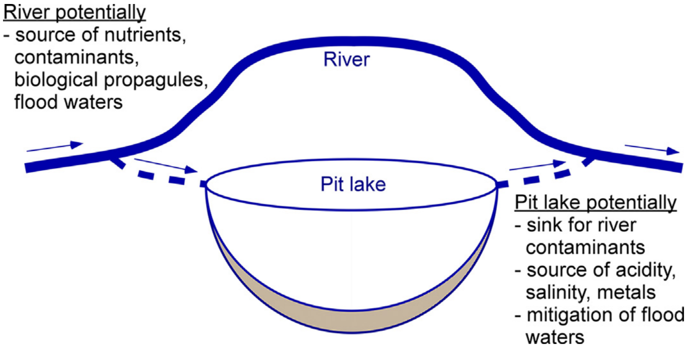
HIGHLIGHTS

- Pit lakes may develop at closure of open cut mining. Pit lakes often have poor water quality and risk contaminating local waterways
- We reviewed international case studies where redirecting nearby rivers through the pit lake was proposed to improve environmental outcomes.
- Chemical and biological processes generally reduced pit lake contaminant concentrations to sustainably acceptable levels.
- Flow-through may be a valid strategy for pit lakes with poor water quality, improving downstream river water quality.
- Flow-through strategies must be scientifically justifiable, risk-based and maintenance of existing riverine system values must be foremost.

GRAPHICAL ABSTRACT



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ABSTRACT

Mine pit lakes may develop at mine closure when mining voids extend below groundwater levels and fill with water. Acid and metalliferous drainage (AMD) and salinity are common problems for pit lake water quality. Contaminated pit lake waters can directly present significant risk to both surrounding and regional communities and natural environmental values and limit beneficial end use opportunities. Pit lake waters can also discharge into surface and groundwater; or directly present risks to wildlife, stock and human end users.
Riverine flow-through is increasingly proposed to mitigate or remediate pit lake water contamination using catchment scale processes. This paper presents the motivation and key processes and considerations for a flow-through pit lake closure strategy. International case studies as precedent and lessons for future application are described from pit lakes that use or propose flow-through as a key component of their mine closure design. Chemical and biological processes including dilution, absorption and flocculation and sedimentation can sustainably reduce pit lake contaminant concentrations to acceptable levels for risk and enable end use opportunities to be realised. Flow-through may be a valid mine closure strategy for pit lakes with poor water quality. However, maintenance of existing riverine system values must be 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 strategies must be scientifically justifiable and risk-based for both lake and receptors potentially affected by surface and groundwater transport. Due to the high-uncertainty associated with this

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complex strategy, biotic and physico-chemical attributes of both inflow and decant river reaches as well as 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 prior to mine relinquishment.

Contents

1. Introduction

Due to operational and regulatory practicalities, pit lakes are significant legacies of many mine lease relinquishments (Castro and 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 produce acid and metalliferous drainage (AMD) forming in pit lakes (Castro and 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 social and environmental values e.g., recreation, aesthetics and ecosystem services (sensu DIIS, 2016) and present practically perpetual risks c.f. Nieto et al. (2013) to surrounding communities and environmental values (Hinwood et al., 2012; McCullough and Lund, 2006). As a result, mine closure guidelines and regulations increasingly require assessment of long-term pit lake risk to surrounding ecological and social environments (McCullough, 2016; McCullough et al., 2009a).

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 (DIIS, 2016; Williams, 2009). 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 and McCullough, 2011; Vandenberg and McCullough, 2017).

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 maximize short- and long-term pit lake opportunities (McCullough and Lund, 2006).

The hydrological setting of lakes is well known as a key factor for determining pit lake water quality (Kratz et al., 2006; Sawatsky et al., 2011; Straskraba, 1999). Lakes are usually storage elements in river networks, reactors transforming many of water constituents and sinks for particles and dissolved water constituents, but lakes may also act as sources. Thus, pit 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 management approach for controlling water quality both in pit lakes and in other surface waters e.g., Schultze et al. (2011a). However, opportunity and values of both types of water bodies, pit lakes and other surface waters, have to be considered when choosing such management approaches.

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:

- 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 and/or lower salinity, river water is required to maintain a minimum pit lake water level or minimum water quality to meet certain criteria, or, conversely;
- 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.

1.1. 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. 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 (Fig. 1a), source (surcharged) (Fig. 1b) and perched above local groundwater levels or flow-through (Fig. 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 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 (Fig. 1c) hydrogeology (may or may not be expressed as surface water down-gradient) or as flow-through surface water hydrology (Fig. 1d).

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

1.2. 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 of 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 often is not able to survive in lakes due to too high sedimentation losses and is replaced by organisms which are better adapted to the hydrodynamic conditions in lakes (Bridgeman et al., 2012; Maavara et al., 2015; Powers et al., 2014; Reynolds et al., 1994). Growth of lake plankton and its eventual death and sedimentation often additionally contributes to the role of lakes as nutrient sinks in river networks (Bowling, 1994; Hanson et al., 2015). However, some lake plankton may also be flushed into the river downstream and influence the plankton development in the river (Bahnwart et al., 1998; Prygiel and Leitao, 1994; Yu 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 below, than in the river reaches above the pit lake.

Nutrients imported by river water into pit lakes may stimulate primary production in the lake, even under acidic conditions (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 for lakes (Fyson et al., 2006; Kumar et al., 2016; McNee et al., 2003; Wen et al., 2015).

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. Such biological processes are usually acting slowly but may become important for improving pit lake water quality over long terms (Kumar et al., 2013; McCullough, 2008; Opitz et al., 2017; Schäfer et al., 2016; Schultze, 2012).

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., (Caraco et al., 1989; Roden and Edmonds, 1997); Wang and Jiang (2016). However, this is only a potential long-term consideration since phosphorus is

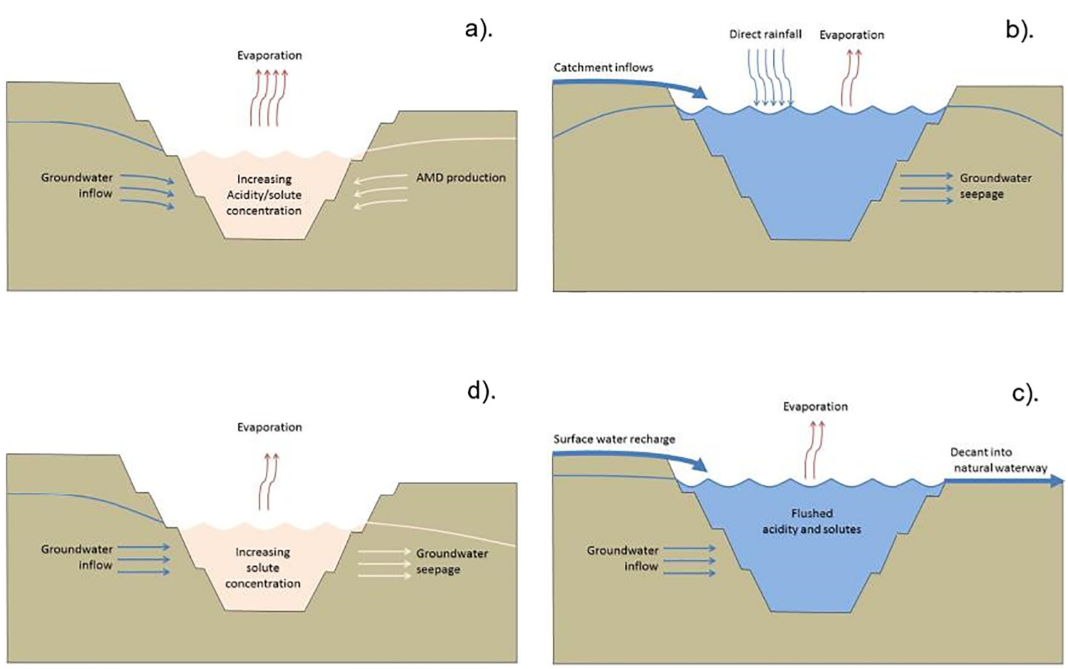

Fig. 1. Conceptual equilibrium hydrogeological regimes for pit lakes. a) evaporative terminal sink, b) surcharged lake, c) surface water flow-through, and d) groundwater through-flow.

usually well fixed in the sediment of pit lakes due to the typically high concentrations of iron and aluminium in pit lake sediments (Grüneberg and Kleeberg, 2013; Herzsprung et al., 2010; Kleeberg and Grüneberg, 2005).

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 with iron (oxy)hydroxide. As long as the lake environment remains oxic and there is 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 is also a source of acidity for the pit lake. 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 pit lake or in its catchment (Blodau, 2006). This may cause continued acidification of a pit lake or a re-acidification of 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 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., 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 affect aquatic life in the receiving river environment also. 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., 2016).

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.

1.3. Evaluating processes and effects accompanying pit lake riverine flow through

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.

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 beside legal, economic and social aspects e.g., existing rights for water use as shown in Table 2.

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 managed 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 neutralization 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 should be directed to maintaining hydrological patterns downstream as necessary for sustaining 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 rivers will be presented 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 worked

Table 1
Potential benefits and risks of flow-through pit lake closure strategy to 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)
Neutralization 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 colonization 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 (Kosík et al., 2011; Stich et al., 2009)
River water can contribute carbon and phosphorus to foodwebs of new pit lakes and especially for acid pit lakes (Kumar et al., 2016; McCullough et al., 2009b)	Lakes may become eutrophic following excess river nutrient imports (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 (McNaughton and Lee, 2010; von Sperling and Grandchamp, 2008)
Nutrients stimulate primary production assisting neutralization (Tittel and Kamjunke, 2004)	Nutrients only available over longer terms due to phosphorus fixation to iron and aluminium in water column and lake sediments (Kleeberg and Grüneberg, 2005; Kopacek et al., 2000)
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 (Santofimia and López-Pamo, 2010; Schultze et al., 2016) 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 presenting risk in case of erosion of the chemocline (Boehrer et al., 2014), chemical stratification gets unstable or even limnic eruption (Murphy, 1997; Sanchez-España et al., 2014)

Table 2
Potential benefits and risks of flow-through pit lake closure 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

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 by anthropogenic catchment activities (McCullough et al., 2013a; McCullough et al., 2012). 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 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.

2. Examples

2.1. Lusatian Mining District (Germany)

The Lusatian Lignite Mining District is a region in eastern Germany strongly impacted by surface mining for lignite in the last about 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 (Geller and Schultze, 2013; Koch et al., 2005; 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 rivers Elbe and Oder is also under discussion (Koch et al., 2009). Fig. 2 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 Fig. 2) are managed as reservoirs and can be used also for flood protection.

We selected the lakes Knappenrode, Lohsa I and Senftenberg for detailed presentation below since they have been in operation already for decades. The presented data on water quality and hydrology were provided by the regional environmental authorities (Landestalsperrenverwaltung des Freistaates Sachsen (LTV) 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 for 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 representatives for water pollution from non-mining anthropogenic activities in the river catchment.

The lakes Knappenrode and Lohsa I are located quite close to each other (Fig. 2, Fig. 3) 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. Fig. 3 shows the details of the connection between the lakes and the local streams as well as the locations of the considered sampling sites. The hydrological and water quality data are shown in Figs. 4 and 5.

For both lakes, only the connection to the main local stream, Hoyerswerdaer Schwarzwasser in case of Lake Knappenrode and Kleine Spree in 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 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 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 Fig. 2) is an example for pit lakes filled and permanently flushed with river water (Werner et al., 2001). Lake

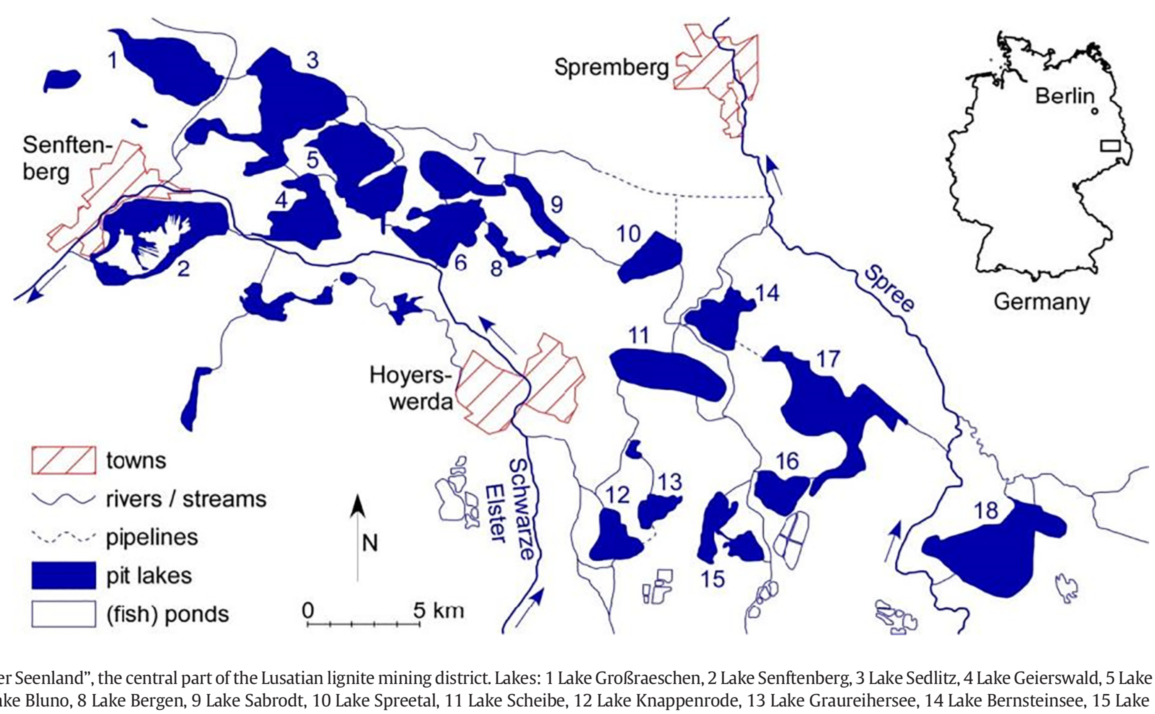

Fig. 2. "Lausitzer Seenland", the central part of the Lusatian lignite mining district. Lakes: 1 Lake Großraeschen, 2 Lake Senftenberg, 3 Lake Sedlitz, 4 Lake Geierswald, 5 Lake Partwitz, 6 Lake Neuwiese, 7 Lake Bluno, 8 Lake Bergen, 9 Lake Sabrodt, 10 Lake Spreetal, 11 Lake Scheibe, 12 Lake Knappenrode, 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.

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

Lake	Lake measurements			Managed upper layer		Year commissioned
	Volume (GL)	Area (ha)	Maximum depth (m)	Volume (GL)	Thickness (m)	
Knappenrode	18.1	286	11	6.4	2.4	1953
Lohsa I	23.3	342	22	5.8	1.8	1972
Senftenberg	102.5	1300	23	20.5	1.7	1973

Senftenberg forms a bypass to the river (Fig. 6) and is intensively managed and used for flood protection (Fig. 7). 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 is 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 gauge Bielen downstream Lake Senftenberg (sampling site R1 in Fig. 6 and Fig. 7) while the mean annual inflow from Rainitza Stream is in the range of 0.08 to 1.0 $m^3 s^{-1}$.

The river water neutralized 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 of diversion of river water resulted in a temporary drop of pH from >7 to 5 in the main basin in 1995 (Werner et al., 2001). This pH drop demonstrated the importance of the river water for maintaining lake water quality. By collecting and neutralizing acidic groundwater, Lake Senftenberg is operating as a reactor and deposition site avoiding adverse impacts on the ecosystem of river Schwarze Elster (inflow of acidity and precipitation of ochreous material). Fig. 7 demonstrates the role of Lake Senftenberg as trap also for phosphorus and nitrogen. Although the sulphate concentration in Lake Senftenberg is higher than that of Schwarze Elser River upstream Rainitza Stream is the main sulphate adding source for Schwarze Elster River in the vicinity of Lake Senftenberg. The sulphate concentration of Schwarze Elster River is already elevated (see sampling site R2 in Fig. 7) before the water from the lake enters the river. The final changes of water quality in the river stretch from diversion into Lake Senftenberg to the river downstream the lake is reflected by the sampling site R1 (Figs. 6 and 7).

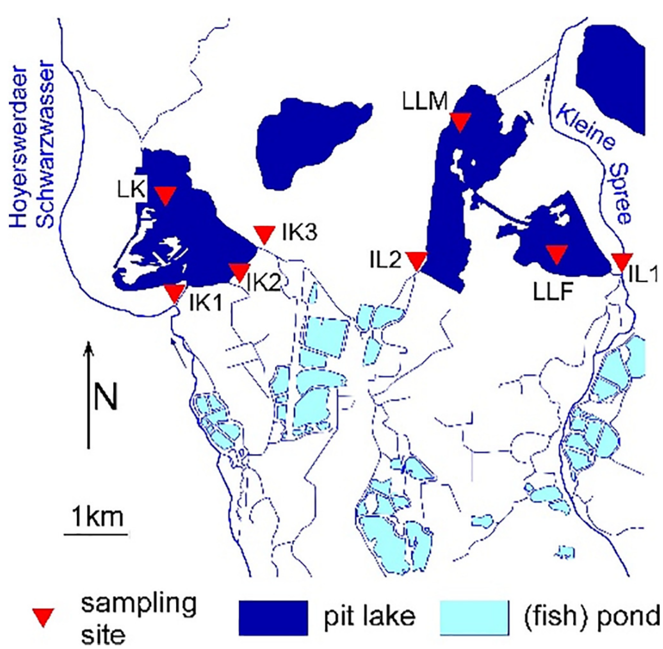

Fig. 3. Location of sampling sites used for Lake Knappenrode (number 12 in Fig. 2) and Lake Lohsa I (number 15 in Fig. 2). LK – Lake Knappenrode; IK1-IK3 – inflows into Lake Knappenrode; LLM – Basin Mortka of Lake Lohsa I; LLF – Basin Friedersdorf of Lake Lohsa I; IL2, IL2 – inflows into Lake Lohsa I.

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 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 Fig. 2, 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 (i) to keep the water of the lakes neutral and its iron and sulphate concentrations below the thresholds for discharge into Schwarze Elster River and (ii) 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 made by filling 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 (Benthaus et al., 2014; Luckner et al., 2013).

2.2. Central German Mining District

The pit 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; Schultze et al., 2011b). 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 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 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 (46.1×10^6 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 105.5×10^6 m^3 in case of use of the full storage capacity. In that case, the water covered area is 5.7 km^2 (LTV, 2007).

Fig. 8 shows that there were only two short periods with inflow from the river for the entire period 2011 to 2015: 7×10^6 m^3 within 3 days in January 2011 and about 30×10^6 m^3 within 5 days in June 2013 during the aforementioned flood event occurring in Central Europe. The frequent small outflow (on average 0.39 $m^3 s^{-1}$ for 2011–2015) results from groundwater entering Lake Borna and giving the lake a slightly positive water balance.

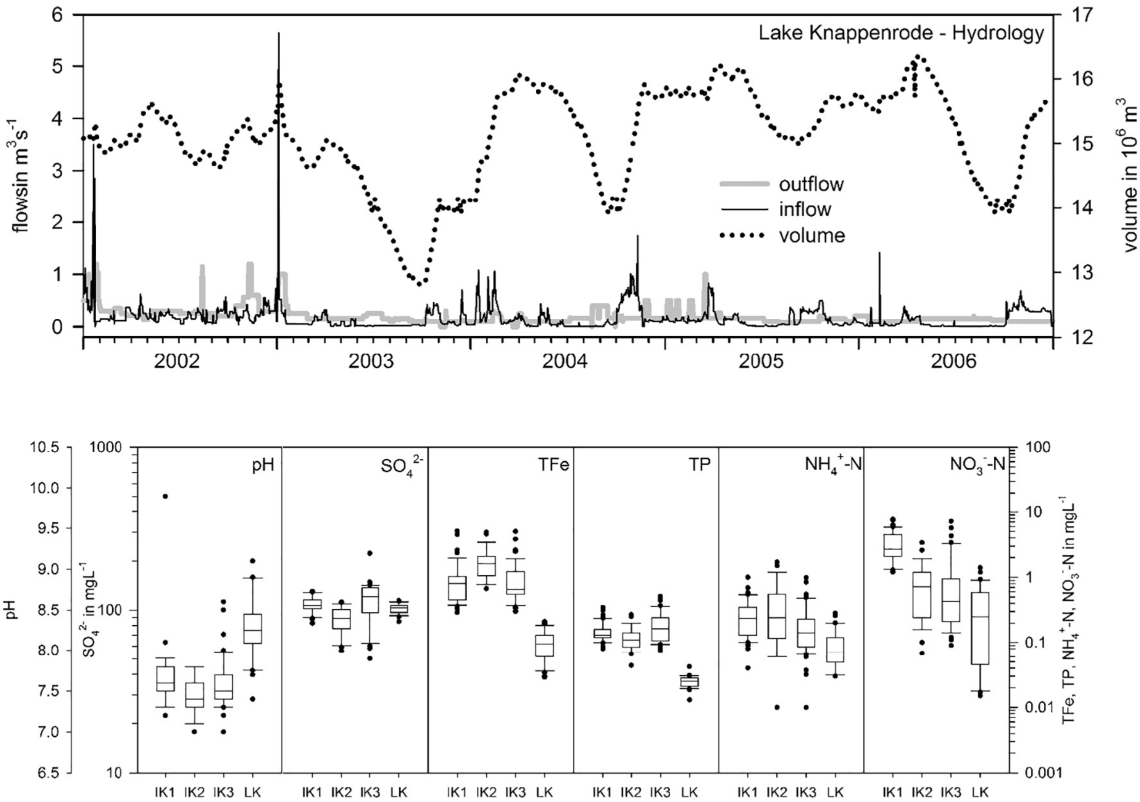

Fig. 4. Hydrology (upper panel; inflow summarizes all surficial inflows IK1-IK3) and water quality of Lake Knappenrode and its inflows (lower panel; IK1, IK2, IK3 – inflows, LK – Lake Knappenrode; for location of sampling sites see Fig. 3) (data provided by LTV).

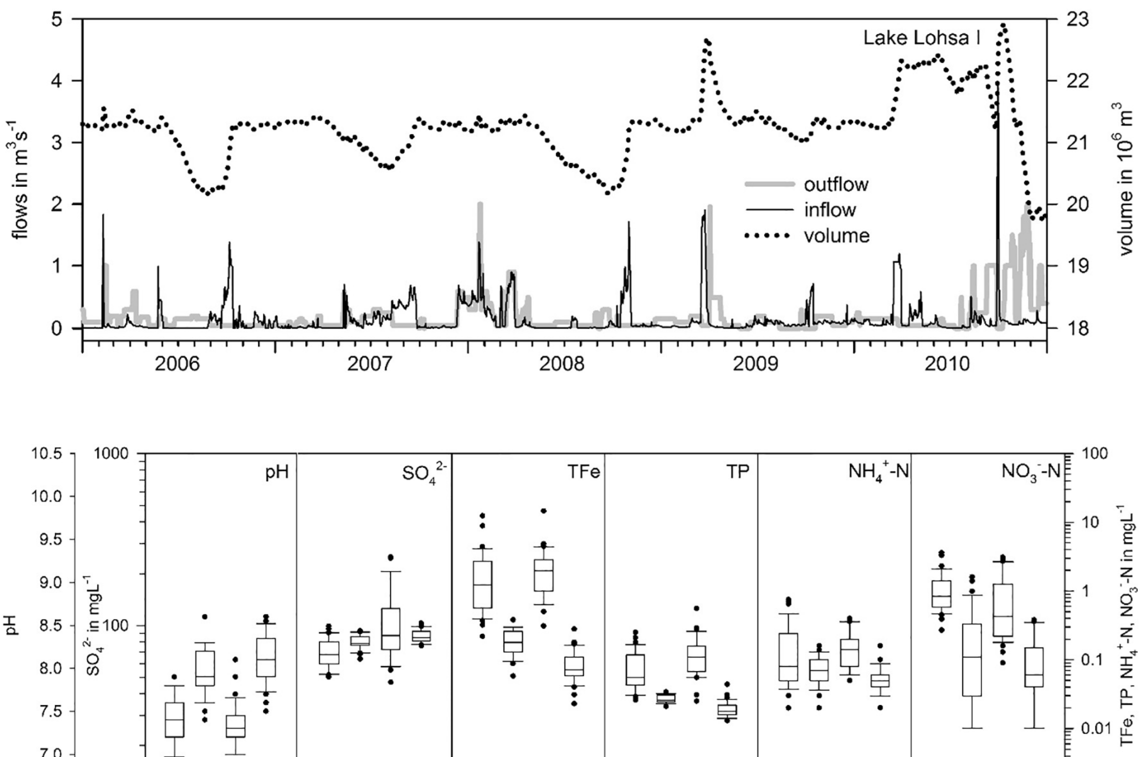

Fig. 5. Hydrology (upper panel; inflow summarizes both surficial inflows IL1 and IL2) and water quality of Lake Lohsa I and its inflows (lower panel; IK1, IK2 – inflows, LLM – Basin Mortka of Lake Lohsa I, LLF – Basin Friedersdorf of Lake Lohsa I; for location of sampling sites see Fig. 3) (data provided by LfULG).

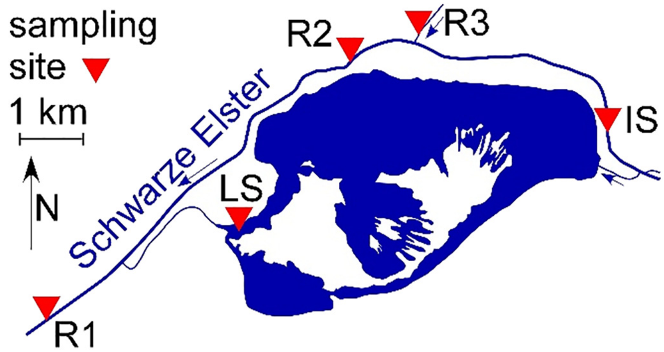

Fig. 6. Location of sampling sites used for Lake Senftenberg (number 2 in Fig. 2). LS – Lake Senftenberg; IS – sampling site at Schwarze Elster River representative for inflows into Lake Senftenberg; R1 – Schwarze Elster River downstream of Lake Senftenberg at gauge Bielen, R2 – Schwarze Elster River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

Lake Borna acts as source of sulphate and iron for Pleiße River (Fig. 8). However, this influence is not very important because of the seldom occurrence of considerable amounts 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 mine Witznitz 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 sink (Fig. 8). The pulses of nutrients entering Lake Borna in case of diversion of flood waters into the lake cause temporarily 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 result in a gradual recovery of lake water quality after a flood event. In case of the flood in 2013, the pre-flood conditions were recovered basically in autumn 2015 as indicated by concentrations of TP at the lake bottom (data not shown).

The Muldereservoir (110×10^6 m^3, northern part of Central German lignite mining district) is our second example from the Central German Mining District. The Muldereservoir was initially filled with river water from Mulde River (1975–1976) which 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 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 load trapped in the sediment of the Muldereservoir shows the importance of this pit lake for the river system downstream with a large load deposited in lake sediments (Junge and Schultze, 2016; Klemm et al., 2005; Zerling et al., 2001) (Table 4).

2.3. Upper Pit Lake, Canada

Pit lakes often offer long-term mine waste containment opportunities (Puhalovich and Coghill, 2011). Canadian oil sand mine closure landscapes contain fine fluid tailings under a water cover as pit lakes. In the future, these pit lakes will be incorporated into the larger mine closure landscape where they are proposed to eventually contain water quality suitable for release to natural systems through in-situ bio-geochemical processes and external freshwater inputs (Dompierre et al., 2017; Dompierre et al., 2016); such as through limited or larger catchment contributions to pit lakes water balances (CEMA, 2012). Thirty EPLs have been included in mine closure plans for the Athabasca oil sands region of Alberta, Canada (McCullough and Van Etten, 2011).

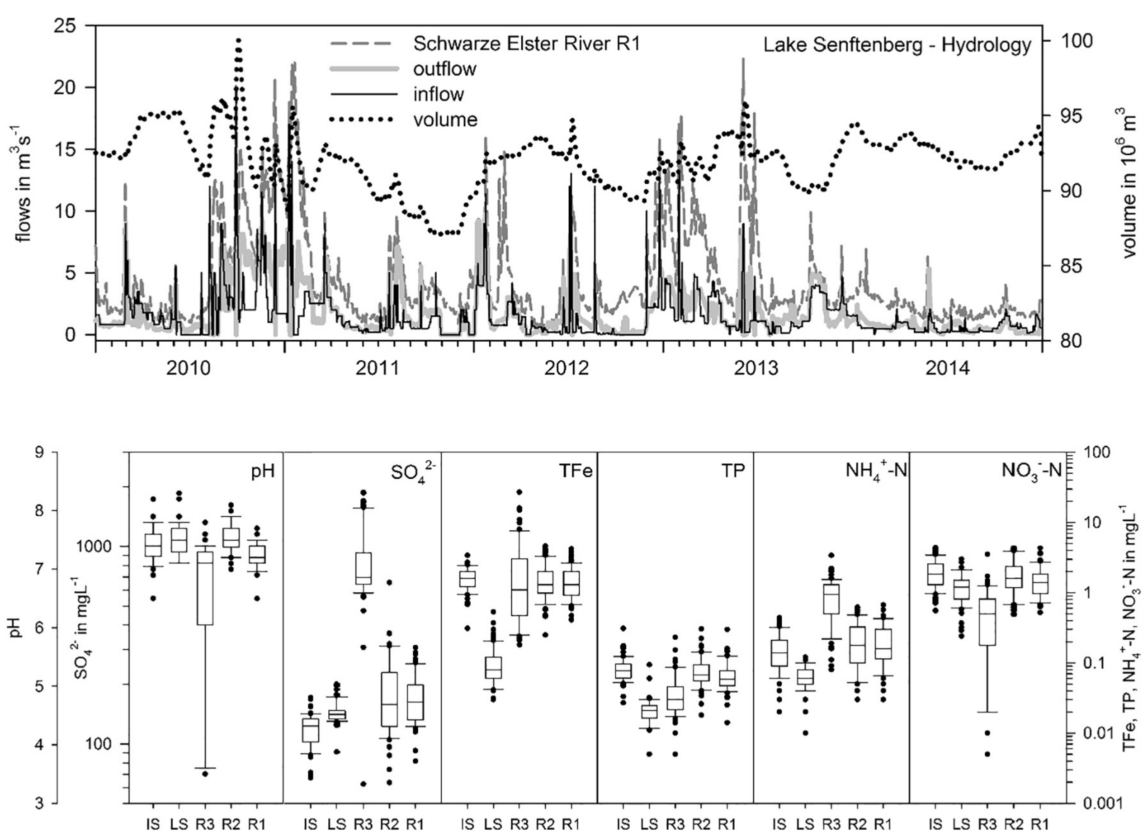

Fig. 7. Hydrology (upper panel) and water quality of Lake Senftenberg, its inflow and Schwarze Elster River at further relevant sampling sites (lower panel; IS – inflow, LS – Lake Senftenberg, R3 – Rainitza, R2 – Schwarze Elster River at Senftenberg Amtsmühle, R3 – Schwarze Elster River at gauge Bielen; for location of sampling sites see Fig. 6) and (data provided by LfU).

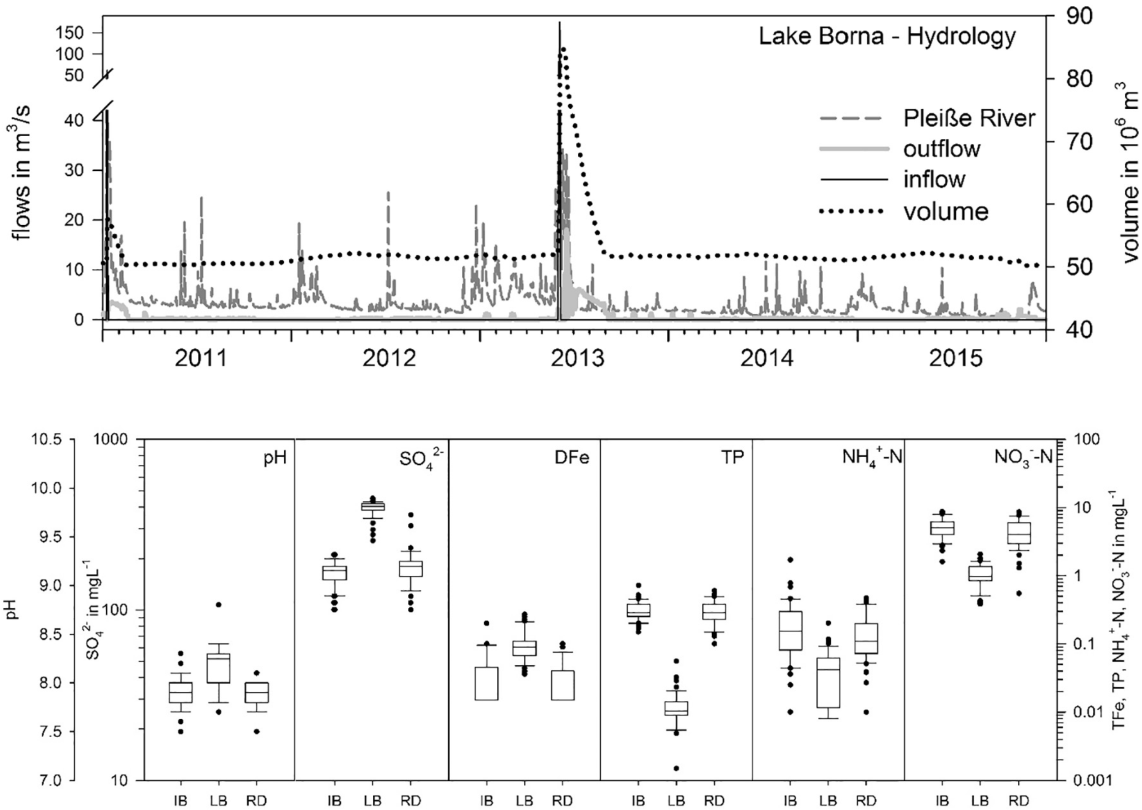

Fig. 8. Hydrology of Lake Borna (upper panel) and water quality in Lake Borna, its inflow and Pleiße River downstream of Lake Borna (lower panel; IB – inflow, LB – Lake Borna, RD – Pleiße River downstream at Lobstädt) (data provided by LTV).

Suncor's DDA3 (Upper Pit Lake; Athabascan oil sand mining region) is planned to contain in-pit tailings with a water cover. That water cover will be in place for some time before discharge to the receiving environment (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.

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).

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

2.4. 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).

2.5. Enterprise Pit Lake, Australia

The Enterprise gold mine pit in the Northern Territory of Australia was closed in 1992 with Pine Creek diverted into the pit void (Fawcett and Sinclair, 1996) (Fig. 9). 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 is now regarded as an off-stream storage that is recharged each wet season with diversion of Pine Creek peak flows into the lake (Boland and Padovan, 2002). Regular flushing offsets the slight acid production that has been found at depth; either due to 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.

2.6. 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) (Fig. 10). This is primarily due to lack of available material to backfill the pit voids. Surface water flow in the region is typically ephemeral, with creek-flow only following heavy or sustained rainfall events. Consequently, although geochemical testing has indicated low to nil AMD risk for pit lake waters, there is therefore a risk otherwise 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 forming a single continuous "channel" pit (Fig. 11). Construction of engineered inlet and outlet structures will be required to mitigate erosion during pit lake filling and discharge enter and exit the channel pit lake i.e. main creeks and smaller tributaries. Construction of levees will also be used to prevent water from entering the channel at uncontrolled locations.

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 e.g., 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), ways to restore the channel pit lake as a regionally representative water body (McCullough and Van Etten, 2011) and habitat restoration priorities for keystone flora and fauna species (Lund and McCullough, 2011).

2.7. Lake Kepwari, Australia

Lake Kepwari is located in the Collie Coal Basin, south-western Australia. The recreation and nature conservation values of the southwest are highly regarded with promotion for wildlife and recreation-based tourism by local business associations and government. The basin now has 13 pit lakes of a range of age, 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 and ceased in 1997. 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 over winters from 2002 to 2008, omitting a 2001 low-flow year. 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 flagged as a water-based community recreation resource for water skiing and swimming (Evans and Ashton, 2000; Evans et al., 2003). However, although CRSB inflow initially raised water pH 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) (Fig. 12). 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 and McCullough, 2009). Consequently, as closure criteria have not been met, the lease remains unrelinquished and proposed end uses are not yet realised.

Fig. 9. Enterprise pit lake.

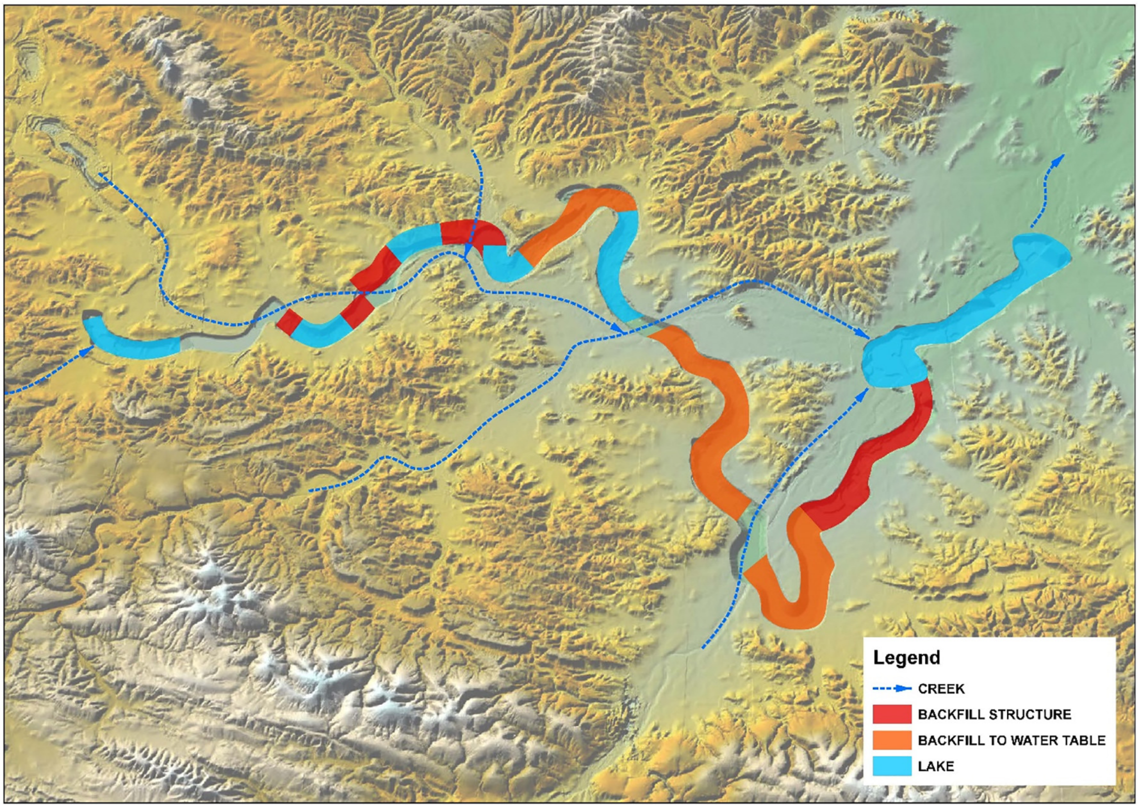

Fig. 10. Closure landforms showing mine pit and flow-through pit lake (after Rio Tinto Iron Ore, 2011).

During August 2011, heavy rainfall led to the CRSB flowing into the lake and decanting downstream again (Salmon et al., 2017). 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 riverine flow-through closure strategy was trialled from 2012 to 2014 (McCullough and Harkin, 2015) with the lake becoming neutral by early 2014 and now becoming fresher over time (McCullough, 2015). Concomitant decreases in metal concentrations and increases in organic carbon and phosphorus concentrations have also occurred with an increase in aquatic biotic diversity and abundance as a result. During flow-through there has been no degradation of downstream values defined by water quality guidelines for aesthetics and recreation, livestock drinking or aquatic ecosystem protection with decreases in nutrient concentrations in the eutrophic river.

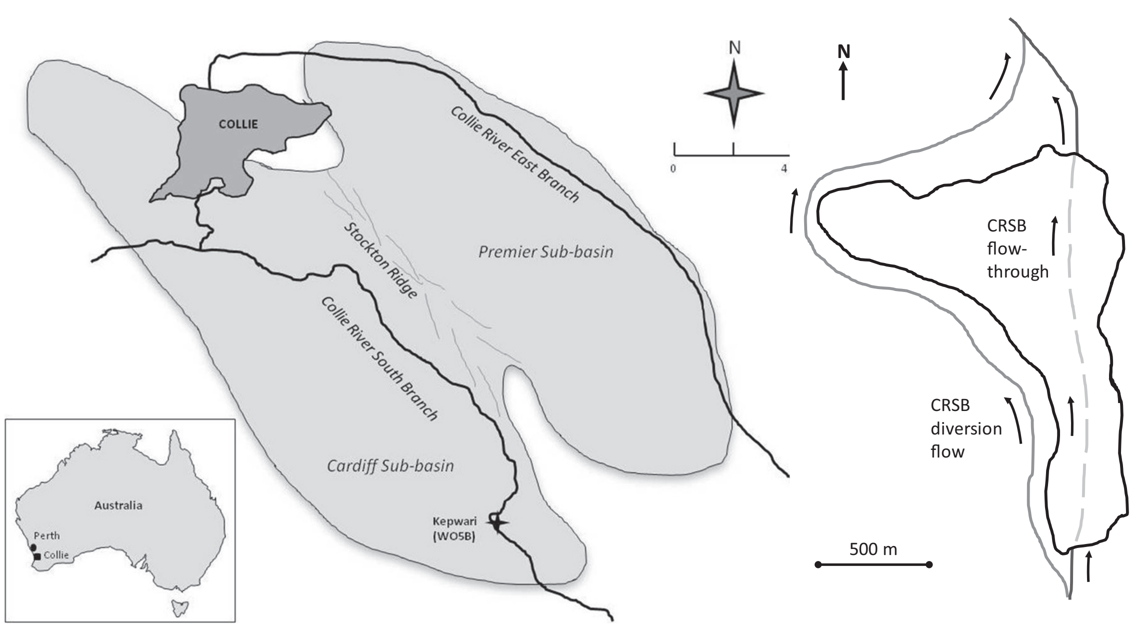

Fig. 11. Location of Lake Kepwari inWestern Australia (left). Lake Kepwari flow-through design showing historicalCRSB channel in black, previous river diversion in dark grey and presumed lakepassage in light grey (right).

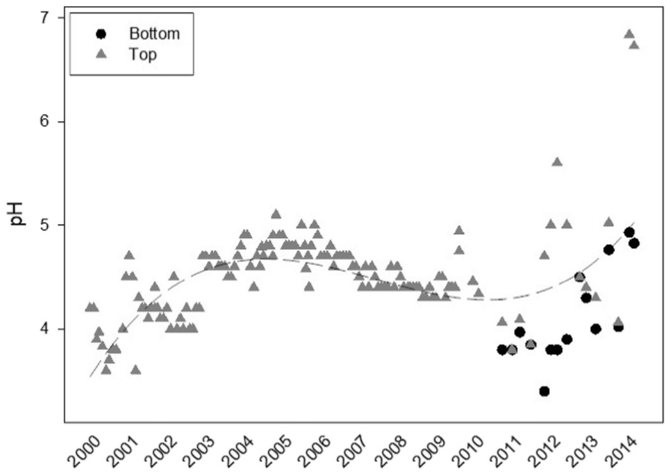

Fig. 12. Time-series graph of Lake Kepwari pH historically, e) Dashed regression line indicates surface water pH trend over time. Dotted vertical line indicates date of breach and flow-through.

Similarly, recreational, stock drinking and ecosystem values have increased in the lake over this period (DIIS, 2016).

3. Discussion

3.1. General aspects

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 flows-through strongly depends on the current and future climate and the existing and likely future use of water downstream of the pit lake concerned. 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.

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 Weisser, (2011) (Austria), and Halír and Žižka, (2008) (Czech Republic).

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

Safe control of riverine inflow and outflow often requires adequate flow-control infrastructure. Considerable structures may be needed to withstand all occurring flow situations including floods. The end use of pit lakes as reservoirs may also require even the construction of impoundment e.g., as was required for lake examples Knappenrode, Lohsa I and Borna. In order to maximize the options for control of water flow sediment and nutrient transport, a bypass structure for the river around the pit lake river is often desirable. This bypass option also has the potential to limit potential undesirable effects of flow-through on river ecology e.g., migration barriers, introduction of river organisms into the pit lakes and vice versa.

3.2. Lessons learned

Lake Senftenberg in Germany and Lake Kepwari in Australia are examples of pit lakes which require river water flow-through to remain neutral. Such lakes are sensitive to the hydrological management as demonstrated by the short re-acidification episode in Lake Senftenberg in 1995 (Werner et al., 2001) and between when river water filling ceased and flow-through began in Lake Kepwari (Salmon et al., 2017; Salmon et al., 2008). Hydrological management requires careful management and monitoring, in particular in periods of reduced water availability and flow-through, e.g. droughts, altered river water allocation priorities, etc. *Re*-acidification, even only for short periods, can impact pit lake aquatic biota and. If water quality deterioration extends to river reaches downstream of the lake, then river biota here may be impacted as well. Should low pit lake water quality result from insufficient availability of river water for flow-through, in-lake measures e.g., neutralization may be required to protect both pit lake and downstream river biota. Therefore, the planning of flow-through requires carful predictive modelling and risk assessment in order to ensure that enough water for flow through will likely be available even in dry periods e.g., climate change; or altered hydrological condition caused by broader catchment management change.

All examples of realised flow-through in Germany and also Lake Kepwari, demonstrated the potential function of the pit lakes as sinks in the river system, for all contaminants except for sulphate. Due to the high concentrations of iron in the lake sediments, phosphorus is captured by the lakes (Grüneberg and Kleeberg, 2013; Herzsprung et al., 2010; Kleeberg and Grüneberg, 2005). Although Lake Borna is also an excellent example of phosphorus removal, Lake Borna indicates at the same time the limitation of this retention capacity. It took more than a year for the lake to fully recover from the phosphorus pulse caused by the huge flood in 2013 (see Section 2.2). That means that riverine flow-through in pit lakes can help limit river eutrophication but may not negate need to limit phosphorus loads to the river. The same applies for other potential contaminants, such as heavy metals retained by the Muldereservoir pit lake.

The plans for future use of flow-through strategy in pit lakes described in Section 2 provide fewer lessons since these plans still have to be realised. However, these plans clearly demonstrate ongoing support and application of flow-through as an increasingly considered pit lake closure strategy.

4. Conclusions

Riverine flow-through as an environmentally holistic closure strategy for mine lakes demonstrates much promise in reducing social and environmental liability and improving end use opportunity for mine closure. However, hydro-chemical processes will vary between operations and sites based on the specific geological, hydrological and climate characteristic of each river catchment, lake and their combined hydrochemical characteristics. As a result, application of general scientific principles will be required in concert with site-wide considerations of riverine flow-through as a closure strategy. Developing flow-through systems must always be evidence-based using current and reliable data, and accurate predictions of water balance and water quality e.g., from deterministic models.

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