May 2017

This research report is to be used for reference, research or record-keeping purposes only. Reports are not updated after their publication date any may not be relied on as a representation of Oil Sands Alliance

LITERATURE REVIEW OF GLOBAL PIT LAKES

Pit Lake – Case Studies

Submitted to:
Dr. Rodney Guest
Manager of Closure Strategic Technology Development
Regional Development – Upstream
Suncor Energy Inc.

REPORT

Report Number: 1777450

Distribution:

digital: Suncor Energy Inc.
digital: Golder Associates Ltd.

Golder Associates

Executive Summary

Pit lakes are closure features of most open pit mines in Albertan, Canadian and global post-mining landscapes. This report presents a review on the use of pit lakes in mine closure; particularly on those that are used to sequester tailings and mine waste. The summary provided in this report does not reflect a statistical review of all pit lakes because many pit lakes, globally, are not well documented.

The use of pit lakes for long-term containment of tailings and mine waste is recognized as best practice by the mine closure community in many jurisdictions and in global guidance documents. Various sectors of the mining industry consider water-capped, in-pit mine waste disposal to be a best practice in terms of geotechnical stability, geochemical stability and protection of regional aquifers (either by directing contaminated groundwater to the pit or by engineering a preferential pathway around the pit to minimize contact with mine waste). Presented in this report are 12 examples of successful pit lakes (6 of which were used to sequester tailings and/or mine wastes), 16 examples of pit lakes that are being extensively managed towards success (14 of which were used to sequester tailings and/or mine wastes) and 5 unsuccessful pit lakes (all of which were used to sequester tailings and/or mine wastes).

Globally, there are case studies of successful pit lakes that provide beneficial end uses, unsuccessful pit lake legacies that require perpetual active water treatment, and those where interventions have been implemented to manage pit lakes on trajectories toward success. All of these case studies provide learning opportunities for achieving successful pit lake closure in the oil sands, and particularly at Suncor.

The term *successful* as used herein applies to pit lakes that have either:

- met their intended purpose such as fish and wildlife habitat, aquaculture, drinking water, recreation, water treatment, or other uses desired by stakeholders; and/or,
- been certified for relinquishment by regulators.

The term *unsuccessful* applies to pit lakes that:

- have water quality issues, requiring water treatment or artificial containment indefinitely;
- do not meet regulatory requirements; and/or
- are not following a deliberately planned trajectory toward meeting regulatory requirements.

The inclusion or exclusion of tailings from pit lakes is not a major differentiator in terms of successful outcomes globally. There are both successful and unsuccessful examples of pit lakes with and without tailings, and success or failure was determined by other factors. A common theme associated with successful pit lakes is adherence to the following practices:

- study and understand the regulatory, social and environmental aspects as early in the mine life as possible, then manage appropriately; with monitoring demonstrating objective achievement and feeding back into a pre-developed adaptive management plan; and
- attain a detailed knowledge of mine pit construction and waste materials, and incorporate that knowledge into a comprehensive mine closure plan that identifies the most appropriate method of treating and storing

each waste stream, and that is developed in advance of mining and adaptively managed throughout operations.

A common theme associated with unsuccessful pit lake case studies encountered in the case studies is:

- mining began before regulatory standards required a full closure plan, and before mine waste characterization and predictive modelling approaches became industry standards.

The option of returning mine wastes such as waste rock, tailings and sludge as mine pit backfill is appealing to the mining industry and generally well received by stakeholders and regulators globally. Pit lakes are used to close mine pits and sequester waste because they carry the following advantages:

- moderation of peak flows and low flows,
- reduced need for above-ground tailings storage facilities,
- prevention of accidental releases,
- long-term geophysical and geochemical stability,
- prevention of acid and metalliferous drainage (AMD),
- hydrogeological containment,
- sediment trapping, and
- water treatment, which may be passive or semi-passive (i.e., requiring occasional intervention).

The case studies show that the major disadvantages of pit lakes are:

- creates or increases legacy liability if improperly planned or if conditions and mine waste characteristics are not well understood, and
- creates a different environment compared to pre-development.

Owing to the advantages listed above, mine pits are commonly used as sites for disposal of mine wastes. Subaqueous disposal of mine waste is often the best overall solution when mine closure is considered holistically.

To date, there are 35 pit lakes planned for the Athabasca Oil Sands Region, including Suncor's Upper Pit Lake. At least 24 pit lakes have been created from coal mine pits in Alberta. Overall, review of the case studies indicated that pit lakes in Alberta have been successful. Pit lakes in Alberta have been iteratively planned and adaptively managed, using lessons learned in each pit lake development to improve the outcome of subsequent pit lakes. Several of the pit lakes in Alberta provide high end use values as recreational and fisheries waterbodies with good water quality.

Consideration of Suncor's recent regulatory applications, as well as the PASS process, shows that Upper Pit Lake closure planning fits within the range of factors that affect pit lake success. The research conducted so far can be considered industry leading in terms of scale of study completed, knowledge gaps addressed, ability to

manage a range of outcomes and incorporation of achievable closure objectives. Suncor's plans for Upper Pit Lake compare favourably to global examples, in terms of:

- **The tailings treatment technology** – the PASS Process appears to address two of the most significant limitations to creating of aquatic habitat in oil sands pit lakes: TSS and toxicity resulting from stored tailings.
- **The filling strategy** – the deposit will be created during operations, which allows for adaptive management while infrastructure is in place
- **Early mine closure planning** – the research and development plans for Suncor`s pit lakes were not reviewed in detail, but the high level description indicates that this program is industry leading in terms of identifying and addressing knowledge gaps early in the mining cycle.
- **Littoral zone creation** – the surrounding area (SD9) will be cut back to create littoral zones, which is often a critical limitation in pit lakes, which often have no feasible option to create additional littoral zones.
- **Closure objectives** – the proposed closure objectives appear to appropriately address some of the key environmental limitations to achieving aquatic ecosystems in oil sands pit lakes. The objectives of meeting CCME water quality guidelines and developing fish habitat in Upper Pit Lake are among the most stringent globally for pit lakes.

The review of global case studies for pit lake closure with and without in-pit waste placement provides the following lessons for mine closure generally and pit lake development specifically:

- **Early planning is key** – few closure management options exist at completion of a mine void, particularly so in the context of a largely completed overall mine site. Development of successful pit lakes typically entailed strategically identifying factors that are critical their success, then incorporating those factors into adaptive closure planning, well in advance of 'Rubicon' moments of mine development.
- **Problematic geochemistry must be understood and managed** – most unsuccessful pit lake closures resulted from misunderstood and/or mismanaged enriched geochemistry within the pit void shell or in-pit waste materials, or by altering the conditions (e.g., redox, moisture) to which mine waste is exposed without understanding the implications of those alterations. A common outcome of this misunderstanding or mismanagement is AMD leading to low pH and elevated metal concentrations and salinity.
- **Holistic planning views the pit lake as one part of a larger closure landscape** – successful pit lake closures were typically well-planned in advance and in consideration of other post-mining landform elements across the closure landscape. Holistic planning may improve overall mine closure outcomes (reduced risk and liability) at the expense of reduced pit lake success.

Table of Contents

1.0 INTRODUCTION 1

2.0 PIT LAKES AND MINE CLOSURE 2

2.1 Terrestrial and Aquatic Closure Approaches 3

2.2 Storage of Mine Waste in Pit Lakes 4

2.2.1 Advantages 5

2.2.1.1 Flow Moderation 5

2.2.1.2 Prevention of Accidental Releases 5

2.2.1.3 Long-term Stability 5

2.2.1.4 Preventing Acid Generation 5

2.2.1.5 Hydrogeologic Containment 6

2.2.1.6 Sediment Trapping and Water Treatment 7

2.2.2 Disadvantages 7

2.2.2.1 Creates Legacy Liability if Improperly Planned and Implemented 8

2.2.2.2 Creates Different Environment compared to Pre-development 8

2.3 Generalised Pit Lake Conceptual Model 8

2.3.1 Filling Strategies 10

3.0 PIT LAKES - REGULATORY CONTEXT 11

3.1 Canadian Regulations 11

3.1.1 Provincial Regulations 11

3.1.1.1 Alberta 11

3.1.1.1.1 Coal Mine Pit Lake Guidance 11

3.1.1.1.2 Oil Sands Pit Lake Guidance 12

3.1.1.2 British Columbia 13

3.1.1.3 Saskatchewan 14

3.2 Global Regulations 14

3.2.1 USA 14

3.2.2 Europe 15

3.2.3 Australia 15

4.0 CASE STUDIES 17

4.1 Pit Lake Case Study - Summary of Learnings 17

5.0 SUNCOR DDA3/UPPER PIT LAKE – PASS PROCESS 22

5.1 Tailings Disposal 22

5.2 Filling Strategy 23

5.3 Early Mine Closure Planning 23

5.4 Littoral Zones 24

5.5 Closure Objectives 24

6.0 ABBREVIATIONS AND ACRONYMS 26

7.0 GLOSSARY 28

TABLES

Table 1: Pit Lakes Described in Case Studies 20

Table A-1: Pit Lakes Around the World A-1

FIGURES

Figure 1: Generic pit lake conceptual model for water balance and water column mixing and geochemical dynamics. (Vandenberg et al. 2015a) 9

Figure 2: Marina and Condominium Development on Post Mining Lake Zwenkau, Germany 15

Figure 3: Quarry Lake, a Former Coal Mine Pit near Canmore, Alberta B-4

Figure 6: Conceptual equilibrium hydrogeological regimes for considering backfill of the two study pit lakes. Clockwise from top left: through-flow system, terminal sink, completely backfill through-flow system, partially backfill terminal sink B-12

Figure 7: Location of Lake Kepwari in Western Australia. B-13

Figure 8: Conceptual model of A/. Lake Kepwari flow-through design showing historical CRSB channel in black, previous river diversion in dark grey and presumed lake passage in light grey) and B/. AMD groundwater source shown as pink arrows, sinks and water balance during flow-through. B-14

Figure 9: Jundee project layout and pits (Shaw et al. 2006). B-15

Figure 10: A Jundee pit lake partially backfilled with mine waste. B-16

Figure 11: Lake Geierswald, now developed into a recreational centre for the region. B-17

Figure 4: Berkeley Pit Lake, Montana B-20

Figure 5: Aerial View of Berkeley Pit Lake and Butte, Montana B-21

APPENDICES

APPENDIX A
World-Wide Pit Lakes

APPENDIX B
Pit Lake Case Studies

APPENDIX C
References

1.0 INTRODUCTION

Pit lakes are closure features of most open pit mines in Albertan, Canadian and global post-mining landscapes. This document summarizes the state of knowledge and practice regarding pit lake closure planning and identifies key indicators that have led to successful pit lake outcomes globally.

The term *successful* as used herein applies to pit lakes that have either:

- met their intended purpose by attaining some beneficial end use, such as fish and wildlife habitat, aquaculture, drinking water, recreation, water treatment, or other uses desired by local stakeholders; and/or
- been certified for relinquishment to the crown by regulators.

The term *unsuccessful* applies to pit lakes that:

- have unanticipated water quality issues, requiring water treatment or artificial containment indefinitely;
- do not meet regulatory requirements; and/or
- are not following a deliberately planned trajectory toward meeting those requirements.

As described throughout this document and in Appendix A and B, there are many examples of both of these types of pit lakes in the literature, and there are many case studies that fall somewhere in between, such as those pit lakes that are in temporary care and maintenance or those that require ongoing manipulation to improve or maintain water quality. The cases where engineers and scientists have designed strategies to improve pit lake water quality can be described as success stories in terms of solving legacy environmental challenges.

The review includes pit lakes that are described in academic journals, conference proceedings, government reports and publicly available consultant reports. The review begins with general considerations related to pit lakes and mine closure, in Section 2.0, followed by a brief review of the regulatory context for pit lakes in Section 3.0.

A summary of case studies is provided in Section 4.0. The summary focuses on pit lakes that contain tailings and other mine waste, and on pit lakes in Western Canada. Some well-documented pit lakes from around the world are included in the summary. Additional pit lakes, globally, are listed in Appendix A, along with basic characteristics. Appendix B includes detailed descriptions of the pit lakes that are listed in Section 4.0.

The final section of this document (Section 5.0) evaluates Suncor's plan for Upper Pit Lake based on the key lessons from the case studies.

2.0 PIT LAKES AND MINE CLOSURE

As a legacy landform at closure, mine closure planning must explicitly plan for pit lake closure and consider how pit lakes fit within broader mine closure objectives.

Mine closure is the practice of planning and executing closure of the mining-disturbed landscape. This landscape includes the project area, and may also entail consideration of the broader region. Leading mine closure practice seeks to holistically reduce the total project closure risk and maximize the total project closure benefit by considering landforms inter-dependently of each other. This holistic practice recognizes the implications of closure options for each landform on other landforms and how these options affect the primary aim of a successful complete site closure.

Closure planning begins for the site and also for landforms, at conceptual levels of understanding. Further detail on final landform risk, and management of this risk, is achieved through increasingly more detailed studies through the life of mine towards closure.

Mine closure landforms are closed in accordance with both the full catchment scale (which includes the entire mine and the natural watershed in which it is located), but also in consideration of each other within the catchment. The closure of any individual landform will affect the design, construction and performance of other closure landforms. Integrated mine closure across a catchment considers:

- long-term stability and overall risk to safety,
- availability of construction materials,
- mine waste material types to assimilate, and their volumes,
- connection with surface and groundwaters,
- pathways to biological receptors,
- climate, and
- timing of individual processes and overall mine closure.

A given interaction may be positive, negative, or neutral, however in complex systems the interactions are often a mixture of these outcomes which means trade-offs between interactions must be understood and assessed. For instance, there are often practical limitations to armoring material available for the slopes of above-ground landforms. Leading closure planning practice understands and plans the use of this material, allocating it to the highest risk of erosion (McPhail and Rusbridge 2006; McPhail and Rye 2008). This risk will not just be the most likely landform and surface expected to excessively erode; but also the landform (entire or part thereof) with the highest consequence faced by excessive erosion, which can affect safety, the environment, and often both.

Surface water flow is also a prime driver of closure risk as water is responsible for failure hazards such as geotechnical instability, erosion and contaminant transport. Catchments containing mining disturbances are useful spatial battery limits on closure planning, as they represent management units for hydrology.

Pit lakes are a significant closure landform that is increasingly recognized in closure planning. Mine pits can often not be rehabilitated back to a previous terrestrial environment and therefore represent a significant change

in land use values (and consequent company and stakeholder planning) for closure strategies (Van Etten et al. 2012). Pit lakes also form important components of overall mine closure outcomes because of how they:

- interact with regional and local surface and groundwaters,
- contribute to project area geotechnical stability, and
- function as waste storage repositories.

Like all mine landforms such as tailings dams and waste dumps, pit lakes cannot therefore be independently closed without a broader context of the overall mine site, and indeed, broader regional landscape (McCullough 2016; McCullough and Van Etten 2011).

2.1 Terrestrial and Aquatic Closure Approaches

Increasingly, closure of pit lakes is being evaluated more holistically, as assets that can reduce post-closure land disturbance and minimise both operational and closure risks and reduce costs. Mine closure necessarily involves trade-offs when considering where and how to dispose of waste, and the option of disposing of waste in pit lakes must be weighed against the pros and cons of disposing elsewhere on site.

Mine waste is placed in a closure landscape either as a terrestrial landform (sub-aerially) or below either surface or groundwater (sub-aqueously). At mine completion, the waste in a disposal facility (in-pit or above ground) is typically covered with either a “dry” or a “wet” cover to create a terrestrial or aquatic closure landscape. The decision to use dry or wet covers depends on numerous site-specific factors and waste characteristics, and must be evaluated on a case-by-case basis.

Dry covers usually consist of one or more layers of earthen materials (rock and soils), but may also include various engineered materials such as plastic liners, geotextiles, etc., depending on the site environmental conditions and the physical and chemical properties of the waste. Pits with a wet cover maintain a layer of water over the waste. In either case, one of the primary objectives of a cover is to minimize the potential for waste oxidation, especially when there is a potential that the waste may generate acid. The overall acceptance of a pit for waste disposal and the type of cover to use are determined by the geologic, hydrogeologic, climatic and geotechnical conditions at a site, the dimensions of the pit, the geochemistry of waste, availability of alternative disposal methods, contaminant transport pathways and the presence and sensitivity of social and environmental receptors. Each of these factors requires detailed study so that alternate disposal and cover methods can be evaluated comprehensively within the broader mine closure plan.

Backfilling a pit with tailings, whereby waste material is maintained below the recovered water table level and the rest of the pit is filled with benign material may be considered advantageous over a water cap when this option is available (ANCOLD 2012; DIIS 2016; DITR 2007). For instance, tailings are covered by the rebounding groundwater level reducing environmental weathering and transport by surface waters. Complete backfill with waste is often undertaken to completely realize the storage potential of the pit. For example, in-pit tailings were disposed in the Perch and Salmon pits (Jundee Mine) (Parsons Brinckerhoff 2002) and K1SE pit (Marymia Mine, Western Australia) (Lane 2000) to ground level followed by terrestrial revegetation. Mine wastes have also been backfilled to near the water table to achieve wetland revegetation (Flambeau Mining Company 2009), similar to the closure of Suncor`s reclaimed Pond 1.

Key regulatory issues that affect the decision of whether to employ wet or dry closure approaches to pit waste disposal include current and proposed future land use and the potential impact to downstream surface waters and downgradient groundwater. A good understanding of closure surface and groundwater regimes is required as part of closure planning involving in-pit disposal. Monitoring programs of water transport processes are also typically required for in-pit disposal sites.

The water level in a pit lake may also be maintained below the regional groundwater level during waste disposal to contain any contaminants during this period. In some cases, pit lakes have been designed with water levels permanently below the regional groundwater table to draw contaminated groundwater into the pit – this closure strategy is termed 'sacrificial', as the water quality of the pit lake is sacrificed so that the regional aquifer is protected.

2.2 Storage of Mine Waste in Pit Lakes

Storage of mine waste in completed mine pits is considered best practice for geotechnical stability (Morgenstern et al. 2015) because it reduces the amount of material stored in above-ground facilities. Storage of tailings and mine waste under a water cap is considered best practice for geochemical stability (Verburg et al. 2009) because it mitigates against AMD and carries additional advantages, listed below. Therefore, water-capped, in-pit tailings disposal can be used to achieve both geotechnical and geochemical stability.

Operating mines create wastes and can expose materials that pose risks to the environment; backfilling with water provides an opportunity to cover or encapsulate these materials cost-effectively (Jones and McCullough 2011). Accordingly, mine pits are used as sites for disposal of tailings, waste rock, overburden, ore milling and refinery waste, by-products of acid mine drainage (AMD) neutralisation, ashes of coal combustion in power plants and industrial wastes (Schultze et al. 2011).

A variety of tailings deposition methods have been proposed, including:

- slurry deposition on a sub-aerial beach (tailings discharge above the water level);
- subaqueous deposition of slurry tailings from a barge floating on a pond;
- subaqueous deposition of paste tailings; and,
- injection of paste tailings through a down pipe into the tailings mass.

Where multiple pits are developed, mined pits provide a cost-effective opportunity to store tailings in an existing engineered structure rather than build and operate a new tailings or waste rock storage facility (Puhalovich and Coghill 2011).

2.2.1 Advantages

There are several potential advantages to the creation of pit lakes and the storage of mine waste in pit lakes, besides often being the most economical option. The following advantages are common to many pit lakes and are in addition to advantages that can be gained through the pursuit of beneficial end uses that are locally desired.

2.2.1.1 Flow Moderation

Due to their large volumes, pit lakes moderate both high and low flows, which can be beneficial to downstream watercourses. Flow moderation can be particularly beneficial in a newly reclaimed mine catchment, which will have higher than normal flow fluctuations and sediment loads while vegetation is becoming re-established.

Flow moderation can also be a disadvantage if the pit lake causes excessive changes to water temperature, dissolved oxygen and other constituent concentrations in downstream fish habitat; this needs to be assessed on a case-by-case basis.

2.2.1.2 Prevention of Accidental Releases

One of the major advantages of in-pit disposal is that it does not rely on an elevated impoundment structure (such as a dam) to physically contain the mine waste. The wastes are confined below final grade within the confines of the pit. Wastes that can be eroded are normally covered with waste rock or a layer of inert sand and a water layer that is sufficiently deep to prevent wave erosion and resuspension of fine particles. Shoreline features can also be engineered to minimize wind-wave erosion. Filling a pit with mine wastes has the additional benefit of stabilizing the pit walls (Golder 1996; Skousen et al. 2012).

2.2.1.3 Long-term Stability

Open pit mines that have ceased production often provide stable environments in their pits for the disposal of wastes including: tailings and waste rock, industrial process residues, municipal refuse and excavation spoils. A study conducted by the Mine Environment Neutral Drainage (MEND) Program in 1995 identified over 40 sites around the world where open pits have been used for mine waste disposal, including Canada, the USA, Australia and Germany (SENES 1995); some of these are listed in Appendix A, Table A-1 and described in Appendix B.

2.2.1.4 Preventing Acid Generation

One of the main reasons for the use of subaqueous mine waste disposal globally is that it is an effective method for preventing AMD. Subaqueous disposal involves placing solid mining waste under a water cover, sometimes along with lime or some other additive to treat or buffer pore water that will migrate from the tailings to the water cap over time. The purpose of the water cover is to restrict exposure of mine waste to atmospheric oxygen and thus limit the formation of AMD (Gammons 2009).

Oxidation of sulphide minerals within mine waste (i.e. either tailings or waste rock) can result in the generation of sulphuric acid, which reduces the pH and greatly increases the dissolution of metals present in the waste solids. This is important because the potential rate of release of metals to the groundwater and surface water will be directly proportional to the concentrations of metals in the pore water. Acidification can directly cause metal leaching, but metal leaching can also occur at neutral or basic pH when redox conditions change during mining and processing.

Saturating Potentially Acid Generating (PAG) mine waste is an effective method for reducing the rate of acid generation. The rate-controlling process is the diffusion of oxygen through the water in the pits of the flooded waste, which is at least 10,000 times slower than the oxygen flux in mine wastes that are exposed to air. In practical terms, the placement of waste in a saturated environment essentially eliminates acid generation. A water cover is considered best practice for permanent storage of PAG materials (DIIS 2016; Verburg et al. 2009).

Other solid mining wastes that are not acid generating but that contain high concentrations of contaminants have also been used for backfilling material and disposed of subaqueously to restrict exposure pathways. Mine closure guidelines and regulator feedback on mine closure plans are consequently showing a greater recognition of water-capped pit backfilling with mine waste in the context of reducing closure risk and achieving agreed post-closure land use (DMP and EPA 2015; INAP 2014; Larratt et al. 2007; Ramsey and Martin 2009).

2.2.1.5 Hydrogeologic Containment

The hydrogeology of the pit is often the most critical factor for determining the suitability of a pit for waste disposal. Pit hydrogeology will dictate the engineering controls necessary to develop an acceptable disposal option. The key factors include:

- presence of extensive hydraulically transmissive features such as karst features, faults and fracture zones that may connect with other mining areas or important groundwater aquifers or surface waters;
- bulk permeability of the rock around the pit;
- location and gradient of the groundwater table;
- pit water balance and the resulting final equilibrium water level in the open pit;
- stratigraphy and permeability of the overburden and bedrock; and,
- hydrogeology associated with any downgradient receiving water body.

The hydrogeology of the pit lake will, in turn, be strongly affected by the regional climate (Niccoli 2009). In a very dry climate, evaporation from the surface of the pit lake can exceed the other pit inflows (i.e. runoff, precipitation and groundwater inflow). In such a case, the equilibrium pit lake water level may be below the regional water table and the pit lake can act as an evaporative sink resulting in inward groundwater flows (McCullough et al. 2013a). By contrast, in wet climates, the pit lake will have a positive water balance and it is likely to flood back until it overflows to surface water (McCullough and Schultze 2015). In such a case the groundwater flow direction (into or out of the pit) will depend on the relationship between the pit overflow elevation and the regional water table. In a moderate climate such as northern Alberta the pit lake water balance and hydrogeology are engineered to provide outflow most of the time and groundwater interactions make up a small portion of the overall water balance.

If necessary, the hydrogeology surrounding the pit can be engineered to manage contamination, as has been practiced at uranium mines in Saskatchewan as 'pervious surround'. This has become internationally recognized as the best practice for containment and storage of milled uranium tailings (IAEA 2004).

The ideal pit for mine waste disposal has a minimal groundwater gradient across the pit so that contaminant transport by groundwater advection is inconsequential. It is also beneficial if the upper part of the aquifer surrounding the open pit is more permeable than the lower part (i.e. below the level of the waste deposit) and that the waste is relatively less permeable so that most of the flow across the pit occurs above the level of the waste, with minimal infiltration through the waste, discharging into the regional groundwater. This is the case at several oil sands mines, with the pit being mined into lean oil sands, which has low hydraulic conductivity relative to tailings due to the remaining bitumen, overlain by sandy or gravelly surficial aquifers.

Historically, some pit lakes (such as Berkeley Pit Lake, see Appendix B) were developed in poorly-characterized, high-permeability settings, and hydrogeological containment was not adequate. This led to seepage that would migrate off site if not actively treated, is obviously a major disadvantage. However, by today`s standards in Alberta and elsewhere, hydrogeological conditions are generally well characterized before mine development, and the likelihood and consequence of seepage out of pit lakes can be detected and mitigated. In the case of oil sands pit lakes, the pit walls are often planned to be lean oil sands, which has extremely low permeability (i.e., advantageous with respect to hydrogeological containment).

2.2.1.6 Sediment Trapping and Water Treatment

As proposed by all oil sands operations, pit lakes are used globally to provide water treatment. The scale and mechanism of water treatment varies, with the simplest treatment consisting of flow equalization and sediment trapping. Pit lakes have been shown to effectively remove total suspended solids (TSS) and associated particulate metals from disposed mine waste and runoff from the reclaimed mine (ARCADIS 2015; Fisher 2002; Vandenberg et al. 2016). Case studies in Appendix B include pit lakes that are used to:

- settle TSS,
- mitigate AMD,
- provide final polishing for mine water treatment effluent, and
- dispose of water treatment by-products such as lime sludge.

2.2.2 Disadvantages

There are a number of well-known case studies of pit lakes that have become acidic, metal-laden, barren, and generally poor in water quality and ecological suitability (see Appendix A and B for examples). These case studies are mainly, though not exclusively, the result of lack of closure planning and regulatory requirements that were commonplace decades ago in most jurisdictions.

Despite the unfortunate outcome of these pit lakes, they provide a number of lessons for planning future pit lakes, as summarized in Section 4.1 as well as in ARCADIS (2015); Castendyk and Eary (2009), CEMA (2012), McCullough (2011), and Vandenberg et al. (2015a). The lessons learned from these case studies were considered with regards to Suncor's pit lake plans in Section 5.0.

2.2.2.1 Creates Legacy Liability if Improperly Planned and Implemented

Once a pit lake is filled, it can create a significant liability if it is not properly understood and managed. There are many examples of pit lakes that have become legacy liabilities, including pit lakes in B.C. (Stevens and Lawrence (1998), superfund sites such as Berkeley Pit Lake in Montana (Appendix B) and Anchor Hill Pit Lake in South Dakota (Lewis et al. 2003), as well as many other acidic pit lakes globally (see Appendix A, Table A-1 and Geller et al. 2013).

The most common unsuccessful pit lakes are those that were developed decades before the closure planning approaches used today were developed and before mine closure regulations were in place in most jurisdictions. A key commonality in the pit lakes with poor water quality is that they were constructed in the absence of environmental regulations, mine closure practice, predictive models, and in some cases in the complete absence of safeguards or controls. In many cases, the discovery that the mine waste or pit lake was becoming acidic has been late in the life of mine or during pit lake filling, when there were no feasible options to avoid forming an unsuccessful pit lake.

Early planning requires a detailed knowledge of waste characteristics, their behavior in different environments, the best practices for long-term disposal of each type of waste, and the site-specific factors that affect the mine. This information allows for strategic waste placement that can minimize closure legacies, which can be implemented during operational phases and into closure (Mackenzie et al. 2016). The success of a pit lake that is formed in the absence of this information depends entirely on the host geology of the mine and the local environmental conditions. Conversely, knowledge of this information early in the mine process, or pre-mining, allows for a wider range of options that can improve the success of the pit lake.

2.2.2.2 Creates Different Environment compared to Pre-development

Few mines are able to be rehabilitated to replicate their pre-mining state (Doley and Audet 2013). In most cases, the creation of a mine closure landscape will result in significantly different landscapes, with differing landforms and, consequently, differing levels of overall risk and opportunity (McCullough and Lund 2006).

Constraints on oil sands mine closure that preclude restoration of a natural state are described in Sections 7 and 8 of CEMA (2012). Given that oil sands mines cannot be restored to predevelopment conditions, the objective is to achieve equivalent land capability, which means that "*the ability of the land to support various land uses after conservation and reclamation is similar to the ability that existed prior to an activity being conducted on the land, but that the individual land uses will not necessarily be identical*" (*EPEA*, Conservation and Reclamation Regulation).

Despite the change from pre-development conditions, pit lakes and other closure features can provide benefit to society, if properly planned, including engagement with stakeholders on desired end uses (McCullough and Lund 2006; Vandenberg et al. 2015a).

2.3 Generalised Pit Lake Conceptual Model

All pit lakes are subject to a number of physical, chemical and biological processes that will determine the suitability of the pit lake environment to support aquatic life and to release water to the receiving environment. Some of these processes are common to all pit lakes (e.g., wind forcing and convective mixing), whereas some are distinct to given mine types (e.g., geochemistry, pit shells reflecting mine plans and mining methods) or

geographies (e.g., ice cover). A general pit lake conceptual model, showing the major components of the water and mass balance, is illustrated in **Error! Reference source not found.**.

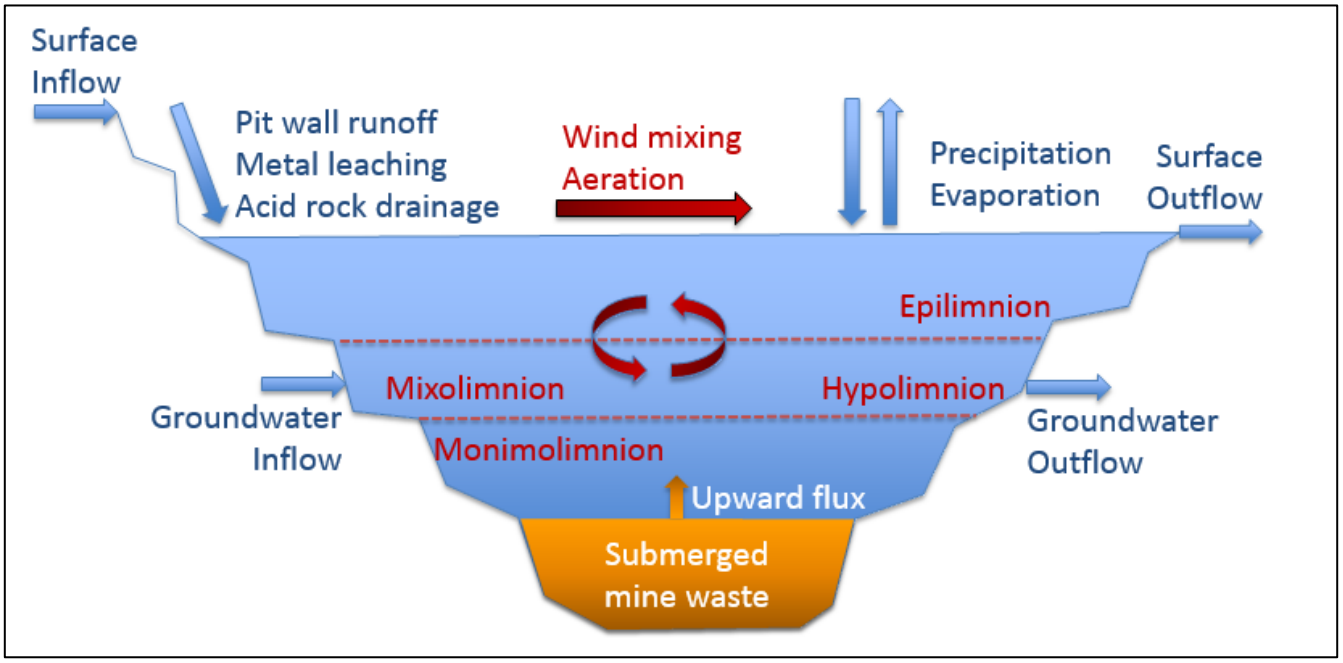

Figure 1: Generic pit lake conceptual model for water balance and water column mixing and geochemical dynamics. (Vandenberg et al. 2015a)

Morphometrically, most pit lakes are deep (often hundreds of metres) with small surface areas (on the order of 10 to 1,000 ha). The ratio of surface area to depth affects the amount of vertical mixing in a pit lake, which will affect its tendency to stratify both seasonally and permanently. Vertical stratification, in turn, affects geochemical processes because a permanently stratified lake will tend to become anoxic at depth. In some global pit lakes, this is a preferable situation because the deeper layer (monimolimnion) can store mine waste that must be isolated from oxygen.

Oil sands pit lakes are generally designed to allow for vertical mixing of the entire water column, to promote aerobic degradation of naphthenic acids and to minimize or avoid the generation of gases such as methane and hydrogen sulphide (CEMA 2012). In this regard, they differ from many global pit lakes which may mix less frequently, or not at all. However, there are many pit lakes, such as the pit lakes created after dragline operations in the foothills coal mines of Alberta, that are long and shallow, and consequently are holomictic (vertically mix at least once per year).

All mine pit lakes integrate mine waste into the receiving environment to varying degrees. Some pit lakes contain submerged mine waste such as PAG waste rock or tailings. Other pit lakes will have water that may only interact with the mine waste that leaches from the pit walls, and in some settings this mass flux may be minimal. Nearly all oil sands pit lakes will receive process-affected water from consolidating upstream reclamation areas. Directly (subaqueously) deposited mine waste is a common feature of pit lakes globally (Appendix A, Table A-1).

There are two main factors that differentiate oil sands pit lakes from the remainder of pit lakes globally:

- the inclusion of oil sands process-affected water, which has unique toxicological characteristics; and,
- the inability of fluid fine tails, which have unique dispersive characteristics, to settle.

All of the other factors in the oil sands pit lake conceptual model are represented globally by other mine pit lakes.

The filling strategy forms an important part of the conceptual model that can be an important determinant of pit lake success, as described in the following section.

2.3.1 Filling Strategies

Pit lakes are formed when an open mine pit is filled with water, either passively by groundwater and precipitation or by diverting surface waters into them. They are usually filled after mining is complete, although some pit lakes can be formed temporarily if dewatering ceases during a period of care and maintenance. Some pit lakes, such as Syncrude's Base Mine Lake, are filled during mining operations while other pits are being mined with the same mining project. Filling a pit lake during operations affords the greatest opportunity to adaptively manage a pit lake, because the mine is usually generating income that can fund pit lake management and closure works. Additionally, infrastructure remains in place to conduct earthworks, pumping and other energy-consuming activities while the lake is being actively managed. Progressively reclaiming pit lakes during operations is a best practice in mine closure because it supports earlier relinquishment back to the crown.

All pit lakes will receive surface runoff; although some may only collect direct precipitation and pit wall runoff; some have reclaimed mine runoff or natural waters diverted through them. Pit lakes that have both surface inflows and outflows are termed "flow-through" pit lakes, and those with groundwater inflows and outflows are called 'through-flow' lakes; whereas those lacking an outflow are called "terminal sinks". The former two lake types are generally associated with better water quality than the latter, which may be deliberately designed to accumulate contaminated mine waters over the long term and to isolate mine waste from the receiving environment.

The volume and quality of groundwater inflow varies as well; many pit lakes globally are filled primarily with groundwater, whereas oil sands pit lakes typically will receive low amounts of groundwater inflow because they are mined into low-permeability, lean oil sands. They are fortunately located next to a river with adequate surplus discharge to fill the pit lakes, which can improve the outcome of pit lakes throughout the region. This filling strategy is also employed by other mines in Canada and elsewhere (Appendix B).

3.0 PIT LAKES - REGULATORY CONTEXT

Disposal of mine waste in mined-out pits is an established practice in several countries, including Canada. However, as described below, there are few laws or regulations in any country that were developed specifically for pit lakes. Some jurisdictions (including Alberta) have developed guidance manuals to promote successful mine closure planning and implementation.

3.1 Canadian Regulations

There are no federal or provincial laws or regulations that are specifically intended for pit lakes. There are, however, laws and regulations that apply to the creation of and discharge from pit lakes, as listed in CEMA (2012) and Suncor (2016). There are also accepted best practices in most jurisdictions, including guidance manuals and documents that were created by, or in consultation with, government agencies.

Water covers are implemented widely across Canada to mitigate acid and metalliferous drainage (AMD). There are over 200 guidance manuals, case studies, and related documents available on the Mine Environment Neutral Drainage (MEND; see Appendix B) website that draw primarily from Canadian mine reclamation experiences.

The option of returning mine wastes such as waste rock, tailings and sludge as some form of pit backfill is conceptually appealing and generally well received by regulators globally, including in neighboring provinces to Alberta, where subaqueous disposal of tailings and waste rock in pits is an acceptable disposal method and is common practice for large open pit mines.

3.1.1 Provincial Regulations

3.1.1.1 Alberta

The principal legislation in Alberta that regulates environmental aspects of mine closure and mine discharges is the *Environmental Protection and Enhancement Act* (EPEA). Authorizations to emit waste are granted under EPEA, and approvals for oil sands mines include conditions related to pit lake research and closure planning.

The Alberta Energy Regulator (AER) has developed oil sands-specific regulations such as the Tailings Management Framework (2015) and Directive 85 (2016) that set requirements for managing fluid tailings. Both documents defer the establishment of criteria and policy related to pit lakes and future water return. Regulatory requirements for pit lakes have evolved in Alberta, similar to many jurisdictions globally, since the first oil sands pit lake was conditionally approved (ERCB 1994).

Oil sands companies are required to demonstrate that pit lakes can support aquatic ecosystems, including fish, at closure. This requirement for mine closure is largely unprecedented in global jurisdictions.

The Alberta government has participated in the creation of two pit lake guidance documents: one for coal mines, and one for oil sands mines.

3.1.1.1.1 Coal Mine Pit Lake Guidance

In a joint program with Alberta Energy, Cardinal River Coals, Luscar (1991) studied pit lake development as an alternative method of mine reclamation for surface coal mines in Alberta's Foothills and Rockies. Pit lakes were deemed likely to be the only cost-effective method of closing open pits in these areas as the cost of backfilling

would be prohibitive. Pit lakes were expected to provide a number of positive end uses, including fish and wildlife habitat, recreational and aesthetics, and were deemed preferable by the public.

Luscar (1991) reviewed the literature related to creation of aquatic habitat in mine pit lakes and concluded that "*the techniques appropriate to creation and restoration of lakes have been well established*". Based on the available literature, they provided a set of design guidelines for the creation of sport fish habitat in mountain and foothill coal mine pit lakes. These covered many of the same topics covered by the *End Pit Lakes Guidance Document* (CEMA 2012) that would later be developed for oil sands pit lakes.

There are a number of pit lakes in Alberta that have been created from former coal mine pits. Overall, the use of pit lakes in Alberta to close mine pits has been relatively successful, considering that some pit lakes are widely used as recreational and fisheries waterbodies. East Pit Lake near Wabamun, was certified as reclaimed in 1994 and was subsequently used as a recreational fishery (Sumer et al. 1995).

There are several other pit lakes in Alberta, as listed in Table A-1. The pit lakes created near Hinton, Alberta have been well documented since their creation in the 1980s and in recent surveys. The case studies below are analogous to oil sands pit lakes in that early findings from pit lake construction were shared industry-wide and used to develop an industry guidance manual, in consultation with the Alberta Government.

The studies listed in Appendix B, in part, formed the basis for a draft *Guidelines for Lake Development at Coal Mine Operations in the Mountains and Foothills of The Northern East Slopes* document that was authored by the End Pit Lake Working Group (EPLWG 2004), comprised of Alberta Environment and coal mine operators. The document was described as "*a reference guide to assist government and industry in designing, managing, monitoring and evaluating pit lakes in the mountain foothills of the Northern East Slopes Region*". Pit lakes were generally viewed as favourable end use features, as they could satisfy the demand for a number of end uses that were applicable to the region. For example, the following beneficial end uses were considered:

- increase habitat diversity in the local area;
- attenuate peaks in discharge and provide more stable flows to downstream rivers; and,
- increase recreational opportunities such as angling.

While the document was generalized to foothill coal mine pit lakes, it stressed the importance of considering site-specific factors and employing adaptive management in creating mine pit lakes; the document itself was structured around the adaptive management process (Allen et al. 2011).

3.1.1.1.2 Oil Sands Pit Lake Guidance

In 2012, the End Pit Lake Guidance Document (CEMA 2012) was developed by a multidisciplinary group of engineers and scientists with experience in oil sands tailings, pit lakes, and related disciplines, under contract for the Cumulative Environmental Management Association (CEMA). Representatives of the Alberta Government attended planning and review meetings during the preparation of the document. The document

> "*presents the scientific and engineering expertise to guide reclamation activities associated with EPL design and construction. It provides practical technical guidance and supporting tools to be used by industry, specifically an interdisciplinary team of operational managers, mine planners, and*

designers. It is also intended to be used as a primary reference by government regulators charged with overseeing the oil sands and designers of research and monitoring programs."

The document is laid out in three parts: The Context section describes oil sands pit lake objectives and regulations, and includes a number of case studies from abroad, some of which are also described herein. Part two describes the natural environment of the Athabasca Oil Sands Region. Part three describes engineering considerations, including timelines and drivers, design, construction and operation.

The End Pit Lake Guidance Document was approved by CEMA and submitted to the Alberta Government for endorsement. In February 2013, the Alberta government provided a letter that supported the use of the document for oil sands mine reclamation and closure planning, with the caveat that the legislative considerations within the "Objectives and Regulations" chapter should be revised in future iterations.

3.1.1.2 British Columbia

Pit lakes are covered generally under the *Mines Act: Health, Safety and Reclamation Code for Mines in British Columbia* (MEM 2017). Similar to the Alberta guidance documents, this Code was developed jointly by government, industry and First Nations.

Because of its steep topography in mountainous areas of B.C., safety considerations in closed pit lakes tend to outweigh environmental considerations more than they do in other jurisdictions. Safety considerations include safe storage of tailings, and safe landforms. In the Code, pit lakes are exempted from some reclamation requirements because the pit walls are considered unsafe to revegetate (Code Section 10.7.13). Part 4 of that section states that "*provision must be made to create a body of water where use and productivity objectives are achieved*". The interpretation and implementation of that requirement is generally left to a Qualified Professional with oversight and approval by government on a case-by-case basis.

In B.C., as in other jurisdictions, subaqueous disposal of tailings in pit lakes is considered best practice for the mitigation of AMD materials at mine closure. The *Guidelines for Metal Leaching and Acid Rock Drainage at Minesites in British Columbia* (MEM 1998) states that:

> "*Underwater storage in flooded pits and declined underground workings can be an effective method of preventing sulphide oxidation from mine walls, fractures, talus debris and backfilled mine wastes… Open pits and declined underground workings which flood unassisted by bulkheads or impoundments have greatly reduced geotechnical stability concerns and maintenance requirements compared to constructed surface impoundments. Backfilling into already constructed flooded pits and underground workings may also reduce the loss of productive land. Disadvantages include the potential for long periods of aerial exposure prior to flooding, potential conflicts with the mining requirements and the high costs of materials rehandling if backfill storage space is unavailable at the time of waste excavation*".

Pit lakes must be assessed in Reclamation and Closure Plans in accordance with BC *Mines Act* conditions, and the plans are required to be updated as part of any mine expansion application, or every five years. Under the *Mines Act*, Metal Leaching/Acid Rock Drainage studies are required, and water quality in the pit must be modelled. If the water quality is not deemed acceptable for discharge, a bond is required for water treatment. Active water treatment plants for closure of pit lakes in B.C. is discouraged

as part of mine closure plans, but they may be approved if necessary and if best practices are practiced (according to a defined Best Achievable Technology policy).

3.1.1.3 Saskatchewan

Environmental agencies in Saskatchewan encourage mining companies to evaluate the use of water-capped pits as a potential disposal option (Donald et al. 1997). Mine operators have even proposed the construction of pits for the sole purpose of disposing of their mine waste. Subaqueous disposal of tailings has been extensively studied and engineered in Saskatchewan, and it is a considered a best practice for the disposal of uranium tailings (See Appendix B and IAEA 2004).

The regulators for the northern Saskatchewan uranium industry (Saskatchewan Environment and Resource Management (SERM) and the federal Atomic Energy Control Board) have recognized in-pit disposal to be the most acceptable means for tailings disposal for nearly a quarter century (SERM 1993). This position recognizes a number of technical advantages, relative to alternative methods, especially over alternative surface-based disposal facilities.

3.2 Global Regulations

Review of global regulations relevant to pit lake closure shows consistency in that pit lakes are considered under broader closure planning requirements, with expectations of demonstrable consideration of safe and non-polluting environments at closure.

Open cut mining that develops pit lakes is common internationally, but regulatory guidance specific for pit lake formation and development is sparse in the international context. Generally, closure guidelines for pit lakes emphasise general aspects of mine closure; particularly safe and non-polluting landscapes (Jones and McCullough 2011). This outcome has best been achieved in pit lakes by applying general mine closure principles while considering every mine site as unique with site-specific constraints and challenges.

The timescale for the evolution of lakes as end uses may range from a few years to hundreds of years. However, in order to be successful, presenting a well-developed pit lake closure plan to regulators and stakeholders should ideally be the conclusion of many years of a well-developed strategy of testing, refinement and stakeholder engagement of an end use development proposal.

3.2.1 USA

The USA and Canada have a similar approach to mine reclamation in that the legislation is found in multiple legislative acts that govern mining (making it sometimes a complicated regulatory framework) (Garcia 2008). Legal requirements for mines proposing to form pit lakes in the US are linked to a number of federal laws governing mining activities and any activity that could harm the environment. A significant difference, however, is that the US has further specific legislation for coal mining activities that would influence those specific pit lake types (Williams 2009).

State laws in the US are unclear as to whether pit lakes as final mining landforms are acceptable or not. Instead, state laws generally rely on other relevant laws regarding ground and surface water quality, and their proposed end use by wildlife and/or humans (as defined in the *Clean Water Act*) to determine whether a pit lake would be acceptable or not. Provincial and State regulations and company reclamation activities are often geared toward returning mining landscapes to some level of productive use, hazard reduction and stable landforms

(DMP and EPA 2015; Government of Alberta 2009; Tuttle and Sisson 1998; Williams 2009). Consequently, it is unlikely that a pit lake with predicted poor water quality would be permitted in the US without an approved plan for remediation at closure (e.g. perpetual external or in-situ water treatment, water diversion, backfilling, etc.).

3.2.2 Europe

The European community (EU) undertook a research and development project with a consortium of partners from February 2001 to January 2004. The overall goal of the Environmental Regulation of Mine Waters in the European Union (ERMITE) project was to provide integrated policy guidelines for developing European legislation and practice in relation to water management in the mining sector (Amezaga and Younger 2004). However, the extensive report did not specifically address the issue of water in mine pits except where those pits have resulted in water being released and impacting water resources in the surrounding environment.

The overriding concern for ERMITE is to prevent pollution resulting from mining, and the concept of pit lakes is not specifically addressed. Significantly different to both Australian and North American approaches, however, there has been collective consideration for development of multiple pit lakes across a region as a 'lake district'. For example, in the former East German lignite mining region of Lusatia, lakes are considered not only from their independent individual contribution to human and wildlife utility, but also on their collective contribution to landscape aesthetics and sustainability opportunities as a novel landscape that can be engineered to meet the needs and desires of local communities regulatory authorities and also regulators (Nixdorf et al. 2005). Post Mining Lake Zwenkau (Figure 2), for example, is a former coal mine pit near Leipzig, Germany, that is now a recreational lake with a marina, lake-front condominium development and PADI dive club.

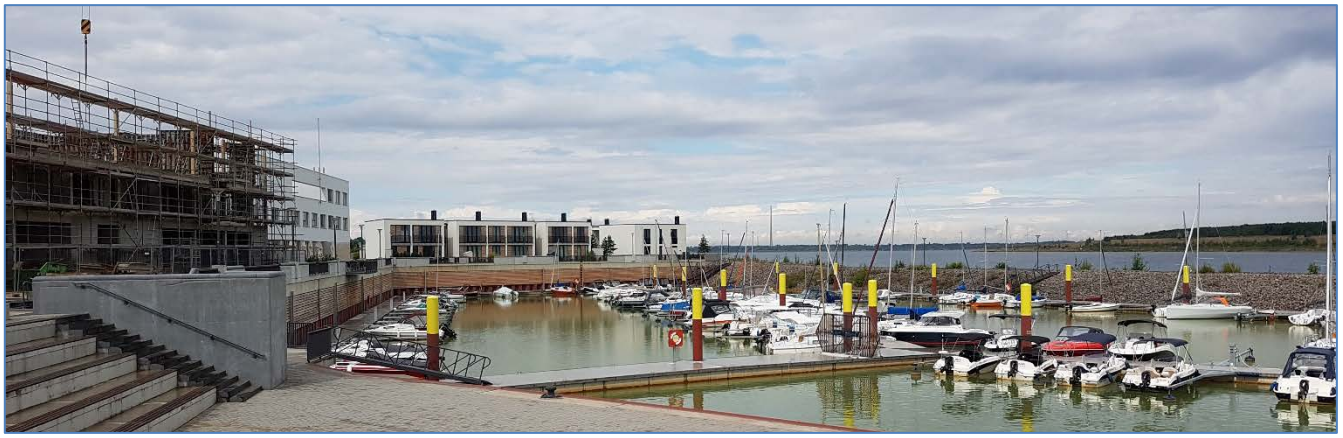

Figure 2: Marina and Condominium Development on Post Mining Lake Zwenkau, Germany

3.2.3 Australia

Australia has mine closure criteria for all commodities except uranium, which is regulated on a state-by-state basis. To address the requirements of these different government bodies, the Western Australian government's Department of Mines and Petroleum (DMP) and the Office of the Environmental Protection Authority have recently jointly prepared *Draft Guidelines for Preparing Mine Closure Plans* (DMP and EPA 2015). These guidelines are unusual in that they explicitly provide guidance on pit lake issues.

Public safety of abandoned open pits in Western Australia is addressed by the Mines Safety and Inspection Act (1994) and the Mines Safety and Inspection Regulations (1995). In part the resulting regulations reflect a case of a member of the public successfully suing the WA local and State governments for approximately $1.8 million in damages following an injury at an abandoned open pit lake (Jones 1996). The Western Australian Mines Safety and Inspection Regulations (1995) contain regulations that apply to the geotechnical considerations that must be adequately considered during the abandonment of an open pit excavation. The Department of Industry and Resources (DOIR) (now Department of Minerals and Petroleum-DMP) publication *Safety Bund Walls Around Abandoned Open Pit Mines* (DOIR 1997) requires that before open pits can be legally abandoned, all long term drainage, stability, and public access issues are adequately considered and controlled. Environmental requirements for abandoned mines are also specified by the license conditions imposed by the Department of Environment and Conservation during the mining project approval process.

Pit lakes with poor water quality are recommended to be isolated from the environment (including fencing and bund walls as required), and pit lakes with saline water/developing salinization are addressed as potential contamination (Dunson 1974; Burke 1990). Pit lakes with good water quality are also addressed as potential risks for feral predators, grazers and stock animal watering, which could impact upon nearby vegetation and disease vector (e.g., mosquito habitat) reservoirs.

A site-specific and risk-based approach to pit lake closure is recommended by government guidelines. This may include specific risk assessments for elements of pit lake risk including geotechnical and water quality within the local and regional socio-environmental context and overall site and pit lake closure objectives.

4.0 CASE STUDIES

This section presents a summary of case studies of pit lakes that have been created in Alberta and globally. A summary of key information about each of the lakes is provided in Table 1, and a description of each pit lake case study can be found in Appendix B. The names of each pit lake in Table 1 are hyperlinked to the description of each pit lake in Appendix B. Basic information about 150 other pit lakes is included in Appendix A.

4.1 Pit Lake Case Study - Summary of Learnings

This review of global pit lake and in-pit mine waste disposal has demonstrated a number of key learnings relevant to Suncor's planned closure strategy of converting the DDA3 pit to Upper Pit Lake and sequestering treated tailings within the pit lake.

- Sub-aqueous disposal of mine waste under a water cap is not a new practice for the global mining industry and is considered best practice based upon peer-reviewed empirical science and globally demonstrated successes.
  - In-pit waste disposal further meets best practice expectations by removing waste landforms from above grade, rehabilitating a topography more congruent with the pre-mining landscape.
- The key to achieving successful pit lakes has been to study and understand the regulatory, social and environmental challenges, then manage appropriately, with monitoring demonstrating objective achievement and feeding back into a pre-defined adaptive management plan, as required.
- The second key factor that appears to determine the outcome of the pit lakes reviewed in Appendix B is the extent of closure planning that occurred before the lake was completed. A common theme of the unsuccessful pit lakes is that they are nearly all legacy open pit mines that began mining before regulatory standards required a full closure plan. Prior to about 1990, the outcome of a pit lake would often be a product of its environment, and there was little or no concern for ecological sustainability. Since that time, closure planning has become a part of the mine planning process, usually beginning at the pre-feasibility stage, or earlier (CEMA 2012). Closure planning is a requirement for approval in all jurisdictions in Canada for open pit mines. For open pit mines, the pit lake closure plan is generally a requirement of the mine closure plan, including a plan to demonstrate acceptable water quality or provide a bond for water treatment.
  - Specifically developed pit lake closure plans have enabled mining companies globally to develop projects that dispose of mine waste in a practicable way that meets regulatory environmental standards and stakeholder expectations. Best practices now include integration of tailings plans, water management plans and mine closure plans.
- A number of Albertan pit lakes have been created from coal mine pits. Overall, pit lakes in Alberta have been relatively successful, considering that some pit lakes provide high end use values and are widely used as recreational and fisheries waterbodies.
- Case studies in Northern Saskatchewan show that a high level of knowledge of mine pit construction and waste materials, combined with an robust mine closure plan developed in advance of mining and adaptively managed, can lead to pit lake outcomes acceptable to regulators and other stakeholders. These in-pit

waste place designs have presented low significant risk and liabilities to local communities and the receiving environment and have provided more practicable mine reclamation. Some pit lakes, such as the Albertan examples, have provided sustainable end use benefit with little maintenance and have met regulatory objectives.

- Following the example of Northern Saskatchewan pit lakes, oil sands pit lakes could serve broader beneficial end uses at closure including long-term reliable and sustainable mine waste containment. After closure, the case studies indicate that well-planned pit lakes containing mine wastes lakes can be compatible with aquatic ecosystems including fisheries.
- Furthermore, in at least three documented cases globally, pit lakes were used to store tailings that were recovered after above-ground tailings facilities accidentally released tailings to the environment. Storage of tailings in pit lakes lowered the overall risk and improved overall mine closure outcomes relative to above-ground storage strategies. In the one documented Canadian example of released tailings, the pit lake was used to passively treat the water overlying the tailings to achieve provincially regulated discharge limits.

- There are a wide range of factors that determine whether a given pit lake's closure outcome will be successful.
  - Pit lakes range in size, shape, geochemistry, climate, hydrogeological setting and nutrient status. However, not all of these attributes consistently contribute to success or failure, with a wide range of values represented by both successful and unsuccessful pit lakes. Nevertheless, the effect of each of these factors need to be considered carefully in mine closure planning, in the context of the mine plan.
- The case studies show a diversity of closure strategies and outcomes globally regarding pit lakes.
  - There are case studies of unsuccessful pit lake legacies that that will require active water treatment indefinitely.
  - The most successful case studies include the Rocky Mountain and Foothill coal mine pit lakes that have established self-sustaining, viable ecosystems in mined out pits.
  - In between these extremes, there are a wide range of issues, some of which have been proven to be reliably mitigated fairly easily and some requiring novel engineering.
  - Intermediate cases include those which have long-term poor water quality but isolate mine contaminants so that other parts of the mine can be successfully reclaimed.
- The most significant challenge to pit lake water quality, globally, is AMD (Castendyk and Eary 2009). Pit lakes developed in the 1980s or prior with unknown or unmitigated AMD tended to become highly acidic with elevated metals, salinity and other constituent concentrations. With the development of modern geochemical analyses and numerical modelling tools, these issues have become much more easily predicted, mitigated, and managed; when these tools are applied. Case studies in B.C., Saskatchewan, Ontario and elsewhere have shown that if geochemical issues are known and appropriately managed before the pit fills, then pit lake AMD can be managed.

- In the Athabasca Oil Sands Region, and in Alberta generally, AMD is a less significant risk than in other places due to buffering provided by alkaline geology. Nonetheless, there are certain mine waste streams that are known to pose AMD risks (Kuznetsov et al. 2015). Testing (required with recent oil sands mine EPEA approvals), can determine the most appropriate method and location for long-term disposal.

Table 1: Pit Lakes Described in Case Studies

Pit Lake Name	Location	Mine Type	Pit Lake Type	Year Filled	Area [ha]	Max Depth [m]	Materials	Planning Details	Function	Key Outcome or Learning
Successful Pit Lakes										
Coal Valley Pit no.1	Hinton, Alberta	Coal	Flow-through	1955	8.5	33	N/A	Limited planning details available	Fish habitat	Subsequent studies identified several factors of pit lakes that can be modified to improve fish habitat suitability.
Coal Valley Pit no. 5	Hinton, Alberta	Coal	Flow-through	1955	3.6	21				
Silkstone Lake	Hinton, Alberta	Coal	Flow-through	1985	6.4	14.8	N/A	Planned based on learnings from Pit 1 and Pit 5	Fish habitat	Natural colonization by local fish was successful; growth rates exceed those in nearby natural lake. Provides habitat for Rainbow trout, Bull trout, Brook trout and Brook stickleback. Some pit lakes have been certified as reclaimed. End use objectives were deemed to have been met by 1991.
Lovett Lake	Hinton, Alberta	Coal	Flow-through	1985	6	18				
Lac Des Roche	Cadomin, Alberta	Coal	Flow-through	1987	16	70				
Sphinx Lake	Cadomin, Alberta	Coal	Flow-through	1998-2005	6.4	50	Lake is mostly filled with waste rock	Planned based on learnings in EPLWG (2004)	Fish habitat	Rainbow trout and bull trout (species of trout listed as Species of Special Concern by Alberta's Endangered Species Conservation Committee) have colonized the lake. Sphinx Lake was awarded the Major Reclamation Award by the Alberta Chamber of Resources.
East Pit Lake	Wabamun, Alberta	Coal	Flow-through	1982-2004	19	7.8	N/A	Planned for fish habitat	Fish habitat	Collaborative effort by TransAlta and the Stony Plain Fish & Game Association. Developed to sustain a sport fishery. Received provincial awards for 'best project to ensure the future of healthy fish or game' and 'best fishery project'.
Springer Pit Lake	Likely, B.C.	Copper	Terminal, pumped outflows	2014-2016	65.2	50	5 Mt tailings and 10 Mm^3 mill process water	None for tailings – was response to tailings dam breach; planned for waste rock deposition at closure	Safe mine waste storage; passive water treatment	Used to store water and tailings since tailings storage facility embankment breach on August 4, 2014. In-pit storage of tailings and water was listed as best practice by the Independent Engineering Review Panel. The pit lake provided passive water treatment of tailings supernatant water and mill process water, such that the water treatment plant was not needed when water first passed through the pit lake.
Trojan Pond	Logan Lake, B.C.	Copper, molybdenum	Reclaimed tailings pond	1991	26	10	AMD tailings	Extensive ecological studies around the mine to understand fish habitat suitability	AMD mitigation; fish habitat; recreation	Fish habitat provides a valuable end use for reclaimed tailings ponds and pit lakes.
Owl Creek Pit Lake	Timmins, Ontario	Gold	Flow-through	1991	15	100	3.26 Mt of acid generating and metal leaching waste rock	Planning occurred when AMD issues were discovered 10 years after mining commenced.	PAG waste rock disposal	Management of PAG waste rock in a flooded open pit is an extremely effective remedial option; a nearby river can be used both to accelerate pit filling and as a receptor once water quality is acceptable. Pit lake can be used to treat mine effluent from neighboring mine.
No.3 Pit Lake	Stratford, Québec	Copper, zinc	Flow-through	1988	1.4	25	0.01 Mm^3 of PAG tailings; 0.276 Mm^3 oxidized waste rock and contaminated soil	Extensive planning and options analysis	Disposal of various waste materials; aquatic recreation	Tailings water cover can be safely discharged and meet provincial water quality guidelines. Pit lake is now a valuable recreation area.
Other pit lakes in MEND study	Across Canada	Various	Various	1950s to present	N/A	N/A	Primarily tailings and waste rock	Varies	Disposal of mine waste	*"In-pit disposal has become a well-accepted practice in many jurisdictions and sectors of the mining industry and in some instances (e.g., uranium in Saskatchewan, Canada) disposal of tailings in mined out pits has become a regulatory policy requirement." (ARCADIS 2015)*
Pit Lakes Extensively Managed Toward Success										
Island Copper Pit Lake	Port Hardy, B.C.	Copper, molybdenum, silver, gold	Manipulated meromixis, flow-through	1996	215	400	Sea water; AMD waste stream	Hydrodynamic and geochemistry conditions predicted and manipulated	AMD mitigation	Natural processes can be harnessed to provide beneficial end uses in pit lakes, such as passive water treatment of AMD waste stream. Mine waste can be successfully contained within monimolimnion of pit lake.
2-South Pit	Campbell River, B.C.	Coal	Flow-through	N/A	2.5	2	0.155 Mm^3 PAG coarse coal rejects	Mostly geotechnical and water balance considerations	AMD mitigation	Transfer of mine waste to pit lake had a number of advantages, including reduced overall footprint; reduced affected catchment area; reduced static water head; eliminated the need for containment dams; eliminated the need to re-slope the pit wall.
B-zone Pit Lake	Northern Saskatchewan	Uranium	Terminal	1991-present	24	57	PAG tailings	Extensive hydrogeological engineering studies	AMD mitigation	PAG and radioactive tailings can be successfully and safely stored in mine pit lakes; requires careful planning and detailed hydrogeological knowledge. Demonstrated "best practice" in Saskatchewan.
DJX Pit Lake	Cluff Lake, Saskatchewan	Uranium	Terminal	1999-present	8	90				
Deilmann TMF	Key Lake, Saskatchewan	Uranium	Terminal	1998-present	N/A	40				
Rabbit Lake In-pit TMF	Rabbit Lake, Saskatchewan	Uranium	Terminal	1985-present	17	122				
JEB Pit	Northern Saskatchewan	Uranium	Terminal	1998-present	14	118				

Table 1: Pit Lakes Described in Case Studies

Pit Lake Name	Location	Mine Type	Pit Lake Type	Year Filled	Area [ha]	Max Depth [m]	Materials	Planning Details	Function	Key Outcome or Learning
Sue C Pit	Northern Saskatchewan	Uranium	Terminal	2008-present	N/A	N/A				
Quirke, Panel, Denison, Stanrock, 7 others	Elliot Lake, Ontario	Uranium	Flow-through	1950s to 1990s	N/A	N/A	170 Mt of tailings	None at time of closure; subsequent studies and management	Tailings containment, AMD mitigation	Pit lake planning is required before mine closure and better yet before mining begins. Given proper planning, pit lakes and water covers are “best practice” for uranium tailings disposal in Ontario.
South Mine Pit Lake	Tennessee, USA	Copper	Meromictic flow-through	2005	8	61	Water treatment sludge	Extensive planning by government and industry, after mining had occurred for 160 years.	Sludge management and water treatment	Modelling and other methods used to understand hydrodynamics can be used to manage pit lake as treatment system, even in a system that has been highly polluted since 1847.
Nifty Copper	Western Australia	Copper	Terminal sink	N/A	N/A	60	PAG waste rock from underground workings	Backfilled to just below equilibrium water level	Sacrificial: containing AMD contaminated waters	Terminal sink pit lakes can contribute to holistic mine closure planning by strategic containment of mine waste in a low geotechnical and water contamination risk setting.
Tallering Peak	Western Australia	Copper	Terminal sink	2012	N/A	15				
Lake Kepwari	Collie, Western Australia	Coal	Flow-through	1998	98	65	PAG waste rock	Backfilled to stabilise and reduce highwall angles below water level	Recreation and wildlife	Pit lakes containing backfill waste materials may accumulate high concentrations of constituents of concern over time. Regular seasonal flushing of pit lake water can reduce the accumulated risk from this as well as assist in achieving high value outcomes from the pit lake.
Jundee	Little Sandy Desert, Australia	Gold	Terminal sink	2002 to present	N/A	N/A	Tailings and waste rock with cyanide and asbestos	Extensively studied and planned	Sacrificial: containing AMD contaminated waters	Evaporation is anticipated to play a dominant role in the chemistry within the pit lake system given the climate at Jundee. This will likely result in gradual increases in concentration of the constituents within the lake system and potentially the development of a density stratified lake ‘trapping’ the poorer water quality at depths in the form of a stratified hydraulic cage post-closure.
Runstädter See	Germany	Lignite	Terminal sink	2001-2002	622	28	Industrial waste (ash and nitrate production)	Aerated to mitigate ammonia	Sacrificial: containing industrial waste	This case study indicates that pit lakes can be used even for the disposal of industrial wastes under certain circumstances.
Lake Geierswald	Germany	Lignite	N/A	2004-2012	620	35	Waste lime	Lime addition and recreation facilities planned	Recreational	Pit lakes can provide valuable recreation opportunities if properly planned.
Unsuccessful Pit Lakes										
Main Zone Pit Lake	Houston, B.C.	Silver, gold	Terminal with water treatment	1994	20.5	120	Waste rock; ongoing disposal of hydroxide sludge	Limited; AMD not discovered until after mining began.	AMD mitigation	Ongoing remediation required; studies being conducted to bioremediate pit lakes. Particulate metals presently being passively treated.
Waterline Pit Lake	Houston, B.C.	Silver, gold	Terminal with water treatment	1994	2.6	40	Waste rock			
Gunnar Pit Lake	Uranium City, Saskatchewan	Uranium	Flow-through	1964	7	110	Waste rock, fish processing waste	None	Economical backfill method	Pit lake provides better method for containing contaminated seepage compared to terrestrial disposal that drains directly to Lake Athabasca that exists elsewhere on abandoned mine site.
Tailings Lake	Northwest Territories	Gold	Terminal	1990-1997	50	14	Wastewater and 11 Mt of tailings	None documented; mine owner went bankrupt.	Tailings containment	Planning is required to develop pit lakes. Mine site has been used for limnological and remediation research.
Berkeley Pit Lake	Montana, USA	Copper	Terminal sink	1982	128	275	130 Mm^3 of AMD; lime treatment sludge	None documented	Sacrificial sink	Elevated metals and ion concentrations. Pit water is used as a benchmark for many innovative treatment process (e.g., EPA Mine Waste Technology Program). Revealed the importance of proper waste characterization, closure planning, monitoring, prediction, and public consultation. These were not practiced at today’s standards if at all when Berkeley Pit was mined.
Natural Lakes used for Tailings Disposal (Successful)										
Wabush Lake	Labrador City, NL	Iron ore	Natural lake	1962 (tailings)	N/A	N/A	Flocculated tailings	None documented for original deposition; switched to treated tailings in 2004	Disposal of tailings	Treated tailings successfully returned Wabush Lake to a more natural state by eliminating dispersal of iron throughout lake.

5.0 SUNCOR DDA3/UPPER PIT LAKE – PASS PROCESS

Considering the case studies identified in Sections 1 and 2, Suncor's aquatic reclamation plans for Upper Pit Lake (DDA3) were evaluated in the context of factors that have led to success or failure in pit lakes elsewhere. This evaluation was not a predictive exercise in the sense of water quality modelling, which has been completed as part of the MOA Application (Suncor 2016), but rather a comparative and qualitative evaluation.

The documents reviewed for this evaluation include:

- Millennium Operational Amendment (MOA) Application
- Suncor Base Plant Application for the Draft Tailings Directive
- Supplemental Information Requests for those applications
- PASS Process Summary provided by Suncor

Note that in the documents above, only the sections related to pit lake environmental performance were reviewed. Considerations such as geotechnical stability of placed tailings are outside of the scope of this review.

5.1 Tailings Disposal

Along with other mine waste types, tailings are frequently placed into pits that will ultimately become pit lakes to avoid above ground tailings dams being left at mine completion.

As demonstrated by the overview of how pit lakes contribute to site-wide mine closure in Section 2.0, the summary of international pit lake regulatory context in Section 3.0 and pit lake closure case studies in Section 4.0; the proposed use of the DDA3 and Millennium Pits for disposal of mine waste under a water cap is not a new practice for the global mining industry.

As discussed in Appendix B, a MEND report (ARCADIS 2015) evaluated Canadian case studies of pit lakes and concluded that;

> *"State of the art in-pit tailings disposal technology includes paste-consistency disposal under a water cover to prevent particle segregation, maximize consolidation and prevent frost penetration in cold climates."*

This statement refers to leading practice placement of tailings sub-aqueously, following treatment. This approach is also that proposed by Suncor's mine closure plans for the pit lake (Suncor 2016).

The general technology was described by authors of that case study as successfully meeting closure objectives of minimal environmental risk as a strategy that contributed to overall site-wide mine closure risk reduction. Nearly all pit lakes globally that store mine waste received untreated wastes; typical of backfill, be it sub-aqueous or sub-aerial. The only other case study that described tailings that were treated prior to subaqueous disposal was Wabush Lake, described in Appendix B.

5.2 Filling Strategy

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

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 successful closure Lake Kepwari case study (Appendix B) shares similarities with respect to the filling strategy of Upper Pit Lake. 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. Regular flushing by more dilute surface inputs of pit lake waters containing elevated COPCs 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 (McCullough and Schultze 2015). Such a strategy must consider risk of pit lake discharge to the receiving environment as well as impact upon both contributing/receiving system and pit lake hydrology; such as flow duration and magnitudes (DIIS 2016). Improved catchment connectivity and incorporation of the pit lake into broader landscape and ecosystem function are further benefits of flow-through closure design.

The filling strategy proposed for Upper Pit Lake supports progressive reclamation, which is a best practice in mine closure.

5.3 Early Mine Closure Planning

As with many aspects of mine closure in general, conducting early studies and trials, followed by increasingly detailed planning and increasing scales of implementation are key factors in successful pit lake closure.

The Elliot Lake and Berkeley Pit Lake case studies (Appendix B) highlight the importance of pre-mining planning and post-mining monitoring to achieving successful pit lake closure. The monitoring programs and planning recommended for Elliot Lake are now typical for all mines in Alberta and generally would be conditions of oil sands mining approvals at both the provincial and federal level. For example, the Fort Hills EPEA Approval 151469-01-00 includes conditions on monitoring (Sections 4.2.5, 4.2.12), environmental management, and pit lake research (Section 6.2). Monitoring, management and research is also required at the federal level to satisfy *Fisheries Act* approvals. The oil sands industry had accumulated a working knowledge of the issues and a general guidance document on pit lakes by 2012 (CEMA 2012), before most oil sands mines had broken ground, and three decades before the aquatic cover is to be placed and aquatic reclamation of DDA3 is scheduled to begin.

The level of early planning required of oil sands pit lakes can be considered industry-leading based on the knowledge base available to the industry. The creation of test ponds at Syncrude and sponsoring of research generated many peer-reviewed scientific articles, several years before their first pit lake was filled (see references in CEMA 2012). The level of research conducted on oil sands pit lakes is comparable to that at other mining industry-leading sites, such as Diavik (Bailey et al. 2013; Neuner et al. 2013; Smith et al. 2013) and Antamina (Beckie 2016).

The Flocculated Tailings testing for tailings is among the most extensive of any encountered in the pit lake literature in terms of pre-testing material properties; with the difference being that most mining operations focus on standard ML/ARD testing. While a detailed review of Suncor's pit lake research program is beyond the scope of this literature review, the high-level description of the program in Suncor (2016) and the more detailed description of the research and development leading to implementation of the PASS process suggest that the overall program exceeds typical industrial practices for developing pit lakes that contain mine waste. And, similar to the research programs mentioned above, Suncor's programs evaluate multiple scales of study, beginning with bench scale tests (geochemical tests in the case of Diavaik [Bailey et al. 2013], column tests in the case of PASS), followed by a small scale version of the system of study (instrumented test waste rock piles at Diavik, test ponds at Suncor), followed by full scale implementation. The filling strategy of Upper Pit Lake affords the opportunity to implement a full-scale pit lake while there are options to recycle water, and to study the outcome of smaller waterbodies in detail before proceeding to larger pit lakes.

5.4 Littoral Zones

Littoral zones are occasionally constructed in pit lakes for ecological habitat. The Alberta coal mine pit lake case studies (Section 3.1.1.1 and Appendix B) have shown the benefit to fish habitat in constructing adequate littoral zones as part of pit lake development. A treated tailings-free littoral zone is planned to be constructed around Upper Pit Lake by excavating into the edge of Sand Dump 9. This is an opportunity that is not commonly available to mining companies when creating pit lakes, because most pit lakes globally are developed in steep-walled mine pits and surrounded by high wall.

5.5 Closure Objectives

Suncor has proposed the following criteria for the PASS process:

- Treatment objectives:
  - Expressing water with < 500 ppm TSS (annual average) from treated tailings; and
  - Producing treated tailings with a clay-to-water ratio (CWR) criterion of 0.5 (annual average).
- Reclamation objectives:
  - Meeting CCME Water Quality Guidelines in the water column.

The closure objective of meeting CCME Water Quality Guidelines in the pit lake is among the most stringent objectives applied to pit lakes, nationally and globally. If these guidelines can be met in the surface water of Upper Pit Lake, it would rank among the cleanest pit lakes globally. It would also result in cleaner water than was found in pre-development conditions. For example, McLean, Wood and Legget creeks all naturally exceed water quality guidelines, as do the Athabasca River and most regional lakes (Suncor 2003).

If laboratory studies to date are replicated at full scale, the water expressed from the treated tailings will be cleaner than what was assumed in the modelling completed for the MOA Application (Suncor 2016), which would make those predictions conservatively high.

The low TSS, high clay to water ratio in tailings, low naphthenic acids, non-toxic expressed water appear to have solved two of the most challenging of the limiting factors with respect to establishment of aquatic systems in oil sands pit lakes. Based on the bench-scale testing completed so far, the PASS process appears to have made significant progress in addressing three of the most important limiting factors with regards to establishing aquatic ecosystems in oil sands pit lakes, as described in Chapter 6 of (CEMA 2012). Namely, the FT process:

- Reduces TSS in the expressed water substantially compared to untreated tailings;
- Sequesters metals and naphthenic acids in the treated tailings; and
- Expresses water that is non-toxic to common sensitive test species.

While additional pit lake closure objectives, such as ecological measures, will likely be required to develop pit lakes and obtain a closure certificate, the PASS process objectives appear to address key limitations in pit lake establishment and appear appropriate at this stage of mine development.

6.0 ABBREVIATIONS AND ACRONYMS

Abbreviation/Unit	Definition
%	percent
≤	less than or equal to
<	less than
AB	Alberta
AMD	Acid Mine Drainage
ANCOLD	Australian National Committee on Large Dams
B.C.	British Columbia
BML	Base Mine Lake
CCAB	Canadian Council of Aboriginal Business
CCME	Canadian Council of Ministers of the Environment
CEMA	Cumulative Environmental Management Association
CID	Channel Iron Deposit
COPC	Constituents of potential concern
COSIA	Canada's Oil Sands Innovation Alliance
CRSB	Collie River South Branch
CVRI	Coal Valley Resources Inc.
CWR	Clay-to-Water Ratio
DDA	Dedicated Disposal Area
DIIS	Department of Industry, Innovation and Science
DITR	Department of Industry, Tourism and Resources (Australia)
DMP	Western Australia Department of Mines and Petroleum
e.g.	for example
EPA	Environmental Protection Authority of Western Australia
EPEA	Alberta *Environmental Protection and Enhancement Act*
EPL	End Pit Lake
ERMITE	Environmental Regulation of Mine Waters in the European Union
FT	Fluid Tailings
GOA	Government of Alberta
ha	Hectare
i.e.	that is
INAP	International Network for Acid Prevention
km	kilometre
km^2	square kilometre
kPa	kilopascals
Luscar	Luscar Ltd.

Abbreviation/Unit	Definition
M	metre
Mbbl	million barrels
m/s	metres per second
m^2	square metre
m^2/g	square metres per gram
m^3	cubic metre
MBI	Methylene Blue Index
MEM	B.C. Ministry of Energy and Mines
MEND	Mine Environment Neutral Drainage
mg/L	milligrams per litre
Millennium	Suncor Millennium Mine
M m^3 or Mm^3	Million cubic metres
MMER	Metal Mining Effluent Regulations
MOA	Millennium Operational Amendment
Mt	million tonnes
NA or N/A	not applicable
No.	number
NWT	Northwest Territories
ON	Ontario
PAG	Potentially Acid Generating
pH	A measure of water acidity or basicity; the negative log of hydrogen ion concentration
Q	quarter (i.e., three months of a year)
QC	Quebec
RoM	Run of Mine
SD	Sand Dump
SERM	Saskatchewan Environment and Resource Management
SK	Saskatchewan
Suncor	Suncor Energy Inc.
Syncrude	Syncrude Canada Ltd.
T	Tonnes
TDS	Total Dissolved Solids
TMF	Tailings Management Framework
TSS	Total Suspended Solids
µm	micrometre
µS/cm	microsiemens per centimetre
USA	United States of America
wt%	weight percent

7.0 GLOSSARY

Term	Definition
Adit	A horizontal mine shaft; sometimes located in a pit lake where a combined pit and underground mine formerly operated.
Anaerobic	Living in the absence of air; generally used to describe biological processes that occur in the absence of oxygen
Anoxic	Devoid of oxygen
Autochthonous	Derived from within – used to describe carbon fixation and other biological growth that occurs within a system, as opposed to that which is transported into it.
Base Plant	The Suncor Energy Inc. Oil Sands Processing Plant and associated Mines, and all associated infrastructure and equipment
Berm	A mound or wall of earth.
Bioaccumulation	The processes of a contaminant progressively increasing in tissue concentration as it moves up the food chain.
Biomass	The total mass of organisms within a given volume of space.
Brackish	A state of salinity in between fresh water and saline.
Bund wall	A constructed berm or wall that is put in place to contain a large spill or release of fluids.
Catchment Area	The area of land from which water finds its way into a particular watercourse, lake or reservoir. Also termed *river basin* or *watershed*.
Closure	The point after shutdown of operations when regulatory certification is received and the area is returned to the Crown.
Cumulative Environmental Management Association (CEMA)	An association of oil sands industry, other industry, regional community representatives, regulatory agencies and other stakeholders designed to develop systems to manage cumulative effects associated with developments in the Oil Sands Region.
Development Area	Any area altered to or planned to be altered to an unnatural state. This represents all land and water areas included within activities associated with the development of oil sands leases.
Dewatering	Removal of groundwater from a geological formation using wells or drainage ditch systems. Also includes the process of removing water from fluid tailings.
Ecosystem	An integrated and stable association of living and non-living resources functioning within a defined physical location. A community of organisms and its environment functioning as an ecological unit. For the purposes of assessment, the ecosystem must be defined according to a particular unit and scale.
Elevation	Measurement of the height of the land above sea level.
Environmental Protection and Enhancement Act **(EPEA) (Alberta)**	The purpose of the act is to support and promote the protection, enhancement and wise use of the environment.
Epilimnion	The upper layer of water in a seasonally stratified lake.
Erosion	The process by which material, such as rock or soil, is worn away or removed by wind or water.
Evapoconcentration	The process of increasing the concentration of dissolved solutes in a lake due to the removal of pure water by evaporation.
Fines	Solids with particle sizes equal to or less than 44 micrometres.

Term	Definition
Flocculant	A reagent added to a dispersion of solids in a liquid to bring together the fine particles to form flocs.
Fluid Tailings	As defined in the draft *Fluid Tailings Management for Oil Sands Mining Projects* Fluid Tailings are defined by the *COSIA Guidelines for Determining Oil Sands Fluid Tailings Volumes*. This guideline provides a set of practices to consistently measure Fluid Tailings top and bottom surfaces.
Footprint	The proposed development area that directly affects the soil and vegetation components of the landscape.
Geochemistry	The chemistry of the composition and alterations of solid matter such as sediments or soil.
Groundwater	That part of the subsurface water that occurs beneath the water table, in soils and geologic formations that are fully saturated.
Holomictic	A lake that vertically mixes (turns over) at least once per year.
Hydraulic Conductivity	The permeability of soil or rock to water. A coefficient “k” depends on the physical properties of formation and fluid. It describes the “ease” with which a fluid will flow through a porous material. “k” is the rate of flow per unit cross-sectional area under the influence of a unit gradient, and has the dimension of $Length^3/Length^2$ x Time or Length/Time (e.g., m/s), but should not be confused with velocity.
Hydrogeology	The study of the factors that deal with subsurface water (groundwater) and the related geologic aspects of surface water. Groundwater as used here includes all water in the zone of saturation beneath the earth’s surface, except water chemically combined in minerals.
Hydrology	The science of waters of the earth, their occurrence, distribution, and circulation; their physical and chemical properties; and their reaction with the environment, including living beings.
Hypolimnetic	Processes that occur in the hypolimnion.
Hypolimnion	The lower layer in a seasonally stratified lake.
In-pit	Below grade, inside the active mine pit. May also be referred to as in-mine.
Land Reclamation	The stabilization, contouring, maintenance, conditioning, reconstruction, and revegetation of the surface of the land to a state that permanently returns the plant to a land capability equivalent to its pre-disturbed state.
Lease	An oil sands agreement that grants rights to develop and use oil sands resources. Two types of leases exist under the Oil Sands Tenure Regulation: primary and continued.
Lithologies	The general physical characteristics of rocks.
Littoral Zone	The outer fringe of a lake, defined as the zone of rooted vegetation, often the portion of a lake up to 2 to 3 m deep.
Macrophytes	Large aquatic vegetation that can be emergent, submerged, or floating.
Meromixis	A state of vertical stratification in which mixing does not occur at any regular frequency.
Mesocosm	Medium sized experimental system conducted outside in order to incorporate natural variation.
Meromictic	A lake that has layers of water that do not mix.
Mesotrophic	The mid-range of trophic status, defined as moderate levels of nutrients and biological productivity.

Term	Definition
Millennium End Pit Lake	An end of mine pit lake that was approved in the TRO application as an area that would include fluid tailings and a water cap. In the proposed plan, Millennium End Pit Lake will be a waterbody without any fluid tailings placement.
Millennium Operational Amendment (MOA)	The Millennium Operational Amendment includes changes to the approved mine, tailings, dedicated disposal area, and reclamation and closure plans. The MOA Application with supporting environmental information, describes the requested approval for the construction, operation, reclamation and closure of planned modifications to the approved mine, tailings, dedicated disposal areas, and reclamation and closure plans as part of Oil Sands Commercial Scheme Approval 8538, as amended.
Mixolimnion	The upper layer of a meromictic lake. The mixolimnion can be vertically well mixed or seasonally stratified.
Monimolimnion	The lower layer of a meromictic lake. The monimolimnion may have gradients of some constituents, but it does not interact with the layer of water above or the atmosphere at any regular frequency.
Neutralisation	The process of adding acid or base to bring the pH of water closer to 7. In pit lakes, neutralization is usually provided by in-situ carbonates or by lime addition.
Oil Sands	A sand deposit containing a heavy hydrocarbon (bitumen) in the intergranular pore space of sands and fine-grained particles. Typical oil sands comprise approximately 10 wt% bitumen, 85% coarse sand (>44 µm), and a fines (<44 µm) fraction, consisting of silts and clays.
Oil Sands Region	The Oil Sands Region includes the Fort McMurray – Athabasca Oil Sands Subregional Integrated Resource Plan (IRP), the Lakeland Subregional IRP and the Cold Lake – Beaver River Subregional IRP.
Oligotrophic	Nutrient-poor with low biological productivity.
Overburden	Material below the soil profile and above the bituminous sand.
Permeability	The capacity of porous rock, sediment, soil or a medium for transmitting a fluid. Has dimensions “length squared”. When measured in cm^2, the value of permeability is very small, therefore more practical units are commonly used (i.e., Darcy [D] or millidarcy [mD].
Pit Lake	An artificial lake located in a mine pit upon closure. Pit lakes may include tailings materials as components of the lower areas of the lake. Pit lakes are typically filled with waters pumped from adjacent rivers, or from runoff waters from reclamation areas.
Porewater	Water in the interstitial space in tailings, rocks, soil and other solids.
Process-Affected Water	Any water that has come in contact with oil sands through an industrial process.
Pycnocline	The zone of maximum gradient in a density-stratified lake; the zone in between the hypolimnion and epilimnion or between the mixolimnion and monimolimnion.
Reclamation	The return of disturbed land or wasteland to a state of useful capability. Reclamation is the initiation of the process that leads to a sustainable landscape (see definition), including the construction of stable landforms, drainage systems, wetlands, soil reconstruction, addition of nutrients and revegetation. This provides the basis for natural succession to mature ecosystems suitable for a variety of end uses.
Redox	Chemical reduction and oxidation; the gain and loss of electrons; state that determines the form of some elements and compounds in pit lakes and can have large effects on water quality.
Riparian	Terrain, vegetation or a position next to or associated with a stream, floodplain or standing waterbody.

Term	Definition
Seepage	Slow water movement in subsurface. Flow of water from constructed retaining structures. A spot or zone, where water oozes from the ground, often forming the source of a small spring.
Surficial Aquifer	Shallow aquifers typically less than 15 m thick in shallow subsurface areas. They consist of unconsolidated sand enclosed by layers of limestone, sandstone or clay.
Tailings	The materials left over after the bitumen is extracted from mined oil sands.
Tailings Ponds	Constructed impoundment structures required to contain untreated fluid tailings. Tailings ponds are enclosed dykes made with tailings sand (i.e., cell construction) and/or overburden materials to stringent geotechnical standards.
Treated Tailings	Any fluid tailings treated through mechanical process or chemical addition (e.g., flocculated fluid tailings). In one of the treated tailings processes (flocculation), after addition of a flocculent, the fluid tailings are expected to quickly densify to ~50% solids, releasing water for recycle. Treated tailings formed during this process are 40 to 60% solids by weight.
Truck and Shovel Operation	The process of using large trucks and shovels to obtain ore from the ground.
Upper Pit Lake	A closure landform that will result from the water-capped DDA3 treatment area. The Upper Pit Lake will have a drainage channel that connects the area to a constructed wetland and eventually to the Millennium End Pit Lake.
Water Table	The shallowest saturated ground below ground level - technically, that surface of a body of unconfined groundwater in which the pressure is equal to atmospheric pressure.
Waterbody	A general term that refers to rivers, streams, and lakes.
Watercourse	Riverine systems such as creeks, brooks, streams and rivers.
Wetlands	Area where the water table is at, near or above the surface or that is saturated for a long enough period to promote such features as wet-altered soils and water-tolerant vegetation. Wetlands include organic wetlands or peatlands, and mineral wetlands or mineral soil areas that are influenced by excess water but produce little or no peat.

Report Signature Page

GOLDER ASSOCIATES LTD.

Document Prepared by:

Jerry Vandenberg, MSc, PChem
Principal, Senior Environmental Chemist

Cherie McCullough, BSc, MSc (Hons), PhD
Environmental Scientist, Mine Closure Specialist
Golder Associates Pty Ltd, Perth, Australia.

Document Reviewed by:

Zane Gulley, MSc
Associate, Project Manager

JV/CM/ZG/kpl

Golder, Golder Associates and the GA globe design are trademarks of Golder Associates Corporation.

https://golderassociates.sharepoint.com/sites/11376g/shared documents/pitlakes_casestudies_may18_2017.docx

APPENDIX A

World-Wide Pit Lakes

Table A-1: Pit Lakes Around the World

Name of Lake	Location	Type of Mine	Area [ha]	Max Depth [m]	Comments	Reference
Canada						
Pit Lake CD	Cadomin, Alberta	Coal	20.5	87	Watershed is primarily comprised of reclaimed mine.	Sonnenberg (2011)
Forestburg Diplomat Mine pit lake	Diplomat, Alberta	Coal	6.2	7	Maintained by County of Flagstaff and stocked with sport fish at time of document. High TDS (2000 mg/L) did not affect trout.	Luscar (1991)
Stirling Lake (Pit 24)	Robb, Alberta	Coal	4.9	23.5	First stocked in 2006 with 750 Rainbow trout, average length: 12 cm. Stocked annually as of 2012.	Hatfield (2008, 2011, 2014); Miller et al. (2013)
Pit 34 Lake	Robb, Alberta	Coal	5.9	5.5	Fishery established through natural recruitment	CVRI (2012); Hatfield (2014)
Pit 35 Lake	Robb, Alberta	Coal	3.5	11.4	First stocked in 2006 with 390 Rainbow trout; Stocked annually as of 2012.	Hatfield (2008, 2011, 2014)
Pit 45 Lake	Robb, Alberta	Coal	6.5	12.5	First stocked in 2006 with 1,100 Rainbow trout; Stocked annually as of 2012.	Hatfield (2008, 2011, 2014)
Pit 43 Lake	Robb, Alberta	Coal	N/A	N/A	Fishery recruitment from Pit 34 Lake.	CVRI (2012); Hatfield (2014)
Pit 44 Lake	Robb, Alberta	Coal	8.8	18.5	Stocked annually as of 2012.	Hatfield (2011); Miller et al. (2013)
Middle and Lower Embarras Lake (Pit 122)	Robb, Alberta	Coal	7.8	17.3	Connected to Embarras River and Pit 142. According to CVRI (2012), Alberta Government plans to use this pit lake as a brood lake for Athabasca Rainbow Trout to stock local fisheries. Fish were documented in this lake by Pisces (2013).	CVRI (2012); Hatfield (2014); Pisces (2013)
Upper Embarras Lake (Pit 142)	Hinton, Alberta	Coal	7.2	7.4	Connected to Embarras River and Pit 122. According to CVRI (2012), Alberta Government plans to use this pit lake as a brood lake for Athabasca Rainbow Trout to stock local fisheries. Fish were documented in this lake by Pisces (2013).	Hatfield (2011, 2014, CVRI (2012; Pisces (2013)
Pit 25E	Hinton, Alberta	Coal	6.8	16.2		Hatfield (2011)
Pit 25S	Hinton, Alberta	Coal	6.8	12.5		Hatfield (2011)
Pit C4	Hinton, Alberta	Coal	5.4	37		Miller et al. (2013)
Luscar Lake	Hinton, Alberta	Coal	10.8	7	Lake is 65% littoral by surface area	Miller et al. (2013)
Black Nugget Pond	Round Hill, Alberta	Coal	7.3	5.4	Successful fish stocking program, despite elevated major ions. The lake remains a sport fishery as of 2017.	www.albertafishingguide.com/location/water/all/black-nugget-mine-pit Luscar (1991)
Quarry Lake	Canmore, Alberta	Coal	2	30	Successful fishery, extensively used for picnicking.	canmore.ca/documents/planning-building.../556-quarry-lake-survey-summary-report
Pleasure Island Pond	Camrose, Alberta	Coal	N/A	N/A	Successful fish stocking program until 1979, discontinued due to dispute with landowners over access road.	Luscar (1991); Mudroch et al. (2002)
Brenda Pit Lake	Kelowna, BC	Molybdenum	38	150	Meromictic. Requires indefinite treatment.	Stevens & Lawrence (1997; 1998) Hamblin et al. (1999)
Nickel Plate Pit Lake	Hedley, BC	Gold	2	N/A	Lake is in care and maintenance. Outflow to shallow aquifer.	Bell (2016), pers. comm.

Table A-1: Pit Lakes Around the World

Name of Lake	Location	Type of Mine	Area [ha]	Max Depth [m]	Comments	Reference
Unnamed	Red Mountain, BC	N/A	N/A	N/A	A person drowned at this pit lake, which is located within the boundary of Red Mountain Ski Resort.	Hoekstra (2014)
Caland Pit Lake	Ontario	Iron	120	180	Inflow of freshwater into Caland resulted in meromictic conditions with a well-defined mixolimnion, chemocline and anoxic monimolimnion. pH remains circum-neutral due to buffering by carbonate wall rock Supported an aquaculture operation for the production of rainbow trout.	Godwin et al. (2010)
Hogarth Pit Lake	Ontario	Iron	100	200	Low inflow and the entire water column was sulfate-saline and aerobic. pH remains circum-neutral due to buffering by carbonate wall rock	Godwin et al. (2010)
Zone 2 Pit	Colomac Mine, NWT	Gold	17	110	Contained relatively saline water contaminated with the mining-related cyanide by-products, thiocyanate and ammonia Phosphate amendments and aeration resulted in removal of ammonia, cyanide and thiocyanate. As a result of snow and ice melt, the pit lake was intermittently meromictic and cycling of contaminants through the oxygenated surface layer would have taken many years. To accelerate the oxidation process, the pit was artificially circulated using two air diffusers at a depth of 57 m.	Pieters et al. (2014); Pieters and Lawrence (2014)
Faro Pit Lake	Faro, Yukon	Lead, zinc	51	90	Strong meromixis with deep mixolimnion	Pieters and Lawrence (2014)
Grum Pit Lake	Faro, Yukon	Lead, zinc	9.5	50	Strong meromixis	Pieters and Lawrence (2014)
Vangorda Pit Lake	Faro, Yukon	Lead, zinc	5.9	50	Strong meromixis	Pieters and Lawrence (2014)
United States						
Oxbow	Louisiana	Lignite	N/A	N/A	Permanent ponds incorporated into the post-mining topography to increase landowner value and provide water for cattle and wildlife	http://www.mii.org/Oxbow/Oxbow.html
Elkville Mine Pit Lake	Illinois	Coal	N/A	N/A	Extensive aquaculture in many area mine pit lakes	Stockinger & Hays (1960)
Pyatt	Illinois	Coal	N/A	N/A		Stockinger & Hays (1960)
Desota	Illinois	Coal	N/A	N/A		Stockinger & Hays (1960)
Lake Ore-Be-Gone (Gilbert Pit Lake)	Minnesota	Iron	56	150	Many pit lakes in area used for fishing, swimming, scuba, drinking water	https://en.wikipedia.org/wiki/Lake_Ore-be-gone
Portsmouth Mine Pit Lake	Minnesota	Iron	49	137	Minnesota Department of Natural Resources has repeatedly stocked the lake with Brook Trout and Rainbow Trout.	*https://en.wikipedia.org/wiki/Portsmouth_Mine_Pit_Lake*
Ridgeway North and South Pit Lakes	North Carolina	Coal	N/A	N/A	Extensive shoreline contouring for erosion control and lake shore development. Creation of wetlands. Support fish population.	http://www.clu-in.org/download/issues/mining/Hard_Rock/Tuesday_April_3/Case_Studies/03_Peacey.pdf
McLaughlin Gold Mine South Pit Lake	California	Gold	N/A	85.3	Meromictic. Intrusion of saline water by subrosion of salt strata in the deeper underground. Accumulation of CO_2 in the monimolimnion.	Rytuba et al. (2000)

Table A-1: Pit Lakes Around the World

Name of Lake	Location	Type of Mine	Area [ha]	Max Depth [m]	Comments	Reference
Spenceville Copper Pit Lake	California	Copper	0.2	17	enrichment of substances due to evaporation Meromictic. Evaporation. Accumulation of iron and other substance in the monimolimnion due to microbial decay of organic compounds.	Levy et al. (1997)
Herman Pit Lake	California	Sulphur, Mercury	9.3	46	The Sulphur Bank Mercury Mine Site (SBM), located in Clearlake, California, is on the Environmental Protection Agency's (EPA) National Priorities List (NPL). Sulfuric acid is produced by oxidation of geothermal hydrogen sulfide venting into the pit; the pH of surface water is approximately 3.	Blum et al. (2015)
Twin City-South Pit Lake	Minnesota	Iron	28.3	69	Intensive aquaculture resulted in degradation of water quality in the lake. Aquaculture was since stopped.	Axler et al (1996, 1998, 2004) Yokum et al. (1997)
Sherman Lake	Minnesota	Iron	N/A	N/A		
Anchor Hill Pit Lake	South Dakota	Gold, Silver, Copper, Lead, Zinc	1.8	26	Meromictic. Measures to neutralize the lake (liming). Addition of organic material to stimulate reductive microbial processes for alkalinity production.	Lewis et al. (2003
Sweetwater Pit Lake	Wyoming	Uranium	24	35	Addition of nutrients accelerated biological activities for an efficient reduction of selenium and uranium below water quality guidelines	Paulson & Harrington (2004)
Robinhood Mine, Dogwood Lake & Tygart River Mine	West Virginia	Coal	0.5	N/A	Rainbow Trout growth trials, public fisheries and reduced reclamation costs.	Miller (2008)
TXU Mining Tatum Mine	Texas	Lignite	N/A	N/A	Reclaimed pit lake using a pond-in-series design to create five wetland areas. Native grasses and forbs planted and more than 40 acres of hardwood species established. Fish stocking also made for 7 local sports-fishing species.	http://www.mii.org/ReclStories/Tatum/Tatum.html
Stone Mining Company	Kentucky	Coal	8.5	N/A	Coal slurry impoundment converted into a recreational lake. Lake stocked with bluegill, channel catfish and largemouth bass.	http://www.mii.org/stonecoal/stonecoal.html
Flambeau Mine	Wisconsin	Gold/silver	N/A	N/A	Site contoured back to its approximate original state, along with the construction of wetlands for a wildlife sanctuary. Also established a series of hiking trails and less intensive walking tracks on the mine site.	Fox (2004)
Mingo Logan	Virginia	Gold	80	N/A	Ponds and wetlands created on previously mined land. Attracts water fowl, aquatic species and other wildlife	http://www.mii.org/ArchWetland/ArchWetland.html
Alford field	Indiana	Coal	N/A	N/A	Two separate pits were mined and reclaimed with several peninsulas and coves, as well as some islands. Numerous ponds and small wetlands included in rehabilitated area to maximize the area's potential for use as fish and wildlife habitat.	http://www.mii.org/Lakewoods/Lakewoods.html
Oxford	Ohio	Coal	N/A	N/A	Large pit impoundment and two large wetland impoundments constructed as part of the reclamation plan. Developed year-round and part-year storage areas, heavily vegetated pasture and areas planted with native trees to enhance specific wildlife habitat.	http://www.mii.org/oxfordcoal/oxfordcoal.html
Twin Creeks	Nevada	Gold	N/A	N/A	Wildlife habitat found safe after an ecological risk assessment was undertaken.	Nicholson *et al*. (2013)

Table A-1: Pit Lakes Around the World

Name of Lake	Location	Type of Mine	Area [ha]	Max Depth [m]	Comments	Reference
Europe						
Saint Louis Pit Lake	France	Coal	N/A	60	Meromictic. Elution of pit walls and inflows of ground water of high TDS concentration due to pyrite oxidation	Denimal et al. (2005)
Fouthiaux Pit Lake	France	Coal	N/A	37	Meromictic initially, then holomictic. Elution of pit walls and inflows of ground water of high TDS concentration due to pyrite oxidation	Denimal et al. (2005)
Lake St Eloy	France	Coal	12.5	13	Small stratified lake created by subsidence of an underground coal mine. Permanent stratification and the development of two water bodies with contrasting chemistry. The superficial oxic layer (i.e. the upper 5 m) is of high water quality and the water, not affected by seasonal changes. In contrast, the deeper layer is permanently anoxic and the waters have a conductivity which is six times greater than in the epilimnion. Drinking water (epilimnion).	Roman-Ross et al. (2005)
Mine Lake 116	Germany	Coal			Mountain bike and walking trails. Wildlife habitat and lookouts and sculptures.	Schultze (2012)
Mine Lake 111	Germany	Coal	10	10.2	Aquaculture. Meromictic. Groundwater inflow of high TDS concentration due to pyrite oxidation.	Karakas et al. (2003
Lake Goitsche	Germany	Coal	105	42	Filling with surface water resulted in rapid acid neutralization	Boehrer et al. (2003) Schultze et al. (2013)
Waldsee Pit Lake	Germany	Coal	0.3	5	Meromictic. Groundwater inflow of high TDS concentration due to pyrite oxidation. Accumulation of iron and DIC in the monimolimnion.	Rücker et al. (1999) Schimmele (1999) Schultze et al. (2013)
Lugteich Pit Lake	Germany	Coal	170	10	Meromictic. Groundwater inflow of high TDS concentration due to pyrite oxidation. Accumulation of iron and DIC in the monimolimnion.	Rücker et al. (1999
Moritzteich Pit Lake	Germany	Coal	16	17.5	Meromictic. Groundwater inflow of high TDS concentration due to pyrite oxidation. Accumulation of iron and DIC in the monimolimnion.	Stellmacher (2004)
Hufeisensee Pit Lake	Germany	Coal	70	29	Meromictic. Intrusion of saline water by subrosion of salt strata in the deeper underground.	Schreck (1998) Maiss et al. (1998) Stottmeister et al. (1999)
Merseburg-Ost 1a Pit Lake	Germany	Coal	280	27	Meromictic. Intrusion of saline water by subrosion of salt strata in the deeper underground.	Böhrer et al. (1998) von Roden and Imberger (2001)
Merseburg-Ost 1a Pit Lake	Germany	Coal	230	36	Meromictic. Intrusion of saline water by subrosion of salt strata in the deeper underground.	Böhrer et al. (1998) von Roden and Imberger (2001)
Lake Wallendorf	Germany	Lignite (Coal)	2.8	27	Two meromictic pit lakes formed in the former lignite mine Merseburg-Ost. Fresh and highly saline groundwater as well as diverted river water filled the lakes. The lakes also received acidic mine water.	Böhrer et al. (1998) Schultze & Boehrer (2008) von Roden and Ilmberger (2001) Boehrer & Schultze (2006)

Table A-1: Pit Lakes Around the World

Name of Lake	Location	Type of Mine	Area [ha]	Max Depth [m]	Comments	Reference
Lake Rassnitz	Germany	Lignite (Coal)	2.3	36	Two meromictic pit lakes formed in the former lignite mine Merseburg-Ost. Fresh and highly saline groundwater as well as diverted river water filled the lakes. The lakes also received acidic mine water.	Schultze & Boehrer (2008)
Lake Baerwalde	Germany	Lignite (Coal)	1290	45	Acidified lake forming in a lignite mine pit. Flooded with surface water from three different rivers and also receives groundwater. Acidity fluxes were underestimated. Reservoir for River Spree (25.5 million m^3).	Fleischhammel, et al. (2010):
Ravlidmyran Pit Lake	Sweden	Sulfidic base metals	4.9	28.9	Meromictic. Primary filling with highly mineralized water caused by elution of pit walls and inflow of high TDS concentration due to pyrite oxidation.	Lu (2002, 2004)
Udden Pit Lake	Sweden	Sulfidic base metals	3.4	50	Oligotrophic, dimictic, acidic, low TSS, elevated metals	Lu (2002)
Iberian Pyrite Belt (IPB)	Spain	Sulfidic base metals	Cueva de la Mora- 1.78 & Confesionarios Pit Lake- 2.48	40 80	Meromictic. Marked vertical trends of increasing temperature and dissolved metal concentrations in the monimolimnia of some pit lakes of the IPB.	Sanchez-España *et al.* (2009)
A Coruna	Spain	Lignite (Coal)	2 km long	187	Several studies concerning stability and water quality of the future pit lake, as well as future use, effects of the Lake on the nearby Barces River and local climate.	Arias & Fernandez (2008)
San Telmo Lake	Spain	Sulfidic base metals	N/A	130	Underground and open pit mining operations, and was abandoned in 1989. pH varies from 2.2–2.6 in the summer to 2.6–3.0 during the rest of the year. pit surrounded by large areas of unremediated pyritic waste rock producing acidic effluent which runs into the lake (the inflows are almost permanent for most of the year). A stream flows out of the lake into a nearby valley and eventually joins the Ribera de la Panera. This small creek is heavily contaminated by metal and sulfate from the pit lake. Most of the AMD pollution, however, is transported further downstream and discharges into the Olivargas river.	Sánchez-España et al. (2012).
Gorka	Poland	Limestone Quarry	3.1	18	Industrial pit lake formed after the cessation of open pit dewatering. Connected with 500,000 m^3 extremely alkaline leachate gathered in flooded quarry. Water within pit lake has rare hydrochemical properties. Industrial red mud wastes influencing water quality.	Czop *et al.* (2008)
AML1	Turkey	Lignite	3.17		Canakkale province of northwestern Turkey. pH 2.56	Yucel et al. (2014)
AML2	Turkey	Lignite	3.34	13.5	Canakkale province of northwestern Turkey. pH 2.53	Yucel et al. (2014)
AML3	Turkey	Lignite	1.6		Canakkale province of northwestern Turkey. pH 2.57	Yucel et al. (2014)
AML4	Turkey	Lignite	2.6		Canakkale province of northwestern Turkey. pH 3.05	Yucel et al. (2014)
AML5	Turkey	Lignite	2.4		Canakkale province of northwestern Turkey. pH 2.65	Yucel et al. (2014)
AML6	Turkey	Lignite	N/A	N/A	Canakkale province of northwestern Turkey. pH 2.79	Yucel et al. (2014)
AML7	Turkey	Lignite	N/A	N/A	Canakkale province of northwestern Turkey. pH 2.87	Yucel et al. (2014)
AML8	Turkey	Lignite	N/A	N/A	Canakkale province of northwestern Turkey. pH 2.71	Yucel et al. (2014)
AML9	Turkey	Lignite	N/A	N/A	Canakkale province of northwestern Turkey. pH 2.79	Yucel et al. (2014)

Table A-1: Pit Lakes Around the World

Name of Lake	Location	Type of Mine	Area [ha]	Max Depth [m]	Comments	Reference
Piast/Czeczott	Poland	Coal	N/A	N/A	Different treatment and disposal schemes are described and compared from a technical-economical point of view. Recommends drying of sodium chloride (NaCl) and sale in Poland and/or on the export market as preferred option.	Ericsson and Hallmans (1994)
Tidenham Quarry	UK	Quarry	N/A	N/A	The UK's National Diving Centre at Chepstow is a flooded quarry and has many sunken attractions including aircraft, vehicles, boats tunnels and training platforms.	Pearman (2009)
Lake Knappensee	Germany	Lignite	52	N/A	Red mud deposited in lake from a nearby aluminum plant from December 1965 to April 1973. Covered by ash layers of up to 20 m thickness. Extremely high pH-values of up to pH=14, while the pH-increase in the lake stopped at circum-neutral pH-values. Wildlife values with emergent macrophytes and self-sustaining alkalinity-generation	Schäfer *et al.* (2016)
Senftenberger See	Germany	Lignite	1200	25	Nature and landscape protection areas, sport and tourism as well as low water management, flood protection, aquaculture and fishery	Uhlmann *et al*. (2016)
Goitschesee	Germany	Lignite	1332	47	Recreation • nature conservation • reduction of water level after flood disaster	Schultze et al. (2005)
Seelhäuser	Germany	Lignite	622	28	Recreation	Schultze et al. (2005)
Golpa-Nord	Germany	Lignite	544	33	Recreation	Schultze et al. (2005)
Delitzsch-Südwest	Germany	Lignite	441	36	Recreation	Schultze et al. (2005)
Merseburg-Ost 1a	Germany	Lignite	338	28	nature conservation	Schultze et al. (2005)
Merseburg-Ost 1b	Germany	Lignite	310	37	Recreation	Schultze et al. (2005)
Cospuden	Germany	Lignite	N/A	N/A		Schultze et al. (2011)
Lusatian lake 77	Germany	Lignite	24	8	The central basin (CB) of this lake shows a dimictic water regime with a non-permanent anoxic deep layer and a homogeneous acidic pH all over the water column (pH3). In contrast, the northern basin (NB) is meromictic with a permanently anoxic bottom layer and a pH increase from pH3 in the mixolimnion (superficial part of the lake) to pH5.5 in the monimolimnion (anoxic bottom layer). Large-scale exchange patterns were defined by the (hydro)geologic setting but superimposed by smaller scale variations caused by variability in sediment texture. Sites characterized by groundwater upwelling (flow into the lake) and sites where flow alternated between upwelling and downwelling were identified.	Miot et al. (2016) Neumann et al. (2013)
Vollert-Sued	Germany	Lignite	20	10	Lake Vollert-Sued shows a monimolimnetic gas pressure close to spontaneous ebullition.•A limnic eruption is unprobable as only methane and nitrogen contribute to gas pressure	Horn et al. (2017)
Los Frailes Pit	Spain	Copper, lead, zinc, silver	48	265	Receives AMD drainage from mine waste	ARCADIS (2015)

Table A-1: Pit Lakes Around the World

Name of Lake	Location	Type of Mine	Area [ha]	Max Depth [m]	Comments	Reference
Aznalcóllar Pit	Aznalcóllar, Spain	Copper, lead, zinc, silver	72	275	Used to dispose of scrap metal, concrete and acidic waste rock. Used for disposal of the recovered spilled tailings and contaminated soil after the tailings dam failure that released tailings over the downgradient landscape. In order to keep the water level below the 1928 groundwater table, lake water is periodically pumped, treated and then diverted to the Agrio river. At a pH of approximately 9.5, the sludge produced in the treatment facility is pumped back into the lake. No future use: at present pit lake used as a disposal site for pyrite-rich rocks from the adjacent S-3 waste-rock pile,	Schultze et al. (2006); ARCADIS (2015)
As Pontes	Spain	Coal	870	206	Recreation	Fleischhammel, et al. (2010)
Westfield lake	Scotland	Coal	N/A	>25	Acidic.	Younger et al. (2005)
Chabařovice Lake	Czech Republic	Lignite	250	22	Recreational and sporting area – bathing, swimming, fishing, sailing, bike route, roller skating, jogging, horse riding etc..	Čech et al. (2010)
Medard Lake	Czech Republic	Lignite	N/A	23	Recreational and sporting area – bathing, swimming, fishing, sailing, bike route, roller skating, jogging, horse riding etc..	Kosik et al. (2011)
Most	Czech Republic	Lignite	N/A	N/A	Recreational and sporting area – bathing, swimming, fishing, sailing, bike route, roller skating, jogging, horse riding etc.	Peterka et al. (2011)
Michal	Czech Republic	Lignite	N/A	N/A		
Milada	Czech Republic	Lignite	N/A	N/A		
Matylda	Czech Republic	Lignite	N/A	N/A		
Bílina	Czech Republic	Lignite	1145	170	Tršboň Basin. Water quality dependent on surrounding land use.	Svoboda et al. (2008)
Chabarovice	Czech Republic	Lignite	226	23		
Ležáky	Czech Republic	Lignite	311	75		
SA	Czech Republic	Lignite	701	130		
Vršany (Šverma)	Czech Republic	Lignite	390	40		
Libouš	Czech Republic	Lignite	1083	76		
Medard – Libík	Czech Republic	Lignite	501	51		
Jirí - Družba	Czech Republic	Lignite	1322	93		
Ocnele Mari	Romania	Salt	0.3	N/A	Highly saline. Landslides trigger decants into nearby river.	Mara et al. (2008)
Cep	Czech Republic	Lignite	123	7	Tršboň Basin. Low in nutrients. Their use is various, and depends on the size, depth and the condition of the lake. The ecological function is important too. Important potable water source.	Kriváckova & Cížková (2008)
Cep I	Czech Republic	Lignite	40	6.5		
Tuš	Czech Republic	Lignite	39.5	5		
Františkov	Czech Republic	Lignite	9	4.5		
Halámky North lake	Czech Republic	Lignite	33.47	16	Tršboň Basin. Low in nutrients. Their use is various, and depends on the size, depth and the condition of the lake. The ecological function is important too.	Kriváckova & Cížková (2008)
Halámky South lake	Czech Republic	Lignite	18.75	4		

Table A-1: Pit Lakes Around the World

Name of Lake	Location	Type of Mine	Area [ha]	Max Depth [m]	Comments	Reference
Halámky Middle lake	Czech Republic	Lignite	22.74	14		
Halámky East lake	Czech Republic	Lignite	N/A	17		
Horusice I	Czech Republic	Lignite	15	2.5		
Horusice	Czech Republic	Lignite	23	6.5		
Veselí I	Czech Republic	Lignite	24	3.5		
Veselí	Czech Republic	Lignite	10	3.5		
Vlkov	Czech Republic	Lignite	46	2.8		
Meirama	Spain	Lignite	N/A	187	Mining completed in 2008. Some waste returned to pit. River-filled over seven years. 2 km long. Golder undertook hydrochemical modelling predicting good water quality.	Arias & Fernández (2008)
Lake Junttiselkä	Sweden	Zinc/copper	570	2.5	The lake is loaded mainly by the Pyhäsalmi Zn-Cu-mine waters and municipal sewages of Pyhäsalmi town. The mine waters are refined by lime treatment/precipitation and thus the effluents contain significant quantities of Ca and sulphate. The seasonal variation in water quality in Junttiselkä is pronounced, because in winter the electrolyte concentration in the water becomes high and the hypolimnion becomes anoxic. After melting of the ice cover and the spring overturn the water suddenly becomes acidic.	Mäkinen (2007)
South America						
Paso de Piedra	Argentina	Rock Quarry (quartzites)	0.3	6	Potential conversion of relict site into a productive aquaculture setup. Baseline studies indicated water suitable for *Odontesthes bonariensis* (Chilean Silverside). Capture and analysis of mature age (2 yrs +) fish.	Mallo *et al*. (2010)
Omai Wenot Pit	Guyana	Gold	N/A	N/A	Tailings slurry and tailings pond supernatant water were pumped into pit after tailings dam failure. Tailings and water contaminated with toxic levels of cyanide. Rate of in-situ cyanide degradation exceeded inputs, and water quality in pit lake met discharge standards for cyanide, ammonia and TSS within four months of deposition. Site is closed and has been returned to government.	ARCADIS (2015)
Lake Aguas Claras	Brazil	Iron ore	70	234	Wildlife. Recreation (swimming, diving, sailing, fishing), amenity value and water supply	Sperling & Grandchamp (2008)
Asia						
Nanshan AMD lake	China	Pyrite	10	15	pH of lake water was stable (of ions varied dramatically. Unexpectedly, ultrahigh concentration of chlorophyll a was measured in the extremely acidic lake, reaching 226.43–280.95 µg/L in winter, even higher than those in most eutrophic freshwater lakes. Both prokaryotic and eukaryotic communities showed a strong seasonal variation. Photoautotrophic algae (primary producers) formed a food web with protozoa or flagellate (top consumers) across all four seasons, and temperature appeared to be responsible for the observed seasonal variation.	Hao et al. (2017)

Table A-1: Pit Lakes Around the World

Name of Lake	Location	Type of Mine	Area [ha]	Max Depth [m]	Comments	Reference
Australasia						
Martha Mine Pit Lake	New Zealand	Gold	28.7	192	Closure of the mine planned for 2006, with filling expected to last 5 years. Reclamation project integrating littoral zones to favor biological activities. Lake predicted to be productive and support wildlife (fish, birds)	Castendyk & Webster-Brown (2007a,b)
Historic and New Collie pit lakes	Australia	Coal	4.5-98.5	81	Used for recreation and tourism	Lund *et al*. (2012)
Capel Lakes	Australia	Mineral sands	N/A	N/A	Rehabilitated open-cut mineral sand mine lease in a series of dune lakes and wetlands. Boardwalks and interpretive signs established to provide a regional wetland education centre.	McCullough & Lund (2006)
Granny Smith Mine pit lake	Australia	Gold	N/A	N/A	Used for aquaculture	McCullough & Lund (2006)
WO5	Australia	Coal	44	81	Acid mine lake water treated by a fluidised limestone chip treatment system and then gravity fed into six polyculture ponds used for silver perch and freshwater crayfish aquaculture research.	Whisson and Evans (2003); Stephens & Ingram (2006); McCullough *et al.* (2010)
Enterprise Pit	Australia	Gold	N/A	N/A	Used for irrigation	McCullough & Lund (2006)
Wedge Pit	Australia	Gold	N/A	N/A	Remote arid region mining town water supply. Water abstracted from bores at edge of mined-out pit to minimise liability of pit involvement (see case-study)	McCullough & Lund (2006)
Garrick East	Australia	Coal	N/A	N/A	Remediated (reduced salinity) pit lake water for haul road dust suppression to relieve pressure on competitive regional water resources	McCullough et al. (2008)
Stockton Lake, Collie, Western Australia	Australia	Coal	15.4	25	Historic lake used for camping by 'grey nomad' caravans. Also used extensively for water skiing and deep SCUBA diving due to very clear (albeit acidic) water and underground adits for cave diving. Also picnics and marron (crayfish) fishing.	McCullough et al. (2010) Buzzacott (2012)
Black Diamond Lake, Collie, Western Australia	Australia	Coal	4.6	8	Historic lake used for camping and BBQs predominantly by local residents. Also picnics and marron (crayfish) fishing.	McCullough *et al.* (2010) Lund et al. (2012) Hinwood *et al.* (2012)
Golden Cross	New Zealand	Gold	N/A	N/A	Surrounding pit lake rehabilitation for revegetation with native plant communities. Although primary intention of the lake is wildlife habitat, there is also development occurring for recreational/commercial fishing facilities.	Ingle (2002)
Lake WO3	Australia	Coal	N/A	8	Acid mine lake water treated by a fluidised limestone chip treatment system and then gravity fed into ponds used for marron (freshwater crayfish) aquaculture by local indigenous business group.	Ngalang Boodja Enterprises Pty Ltd (2013) McCullough *et al.* (2010)
Marymia Pit Lake	Murchison Desert, Australia	Gold	2.5	50	Received tailings from nearby pit. Tailings were disposed of under a water cover to minimize exposure to hazardous fibres in tailings.	ARCADIS (2015)

Table A-1: Pit Lakes Around the World

Name of Lake	Location	Type of Mine	Area [ha]	Max Depth [m]	Comments	Reference
Africa						
Klien Kopje Colliery	South Africa	Coal	N/A	N/A	Mine water used for irrigation of agricultural crops. Sugar beans and wheat were irrigated with three center pivots, on both virgin and rehabilitated land.	Whisson and Evans (2003)
Nyala Mine	South Africa	Magnesite	11	22	Generally, the water in the pit lakes is used by domestic animals from nearby communities as drinking water. However, the water in the major pit lake of the Nyala Mine is also used by the community of Zwigodini Village for different domestic purposes that include washing of cloths, swimming (recreational purposes) and fishing.	Mhlongo & Amponsah-Dacosta (2014)
Tau	Botswana	Copper, nickel	12.6	95	Wildlife drinking. Potential water quality issues.	Duthe et al. (2011)
Tholo	Botswana	Gold	ca. 5	10	Wildlife drinking. Potential water quality issues.	Duthe et al. (2011)
Pit Lakes in General:						
General- Lake Districts	Australia, Germany	Various open cut	N/A	N/A	Historical and current practice, pit lakes as environmental offsets, environmental restoration goals for pit lakes, compromised ecosystems and restoring ecosystem values.	McCullough & van Etten (2011)
Various residual pit lakes (Rudy Sever, Saxonie, Vrbensky, Venuse, Benedikt, Elisabeth)	Czech Republic (North Bohemian Brown Coal Basin)	Brown Coal	N/A	N/A	Lack of proper planning. Poor design, series of lakes and dumps left in place due to reduction in mining capacity. High mineralisation of mine waters due to presence of coal seam, enriched with iron sulfides.	Halif & Zizka (2008)
General	United Kingdom	Various	N/A	N/A	Using compost based passive remediation systems for acidic mine waters, an alternative end use for open pit mine pits that is a sink for atmospheric CO_2.	Younger & Mayes (2014)

APPENDIX B

Pit Lake Case Studies

B-1 PIT LAKES WITHOUT TAILINGS OR MINE WASTE

B-1.1 Successful Pit Lakes

Fish Habitat in Coal Valley Mine Pit Lakes, Alberta, Canada

Pit lake development and fish habitat creation at Coal Valley Mine was first described by Hildebrandt et al. (1982) for Luscar Ltd. (Luscar), the mine owners at that time. The study examined previous pit lakes that were developed by Luscar – in particular, the factors that limited fish habitat in those waterbodies – and made recommendations for physical, chemical and biological objectives of subsequent pit lakes to enhance fishery and recreational value. This report also documented a bathymetric, water quality, and biological survey of Pit No. 1 and Pit No. 5 that was completed in 1981 and 1982. Both pits were created by truck and shovel mining between 1950 and 1955.

At the time of the survey, the lakes had maximum depths of 33 m and 21 m, respectively, and were thought to be meromictic. The monimolimnion of Pit 1 was anaerobic, and Pit 5 had low concentrations of dissolved oxygen. Both lakes had elevated concentrations of trace elements such as mercury and selenium. The ponds contained varying biomasses of benthic invertebrates, zooplankton and vegetation, and the fishery habitat was generally poor. Limiting factors for fish habitat included:

- steep shorelines and banks that hinder wind-driven mixing and lead to oxygen deficiencies;
- steep shoreline limited the littoral area, which limited biological productivity and diversity;
- acidity was evaluated but was not an issue as the mines are located in alkaline basins;
- high turbidity was limiting light;
- low nutrients were limiting productivity;
- newly exposed rock was thought to be leaching metals into the lakes; and,
- water fluctuations from withdrawals for use for ongoing mining was a limiting factor for habitat.

Based on these limiting factors, Hildebrandt et al. (1982) made recommendations for establishing successful fisheries in coal mine pit lakes (the first three of which are relevant to all pit lakes):

- create shoreline slopes of 1:5 in the top 1 m and 1:3 to 15 m depth; below that, slopes are less critical;
- create irregular shorelines to improve habitat, decrease erosion and enhance aesthetics;
- lakes should be deep enough to support fish overwintering; 5 to 8 m or deeper; and,
- several detailed recommendations to replicating natural lakes that were site specific, considering the hydrology, soils, and biology of the Alberta foothills region.

Fish Habitat in Silkstone, Lovett and Lac des Roches, Alberta, Canada

Luscar (1991) noted some limitations in existing pit lakes, as noted by Hildebrandt et al. (1982), and studied three existing pit lakes to make recommendations for improving water quality and habitat in future coal mine pit lakes.

The first phase of the study was a literature review of mine pit lakes, which focused on American case studies because Alberta case studies were not well documented. They cited Brenner et al. (1987) as documenting 138 waterbodies created by coal mine closure in Pennsylvania, which covered 50% of closed mines by surface area. They reviewed a number of water quality studies from alkaline pit lakes and found that total dissolved solids (TDS) was usually about three times higher than control lakes, with various elevated metals concentrations. Habitat quality varied, as lakes developed prior to regulations in 1977 were steep walled and less productive, whereas lakes that were planned and developed for specific end uses produced a number of positive case studies.

They completed surveys in Silkstone and Lovett lakes, which were created in 1985 following dragline operations, as well as Lac des Roches, which was created in 1987 following truck and shovel mining. A nearby, natural lake named Fairfax Lake was studied for comparison. Silkstone and Lovett lakes were deemed to have limited fish stocking potential, owing to low primary productivity, despite having 37% and 32% littoral zone by surface area. Lac des Roches, in contrast, had been planned and constructed with extensive fish habitat features in the inlet and throughout the lake. Due to a prohibitive cost of further development, the littoral zone was constructed in 5% of the lake. Water quality was initially poor in the lake but it improved within about two years of filling.

Brinker (1991) summarized the studies above and noted that all lakes were meeting end use objectives at that time. A follow-up study completed three years later (Luscar et al. 1994) found that water quality was suitable for fish in all three pit lakes, and the results indicated that the lakes would be capable of sustaining populations of sport fish. Within three years of lake filling, the water quality in the lakes was meeting federal and provincial water quality guidelines, although the concentrations were higher than in nearby natural lakes. Lovett and Silkstone Lakes were considered oligo-mesotrophic, and Lac des Roches was considered oligotrophic. Although the productivity was lower in Lac des Roches, it hosted a self-sustaining population of native fish (rainbow trout and bull trout) that colonized the lake from downstream. The lakes were expected to add to the diversity of the region because lakes that support fish over winter are relatively rare in the Eastern Slopes. The lakes were also documented as providing habitat to wildlife, including birds, ungulates, amphibians, furbearers and bats.

Surveys were conducted for Coal Valley Mine on five pit lakes in 2006 (Hatfield 2008), as well as a reference lake, Fairfax Lake. These studies were conducted in support of the Mercoal West and Yellowhead Tower Mine projects, which proposed end-pit lakes as closure waterbodies. The surveys were conducted to improve the understanding of these lakes and to derive guidance for the construction of additional lakes. The pit lakes were alkaline, with similar ionic composition but TDS levels 2-3 times higher than Fairfax Lake, and low TSS and turbidity. Some water quality guideline exceedances were noted, such as total phosphorus, sulphide, mercury and selenium. All five pit lakes were deemed to be meromictic or to have limited vertical mixing. Benthic invertebrate diversity and Fish Habitat Effectiveness were highest in the oldest pit lakes (Silkstone and Lovett) and were comparable to Fairfax Lake.

The 2006 survey was repeated in 2010 and 2011, and four more pit lakes were included in the later survey. This survey largely confirmed the results and conclusions of the 2006 survey, except that three pit lakes (Pit 35, Pit

142 and Pit 25S) were deemed to be B-3ypolimnet. Overall, water quality and trophic status were deemed to be similar in all pit lakes to that of the reference lake. Water quality variables such as dissolved oxygen were different in the lower layer of the stratified lakes (the monimolimnion), but these differences were thought to have low implications to the overall suitability of the lakes for fish.

Other Pit Lakes in Alberta

Four pit lakes south of Hinton were evaluated for risks related to selenium bioaccumulation by Miller et al. (2013). Two pit lakes were selected to represent thermal coal mine pit lakes, which had lower aqueous selenium concentrations, and two were selected to represent metallurgical coal mine pit lakes, which had higher aqueous selenium concentrations. All four lakes were stocked with similarly aged juvenile rainbow trout and brook trout, and were monitored five times over a two-year period. Monitoring included water, invertebrate and fish selenium concentrations, among other variables. In all four lakes, water quality guidelines were met for all trace elements except selenium. The lakes generally exceeded selenium tissue guidelines as well, leading the authors to conclude that the lakes were not suitable as put-and-take fisheries.

There are undocumented pit lakes on the prairies in Alberta, some details of which are provided in Appendix A, Table A-1. Quarry Lake (APPENDIX B), near Canmore, is a former coal mine pit that is now a well-used lake for hiking, swimming and fishing (Tourism Canmore 2017).

Strip mining for coal near Wabamun Lake began in 1962 and concluded in 1982. The lake was filled primarily with groundwater, and reached full elevation in about 2004. Water-quality monitoring and habitat assessment between 1988 and 1994 demonstrated that East Pit Lake was suitable for establishing an arctic grayling recreational sport fishery. Alberta Environmental Protection awarded TransAlta a reclamation certificate for the lake in 1994 (Sumer et al. 1994).

Figure 3: Quarry Lake, a Former Coal Mine Pit near Canmore, Alberta

B-2 PIT LAKES WITH TAILINGS OR MINE WASTE:

B 2.1 Successful pit lakes

Fish Habitat in Sphinx Lake, Alberta, Canada

Sphinx Lake is another pit lake created at the Luscar Mine (now owned by Teck) in a pit that was mined from 1992 to 1998. The lake was constructed using guidance provided by the End Pit Lake Working Group (2004). Before filling, the pit was mostly (85% by surface area) filled with waste rock. The waste rock was re-contoured and covered with clean soil to create littoral zones covering 25% of the lake by surface area. Rock piles and coarse woody debris were added as habitat, and inlet and outlet channels were constructed. Sphinx Creek was diverted back through the lake in 2006 when physical reclamation was complete. Water quality in the lake is good, with selenium being the only constituent of concern; as of 2008, selenium concentration in the lake was

5.9 µg/L and showing a declining trend with time. Similar to the pit lakes described above, Sphinx Lake is inferred to be meromictic, and this does not appear to have adverse effects on fish or fish habitat. Within five years of lake filling, rainbow trout and bull trout (species of trout listed as Species of Special Concern by Alberta's Endangered Species Conservation Committee) had colonized the lake, which was more highly productive for these species than the pre-development Sphinx Creek (Brinker et al. 2011).

Three pit lakes in the Alberta Rocky Mountain Foothills were the focus of a Master's thesis by Sonnenberg (2011). The first objective of the study was to "*Investigate whether alpine streams with pit lakes are capable of maintaining self-sustaining populations of native fish species*". These pit lakes, located near the headwaters of the Athabasca watershed, include Sphinx Lake, Pit Lake CD, and Lac des Roches. Sonnenberg (2011) surveyed these pit lakes and three natural lakes in the region, including water chemistry, zooplankton, macrophytes, invertebrates and fish communities. At the time of the study, Lac des Roches had been isolated from the receiving environment and was devoid of fish. Sonnenberg (2011) found that the biological communities in Sphinx Lake and Pit Lake CD were similar to those in natural systems, despite differences in water chemistry such as elevated selenium. Fish habitat in these lakes was more productive than nearby streams that lacked pit lakes, because of the moderated flows and warmer temperatures in the pit lakes. "*Populations of Rainbow trout and Bull trout have been identified and appear to be flourishing in Sphinx Lake. Rainbow trout in Sphinx Lake grow significantly bigger and faster, and mature sooner than their counterparts in nearby streams*". These fish populations were deemed to be self-sustaining.

Fish Habitat in Robb Trend Project Pit Lakes, Alberta, Canada

In 2012, Coal Valley Resources Inc. (CVRI) submitted a Reclamation Plan for the Robb Trend Project (CVRI 2012). The Reclamation Plan lists 28 pit lakes, of which:

- one pit lake is listed as having obtained a reclamation certificate (Silkstone Lake),
- five pit lakes are listed as "complete",
- thirteen pit lakes are listed as "under development",
- six pit lakes are listed as "mining not complete", and
- three pit lakes are listed as "planned".

The pit lakes that are documented as complete by CVRI (2012) or by other literature sources above are listed in Appendix A, Table A-1, along with basic details about each pit lake. According to CVRI (2012), "*many of the end-pit lakes that have been developed support sport fishery populations of stocked fish and are frequented by anglers*". An additional 12 pit lakes are planned for the Robb Trend Project, which would bring the regional total number of pit lakes to 40 – more than the 35 currently planned for the Athabasca Oil Sands Region.

In response to the CVRI (2012) application, Department of Fisheries and Oceans requested that CVRI backfill some pits to reduce overall size. CVRI (2014) responded that one of the 12 pits will be backfilled entirely and seven of the remaining 11 pits will be partially backfilled with mine waste.

Geotechnical Stability and Passive Water Treatment: Springer Pit Lake at Mount Polley Mine, British Columbia, Canada

Springer Pit Lake is a former mine pit at the Mount Polley Mine, a copper mine in Central B.C. The pit lake was used to store water and tailings after the tailings storage facility embankment breach that occurred on August 4, 2014. Storing the tailings in a mined-out pit was listed as Best Available Tailings Technology by the Independent Engineering Review Panel (Morgenstern et al. 2015), based on geotechnical stability. Between August 2014 and August 2015, tailings supernatant water and mine runoff were diverted to the pit lake. Upon resumption of mining in August 2015, mill process water and tailings were also deposited in the pit lake. A water discharge permit was granted, and the pit lake was used as the primary feed source for the water treatment plant. After a few months, it was observed that Springer Pit Lake provided sufficient passive water treatment for the active water treatment plant to be switched to "passive mode" (Vandenberg et al. 2016; Vandenberg and Litke, submitted). Water quality in the pit lake followed predictable trajectories (Beddoes et al. 2016) and was suitable for discharge to the receiving environment. At present, the pit lake is being drawn down, and tailings are planned to be removed from Springer pit to allow mining to resume in the pit. At mine closure, approximately 15 Mt of PAG waste rock will be placed into the pit, which is considered best practice in terms of mitigating acid and metalliferous drainage from the PAG waste rock (MEM 1998; Verburg et al. 2009) and is a B.C. *Mines Act* permit requirement.

Creation of Aquatic Habitat – Highland Valley Copper Mine Pit Lakes, British Columbia, Canada

At Highland Valley Copper Mine, Teck has successfully reclaimed the Heustis Pit Lake and Trojan Tailings Pond to support fisheries resources. The Trojan Pond was a 26-ha tailings pond that was covered with up to 10 m of water to mitigate AMD and to create aquatic habitat (Otchere et al. 2002). Aquatic plants and invertebrates were introduced, riparian vegetation was transplanted onto the shorelines and the lakes were stocked with rainbow trout between 1991 and 1994 (Otchere et al. 2004). Colonization of the lakes was closely studied, and several experiments were conducted that resulted in removal of metals (including some dissolved metals) through fertilization, which stimulates primary productivity and uptake of metals by phytoplankton (Hamaguchi et al. 2009; Larratt et al. 2007). Trojan Pond has now been self-sustaining for 20 years and serves an important role both in ongoing research on tailings pond reclamation techniques and as a recreational area for the community. Highland Valley Copper hosts multiple fishing derbies at Trojan Pond each year, with funds raised going to support charities in the region.

Owl Creek Mine, Ontario, Canada

The Owl Creek Mine, near Timmins, Ontario, extracted gold by open pit mining between 1981 and 1989. The mine generated AMD that was only discovered ten years after the mine began operations. Acidic drainage from the mine was observed reaching the nearby Porcupine River, and the flow was traced back to waste rock seepage. To mitigate this drainage, 3.26 Mt of acid generating and metal leaching waste rock was relocated to the pit in 1990 and 1991. Crushed limestone was added to the pit in buffering layers, the waste rock was covered in clay-rich soil, and the pit was filled with 22 m of water from the Porcupine River (Martin et al 2016). The mine employed a pit filling and discharge strategy that is similar to many planned oil sands pit lakes, which is to use water from a nearby river to accelerate filling, then ultimately discharge water back to the same river when it meets water quality objectives (ARCADIS 2015).

Between 2000 and 2012, the pit was used as a polishing pond for mine effluent from the nearby Bell Creek Mine. Likely due to settling in the pit lake, metals concentrations were lowered by the time the water reached the

outflow, meeting provincial water quality standards. The effluent did not cause adverse impacts in the Porcupine River, as demonstrated by federally mandated Environmental Effects Monitoring (ARCADIS 2015).

The pit lake is meromictic, with a pycnocline depth of 8 m. Particulate metals are thought to settle into the monimolimnion without becoming suspended (Rodgers 2016). Consequently, the pit lake did not require active treatment during filling or post-closure (ARCADIS 2015).

After studying the pit lake ten years after closure and 25 years after the materials had been placed, Martin et al. (2016) listed the following lessons learned:

- *"Don't rely entirely on historical precedent; testing is required,*
- *ARD can still occur if only small volumes of PAG material are mixed with non-PAG rock,*
- *[It is] best to segregate potentially problematic materials,*
- *Management of PAG waste rock in a flooded open pit is an extremely effective remedial option, and*
- *The implemented closure plan [was] very effective*".

Solbec Mine, Québec, Canada

The Solbec Mine, near Montreal, Québec, operated as a copper, lead and zinc mine in the 1960s and 1970s (ARCADIS 2015). At the end of mining, tailings were disposed of in the pit, and waste rock was later placed above the tailings. Contaminated soil was also co-deposited. A calcite limestone cover was placed over the waste rock to neutralize seepage waters. The cover was then capped with water, with a maximum depth of approximately 25 m. Dissolved oxygen was low in the pore waters, indicating that the cover had performed as intended. Seepage out of the pit was deemed to be low based on drilling and hydraulic conductivity testing around the pit. The outflow is treated for zinc using a biofilter, and it subsequently meets provincial water quality standards.

Additional Mine Environment Neutral Drainage (MEND) Case Studies

MEND is a cross industry-government organization that was formed in 1989 to develop technologies to prevent and control acidic drainage. MEND is a Canadian Member of the larger Global Alliance, which is similar in technical scope but global in geographical scope. On behalf of MEND, ARCADIS reviewed nine pit lake case studies, listed in Table A-1, including five of the Canadian case studies listed above. The case studies of pit lakes that contain submerged mine waste are documented in MEND Report *In-Pit Disposal of Reactive Mine Wastes: Approaches, Update and Case Study Results* (ARCADIS 2015). Several of their observations and recommendations are relevant to oil sands pit lakes that contain tailings and are quoted at length below:

> "*Although not new, the disposal of mine wastes into mined-out pits has, in recent years, received increased acceptance particularly for acid generating, metal leaching, radioactive and perceptively hazardous tailings, waste rock and water treatment sludges… The published results for a selection of in-pit disposal options have been, in general, very positive in demonstrating the long-term isolation demanded by companies, regulators and the public…*"
>
> *"The incentives for using pits for disposal of mine wastes include the following aspects:*

Environmental

- *Prevention and control of acid generation;*
- *Reduction of metal leaching and isolation of dissolved metals;*
- *Permanent physical isolation of wastes;*
- *Minimization of the need for engineered control systems and long term monitoring;*
- *Return of waste rock and tailings to the original geochemical conditions; and*
- *Restoration of pre-mining conditions.*

Physical

- *Stabilization of pit walls;*
- *Elimination of potential accidental release of solids;*
- *Reduction of long term waste management care and maintenance; and*
- *Elimination of potential for unauthorized removal of wastes.*

Financial, Legal and Social

- *Potential lower cost;*
- *Potential earlier return of the land to previous and traditional uses;*
- *Improved acceptability by various stakeholders including permitting agencies; and*
- *Improved site aesthetics on closure."*

"In-pit disposal has become a well-accepted practice in many jurisdictions and sectors of the mining industry and in some instances (e.g., uranium in Saskatchewan, Canada) disposal of tailings in mined out pits has become a regulatory policy requirement."

"State of the art in-pit tailings disposal technology includes paste-consistency disposal under a water cover to prevent particle segregation, maximize consolidation and prevent frost penetration in cold climates."

B-2.2 Pit lakes that are extensively managed toward success

Meromixis by Design: Island Copper Mine Pit, British Columbia, Canada

In 1996, the Island Copper Mine pit on Vancouver Island was flooded up to 90% full with seawater and then capped with freshwater as a tailings containment strategy and as a mitigation against in-pit development of acid rock drainage. The objective in inducing meromixis was to promote anoxia in the monimolimnion and to remove trace metals through reductive sulphide precipitation. The strategy also mitigated against biogeochemical reactions that oxidize sulphide minerals exposed in submerged wall rock. Sulphide mineral oxidation, if unmitigated, could lead to acid generation and metal mobilization in the water column.

By 2000, the pit lake had developed three distinct strata. The lower layer had become anoxic but the intermediate layer had not. Therefore, anoxia was promoted by fertilizing the hypolimnion with liquid ammonium polyphosphate and urea ammonium nitrate to increase primary production. The accelerated primary production

was intended to increase autochthonous (generated in-lake) biochemical oxygen demand and uptake and settling of metals. The consumption of oxygen led to chemically reducing conditions that prevents oxidation of AMD materials. As of 2015, the fertilization was proving successful, although time frames to become a fully passive system were not yet established. Further details regarding Island Copper Mine pit are provided in several publications (Fisher 2002; Fisher and Lawrence 2006; Pelletier et al. 2009; Poling et al. 2002, 2003; Wen et al. 2015).

Water Cover for Potentially Acid Generating Mine Waste at Quinsam Coal, British Columbia, Canada

At the Quinsam Coal Mine near Campbell River, an open pit was closed by placing a soil-bentonite liner over a pit floor and wall to allow subaqueous storage of 155,000 m^3 of PAG coarse coal rejects (Golder 2011). The PAG material is stored in the pit below a 1.2-m water cap. The water cap was intended to limit oxidation of the subaqueous materials and, thereby, to maintain water quality of drainage waters. Portals in the pit wall were plugged and waste rock around the pit was re-graded, then the pit was lined with a soil-bentonite liner to limit seepage out of the pit.

Originally, the PAG materials were planned to be disposed of in an above-ground facility. However, in response to reviews by the Ministry of Energy, Mines and Petroleum Resources, the materials were placed in the pit lake. Storage in the pit lake rather than above ground:

- reduced the overall in footprint;
- reduced the affected catchment area;
- reduced the static water head;
- eliminated the need for containment dams; and,
- eliminated the need to re-slope the pit wall.

Uranium Mines, Saskatchewan, Canada

Some of the existing and all of the proposed uranium facilities in Canada use some form of subaqueous deposition. That is, a depth of water is always maintained over the previously deposited tailings, and the tailings themselves are discharged into the water by some type of tremie pipe or injection pipe.

There are at least 36 former uranium mines or mills near or along the shores of Lake Athabasca in Northern Saskatchewan (Schramm 2012). Most of these mines operated in the 1950s and 1960s and were closed with little to no remediation (Schramm 2012). As of 2005, there were seven reported operating, proposed or closed open pit uranium mines, of which five included pit lakes, in Northern Saskatchewan (Dessouki et al. 2005).

Two publications (Rowson and Tremblay 2005; Pollock 2008) document a number of pit lakes that are used or will be used to store PAG materials in Northern Saskatchewan; both documents refer to this as “best practice” and “state of the art” for long-term safe storage of PAG tailings at uranium mines in Saskatchewan. Water-capped tailings were deemed preferable to protect against multiple exposure pathways including: radiation; wind-borne dust; groundwater seepage; and surface overflow. Additionally, subaqueous disposal was deemed preferable because it allows tailings to consolidate without annual freeze up. Subaqueous disposal of PAG

tailings in pit lakes is currently employed at McLean Lake (JEB Pit), McArthur River, Key Lake and Rabbit Lake mines.

The “pervious surround” concept is a key element of the design for closure of these in-pit uranium disposal facilities. The uranium tailings has a permeability that is several orders of magnitude smaller than that of the surrounding pit rim. As a result, the regional groundwater flux will be around rather than through the tailings mass. With very little advective flux through the tailings, the release of contaminants from the tailings porewater (the “source term”) is limited to the diffusive flux from the porewater into the adjacent pervious surround. In some cases (e.g. Key Lake Deilmann Pit) the “pervious surround” condition occurs naturally because the pit is rimmed with sandstone. In other cases (e.g. Rabbit Lake) the pervious surround was constructed by placing rockfill and a sand filter between the tailings and the pit rim.

Elliot Lake, Ontario, Canada

A number of uranium mines were operated around Elliot Lake, Ontario for about four decades, ending in the mid-1990s (ELUMTAEAP 1996). Denison Mines Limited operated three uranium tailings management areas and Rio Algom Limited operated at least eight. The total amount of uranium tailings stored exceeded 170 Mt. The storage facilities consisted of above ground tailings impoundments, not in-pit disposal. After closure, six of the tailings areas were provided with a permanent shallow water cover to limit acid generation. The flooded closure was licenced under the federal Atomic Energy Control Board, now the Canadian Nuclear Safety Commission.

The relevance of the flooded tailings areas at Elliot Lake is that they provide many years of records on the performance of shallow water covers over tailings. Davé (2009) presents Natural Resources Canada`s findings from studies on these waterbodies a decade later, and concluded that water covers were “*Suitable for both existing and new waste management sites*”. Davé (2009) found that the water quality was suitable for release, and hosted local biota.

In 1993, the mines had already been closed, but the environmental assessment had not been completed. Two mining companies were applying for closure certification of Quirke and Panel Waste Management Areas and the Denison and Stanrock Tailings Management Areas. The panel tasked with deciding on the assessment recommended a number of measures to minimize the long-term risk of the facilities, such as monitoring, research and maintenance programs. The recommended programs are typically part of contemporary mine permitting and closure practices.

South Mine Pit Lake in the Tennessee Copper Basin, USA

South Mine Pit Lake is used as disposal site for sludge from a treatment plant neutralising acidity in the North Potato Creek. The creek is a tributary of the Ocoee River, Tennessee, and drains a major part of the Copper Basin in Tennessee (Faulkner et al. 2005; Wyatt et al. 2006). The South Mine pit lake (550 m long, 146 m wide, 61 m deep) is located close to the confluence of the North Potato Creek and the Ocoee River, provides the potential use of the lake for treatment purposes. Since the pit lake is meromictic, it also serves as a source of iron as an additional flocculant for the treatment plant: Water from the monimolimnion is added to the mixing tank of the treatment plant together with lime in order to achieve better removal of metals. The initially acidic mixolimnion of the pit lake became neutral within a month after the start of the treatment system (Wyatt et al. 2006). Model simulations proved the stability of the permanent stratification of the lake (Colarusso et al. 2003). An essential step of the overall treatment procedure is the re-dissolution of part of the iron under the reducing

conditions in the monimolimnion (i.e., the monimolimnion is not simply used as a safe disposal site but also as a reactor).

Nifty Copper (Aditya Birla) and Tallering Peak T5 Pit Lake (Mount Gibson Iron Ore), Australia

Best management of AMD in pit lake water is practiced by preventing acid generation in waste and pit wall rock through good geochemical characterisation and encapsulation of PAG material in alkaline/neutral waste to minimise AMD production. Historically, many mines have not practiced such strategies, leaving potential legacies of acidic pit lakes.

Interaction of pit lakes with surrounding groundwater can be as a variety of forms, with those presenting as through-flow often the most problematic, where constituents of concern can seep from the pit lake into surrounding groundwater resources and be transported to receptors away from the pit lake. Through-flow lakes may be a permanent feature for some pit lake water balances, a seasonal feature during surcharge over wetter months, or even an initial feature that ceases to seep pit lake water to groundwater as regional climate becomes hotter and drier (e.g., through climate change).

In an arid climate, pit lake evaporation rates can exceed influx rates, causing the pit lake to function as a hydraulic “terminal sink,” with water levels in the pit remaining below surrounding groundwater levels (McCullough et al. 2012a). Localised groundwater contamination is entrained toward the pit lake and pit lake water itself is contained as a point source of contamination. Two case studies from Western Australia were used to describe how pit lakes could be used in this manner to achieve best available practice to overall site closure in dry climates (McCullough et al. 2013a).

The Nifty Copper site is in a hot, arid region with highly dispersive soils. Waste dump covers over PAG material were not expected to resist erosion satisfactorily over the long term. The second site of Tallering Peak had PAG material management limited by current waste rock dump location and again by suitable cover materials.

Pit lake water balance modelling indicated that both pit lakes would function as hydraulic terminal sinks if not backfilled above long-term equilibrium water levels. Regardless of waste backfill; poor water quality was expected to develop as evapoconcentration increased contaminant concentrations from pit rock and mining disturbed catchment surface and groundwater inflows. The studies conclude that the best current opportunity to limit AMD risk and protect regional groundwater environments is to only partially backfill, intentionally producing a terminal sink pit lake (Section 2.2). Backfilling with PAG material would also reduce exposure to oxidation and weathering.

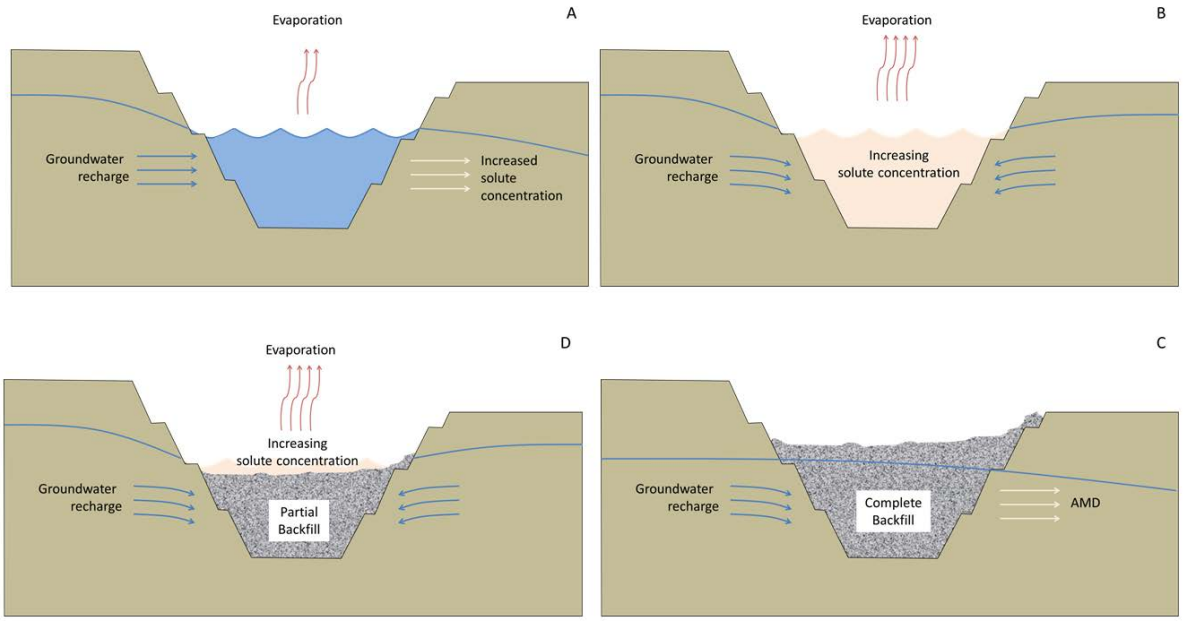

Figure 4: Conceptual equilibrium hydrogeological regimes for considering backfill of the two study pit lakes. Clockwise from top left: through-flow system, terminal sink, completely backfill through-flow system, partially backfill terminal sink

Lake Kepwari (Yancoal Premier Coal), Australia

The Collie Coal Basin is the centre of the coal mining industry in Western Australia and is located approximately 160 km south south-east of Perth. Collie mine lakes are acidic due to moderate AMD production from oxidation of the regional low sulfide lithologies.

Mining began in the Lake Kepwari (WO5B) pit with diversion of the Collie River South Branch (CRSB) around the western pit margin (Figure 5). The closure aims for the lake were to provide a recreation resource for water skiing, diving and other aquatic recreational pursuits. When mining ceased in 1997, most reactive overburden dumps and exposed coal seams were covered with waste rock backfilled into the pit to cover PAG sources. Lake edges were backfilled and graded in some areas to form beaches and an island, and then extensively revegetated with endemic flora by direct seeding. The diversion channel was then maintained to permanently divert the CRSB around the pit.

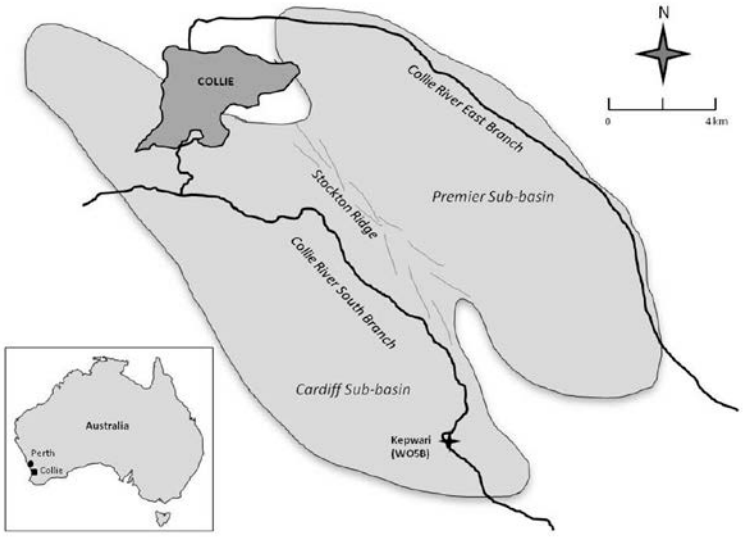

Figure 5: Location of Lake Kepwari in Western Australia.

The volume of Lake Kepwari is around 32 Mm^3, with a maximum depth of around 65 m and surface area of 1.0 km^2 (McCullough et al. 2010). To further reduce wall exposure and rates of resulting acid production, the lake was rapid-filled by seasonal diversions from the CRSB over the winters from 2002–2008 (Salmon et al. 2008). The surrounding mining-disturbed landscape was then revegetated with native forest. Although the input of CRSB water initially raised the pH to above 7, the pH then fell below 4 once river inflows ceased. This low pH and associated elevated concentrations of some metals and metalloids reduced water quality values and restricted end use opportunities.

Heavy rainfall in August 2011 led to the CRSB overtopping the diversion channel along the south branch wall that separates it from Lake Kepwari (McCullough et al. 2013b). This unintentional flushing had the effect of substantially improving the water quality and ecosystem values (McCullough et al. 2012b) indicating that maintaining the partially backfilled lake as a flow through system would likely provide a leading practice closure strategy. Regular seasonal flow-through is expected to yield a seasonal thermally stratified brackish lake of circum-neutral pH (McCullough and Schultze 2015).

Following broad stakeholder engagement, including community presentations, and approval by state regulators, a flow-through trial was proposed to assess the benefits of this leading practice management option. The trial was run between 2012 and 2014 with over two years of flow and one year of no flow due to low rainfall. Regular quarterly assessment of biota and chemistry of both Lake Kepwari and the CRSB, and annual reporting of the findings to regulators and community was a key component of the trial.

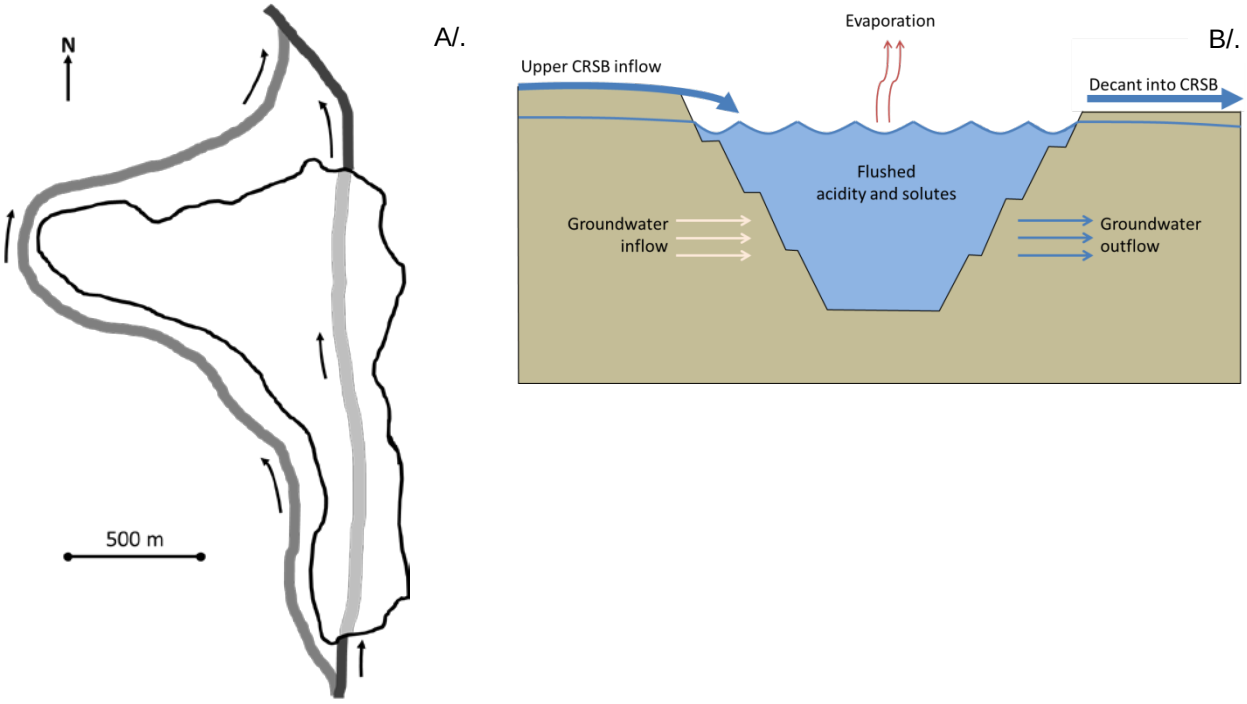

Figure 6: Conceptual model of A/. Lake Kepwari flow-through design showing historical CRSB channel in black, previous river diversion in dark grey and presumed lake passage in light grey) and B/. AMD groundwater source shown as pink arrows, sinks and water balance during flow-through.

The monitoring results showed that downstream river water quality is not significantly degraded by flow-through since the greatest decant volumes occur predominantly during high CRSB flow with consequent high lake water dilution. Further, river water quality may actually be improved (relative to upstream) through trapping of sediment including particulate forms of nutrients by the lake benthos, and removal of soluble forms of phosphorus by co-precipitation with dissolved aluminium species present with lake AMD (McCullough and Schultze 2015). Monitoring indicates that, following implementation of flow-through, lake pH is higher than historic levels, and importantly, on an upward trend.

Flow-through may not work as leading practice for all pit lake closures, particularly those with high downstream river water quality and end uses. The strategy has worked particularly well in the Lake Kepwari pit lake situation as the river channel was able to be maintained in its historical course and was already degraded; reducing risk of AMD on downstream river values. A literature review at the beginning of the project, coupled with early and regular engagement, provided confidence to stakeholders that the approach was leading international practice. Similarly, the monitoring period has validated the closure approach.

Yandi Iron Ore Mine (BHP), Western Australia, Australia

Along with a number of other mining companies, the Yandi Mine extracts Channel Iron Deposit (CID) from beneath the water table in the Pilbara desert region of Western Australia. Open cut mining occurs at four sites along Marillana Creek, and ultimately mining will remove the entire CID.

As much of the Marillana Creek CID aquifer will be removed during mining operations, closure strategies are to ensure adequate groundwater flow-through to protect the down-gradient Weeli Wolli CID aquifer and maintain the values of the groundwater resource.

The very low overburden to ore ratio (0.2:1) realises little material for backfilling of final mine pits. In the long term, evaporation of the pit lakes will result in an increase in salinity, as water is lost through evaporation and salt is left behind. Current mine-closure plans have opted for partial backfilling of the pits with overburden mine waste, in order to minimise pit lake surface area and hence evaporation rates. This increased positive water balance will help maintain a degree of flow through the system. These plans involve the creation of a number of shallow elongated final pits.

Jundee Gold Mine Pit, Australia

This mine site consists of an open pit and underground mine near Wiluna (Figure 7). Open pit mining stopped in 2002 and some of the open pits have been partially backfilled with waste rock or tailings and left to flood with water (Figure 8). Pyrite and arsenopyrite were the primary sulphides in the waste rock and the wall rock. Carbonates are extensive on the site, consisting predominantly of calcite and ankerite. Given the rock types, mineralization and hydrothermal alteration of the waste rock, AMD is not anticipated; however, there is the potential for neutral drainage metal leaching and related water quality issues.

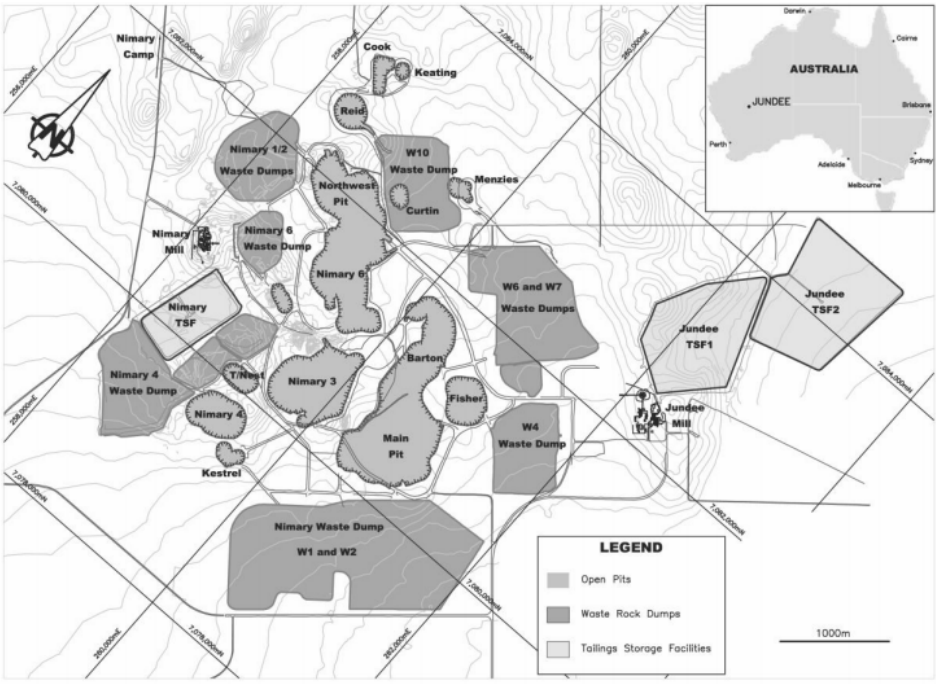

Figure 7: Jundee project layout and pits (Shaw et al. 2006).

Figure 8: A Jundee pit lake partially backfilled with mine waste.

Much of the backfill material and primary pit wall rock sampled in this study contains substantial neutralization capacity in the form of carbonate veining. It is expected that these materials will add net alkalinity to the pit systems.

Best estimates of pit water quality are qualitative to date, but suggest a slightly alkaline, saline pit lake with elevated TDS values dominated by sodium, chloride and sulphate, with lesser amounts of calcium, magnesium, bicarbonate, nitrate and negligible trace metals with the possible exception of arsenic, cadmium, cobalt and nickel.

Evaporation is anticipated to play a dominant role in the chemistry within the pit lake system given the climate at Jundee. This will likely result in gradual increases in concentration of the constituents within the lake system and potentially the development of a density stratified lake 'trapping' the poorer water quality at depths in the form of a stratified hydraulic cage post-closure.

Central German Lignite Mining District Mine Lakes, Germany

The pit of the former lignite mine Großkayna was used for the deposition of industrial wastes from 1969 to 1995. The wastes mainly consisted of ashes from lignite combustion in power plants and from production of synthetic gas. However, waste materials from the production of nitrogen fertiliser and from other chemical productions were also deposited among the ashes. Differing from initial plans, only the lower part of the pit (about one third by volume) was filled with waste. A pit lake (Lake Runstedt) was established on top of the waste material by diverting water from the river Saale from May 2001 to December 2002. Model simulations showed that this lake

will have only inflows and no outflow if neighbouring pit lakes will be held at certain levels. The only loss of water is evaporation. In this way, the transport of fluids from the waste into the groundwater is prevented as the lake functions as a terminal sink (Schroeter 1997; Fritz et al. 2001).

The major concern regarding water quality results from the high ammonia concentration in the pore water of the waste. In order to manage the oxygen consumption accompanying the import of ammonia into the lake, three hypolimnetic aerators are operated in the lake (Fritz et al. 2001), mainly during seasonal stratification in summer and during ice cover in winter. The system was reportedly working well. Monitoring indicates that denitrification established naturally in stands of emerged macrophytes in the littoral avoiding enrichment of nitrate in the lake water. This case study indicates that pit lakes can be used even for the disposal of industrial wastes under certain circumstances.

Lusatian Lignite Mining District Mine Lakes, Germany

Some mine pits of former lignite mines in the Lusatian mining district of Germany were used as disposal sites for waste lime sludge, ash from power plants and sludge of a liming based mine water treatment plant (Schultze et al. 2011).

Lake Geierswald (Figure 9) was partially neutralised during five months in 2004 and 2005 by re-excavation and spreading of waste lime formerly deposited at the lake bottom (Benthaus and Uhlmann 2006). About 500,000 m^3 of a 1.9% lime suspension were re-excavated, corresponding to 10,000 t of lime. The treatment with waste raised the pH, which had been as low as 3.0.

Sludge of the mine water treatment plant Schwarze Pumpe has also been dumped in Lake Spreetal. The sludge contributed about 30% to the overall improvement of the lake water until the end of 2006 (Uhlmann et al. 2007). This neutralising activity of the sludge was based on remaining reactive lime. The disposal of the sludge is still in operation. Unger-Lindig et al. (2010) found that addition of CO_2 could even improve the alkalinity gain for the lake water from added sludge by formation of bicarbonate.

About 26 Mm^3 of fly ash was deposited in the former mine Burghammer (Koch C. et al. 2008). Rising groundwater formed Lake Bernstein in the remaining space of the former mine pit. The use of the ash deposits for lake neutralisation was tested successfully by re-suspension and redistribution of a small portion of the ash (Koch C. et al. 2008; Koch T. et al. 2008). The full neutralisation of the lake water would require resuspension of about 1% of the deposited ash (Koch C. et al. 2008; Koch T. et al. 2008).

Figure 9: Lake Geierswald, now developed into a recreational centre for the region.

B-2.3 Unsuccessful pit lakes

Sludge Disposal in Equity Silver Mine Pit Lakes, British Columbia, Canada

The Equity Silver Mine, a gold, silver and copper mine near Houston, B.C., operated between 1980 and 1994. Three pits were mined during operations, and two were flooded to form pit lakes at closure. The third pit was backfilled with waste rock and tailings. Shortly after operations began, AMD issues were identified, and the mine now treats AMD waters with an active lime water treatment plant. The AMD is thought to be entering the pit lake via groundwater, and was being mapped in 2012 (Goldcorp 2013).

The Main Zone and Waterline pit lakes have a number of unique characteristics that have been well studied and documented. Hydroxide sludge from the water treatment plant is discharged to Main Zone Pit Lake, where it quickly plunges to depth due to its high density. The sludge entrains some oxygenated surface water, which results in aerobic conditions in the deep section of the lake, which would likely otherwise be anoxic. The Main Zone Pit Lake also contains some backfilled waste rock. The Waterline Pit Lake, which is just upstream of the Main Zone Pit Lake, does not receive sludge input and has reducing conditions at depth. The differences in redox conditions leads to very different metals concentrations in the two pit lakes at depth (Crusius et al. 2003). As of 2003, studies were being conducted to investigate in-situ water treatment methods for these pit lakes. ARCADIS (2015) reported that water quality was relatively good in the pit lakes, and that the pit lakes were acting as sinks to remove particulate metals, similar to Springer Pit Lake described in Section 4.1.

Gunnar Pit Lake, Saskatchewan, Canada

Gunnar Pit Lake in Northern Saskatchewan, near Lake Athabasca, was first described by Tones (1982), and later by SRK (2008) and Muldoon and Schramm (2009). Gunnar Pit Lake is located at a former uranium mine that began mining in 1955 and closed in 1964. After closure, a trench was blasted to connect the pit lake to Lake Athabasca, and the entire pit was flooded, with no induced stratification. The trench was later closed by backfilling with about 2.7 Mm^3 of waste rock. Over time, the lake established a meromictic density gradient and pycnocline (zone of vertically changing densities). The lake stratifies seasonally at a depth of about 10 m and has a pycnocline over a gradient from 75 m to 90 m deep. The specific conductivity is reported as 300 µOhm/cm in the mixolimnion and 1,900 µOhm/cm in the monimolimnion, suggesting strong meromixis. From 1971 to 1981, fish processing waste, including wastewater effluent and fish offal, were disposed of in the pit lake. The lake water concentrations were high in nutrients such as phosphorus, and low in metals except uranium. Uranium was measured at 2.8 mg/L in the monimolimnion, and was expected to be acutely toxic to fish (Tones 1982). At that time, seepage from the pit lake to Lake Athabasca was deemed to be negligible. Meanwhile, drainage from waste rock at the abandoned mine was ten times higher in uranium concentration, and flowed directly into Lake Athabasca. Bare waste rock was also left at the site along and within the lake (Schramm 2012). Despite elevated uranium concentrations in the monimolimnion, fish were observed in the mixolimnion, including northern pike, common suckers and longnose suckers. The presence of these fish in an enclosed pit lake above acutely toxic waters indicates that meromixis has effectively isolated the toxic underlying waters.

Similar to Gunnar Pit Lake, the B-zone Pit Lake, which was a uranium mining pit until 1990, was flooded with the adjacent Wollaston Lake in 1991. The two lakes are now separated by a retaining wall (Kalin et al. 2001).

Northwest Territories and Yukon Territory, Canada

There are a number of legacy pit lakes in the Northwest Territories and Yukon Territory, such as those at Colomac and Faro Mines (Pieters et al. 2014). Like other sites from historical mining in the north, these pit lakes were mined and filled before closure was considered and planned according to today's standards.

In contrast, to the legacy mine sites, present-day projects such as the diamond mines in Northwest Territories include planning for sustainable pit lake closure. All three of the operating open pit diamond mines will include pit lakes at closure. Pit lake closure plans are described in for Ekati by Rescan (2012), Gahcho Kue by Vandenberg et al. (2015b) and Diavik by DDMI (2010). In the case of Ekati and Gahcho Kue, some of the pit lakes will be used to permanently store waters with higher salinity that are captured during mining and that will flow into the lakes at closure from the naturally elevated groundwater at depth.

Berkely Pit Lake, USA

Perhaps the most widely reported pit lake case study globally is the Berkely Pit Lake (Castendyk and Eary 2009; Davis and Ashenberg 1989; Doyle and Runnells 1997; Gammons et al. 2003; Gammons and Duaime 2006; Geller et al. 2013; CEMA 2012; Jonas 2000; Madison et al. 2003; Pellicori et al. 2005; Robins et al. 1997; Sonderegger et al. 1987; Stierle and Stierle 2005). The pit lake is one of the largest AMD accumulations on Earth and is part of the largest Superfund site in the USA. The pit lake is surrounded on about half of its perimeter by the city of Butte, Montana. It is formed in a pit at the former Anaconda Mine that operated from 1955 to 1982; the dewatering pumps were shut off on Earth Day of that year. Water quality issues were first documented by Sonderegger et al. (1987) and Davis and Ashenberg (1989), after the pit began filling.

By 1989, the pit was filling at a rate of 22 m per day, with 10,000 to 20,000 m^3 per day flowing into the pit, from an underground mining complex and seepage from aboveground waste rock and tailings. The groundwater was contaminated by oxidation of pyrite and other minerals in the surrounding formation, which led to low pH (<3) and extremely high concentrations of sulphate (6780 mg/L), arsenic (1 mg/L), copper (202 mg/L), zinc (512 mg/L) and several other metals in the water column. For reference, those concentrations are two to five orders of magnitude above water quality guidelines in Alberta and other Canadian jurisdictions.

The pit lake was predicted to rise above surrounding groundwater levels by 2009, which would cause a contaminated plume of water to migrate through the groundwater away from the pit toward downgradient Silver Bow Creek. Therefore, the inflowing groundwater was diverted to an active water treatment plant to maintain water levels in the pit below the groundwater table to avoid off-site contamination. Active treatment continues to this day and will be required for the foreseeable future.

Figure 10: Berkeley Pit Lake, Montana

The Berkeley Pit Lake twice received widespread media coverage when migratory snow geese died as a result of landing on the water – over 300 in 1995 and several thousand in 2016.

Gammons and Duaime (2006) note that Berkely Pit Lake represents the worst end of the spectrum of pit lakes, and that Berkely Pit Lake "should never be touted as a typical example of a mining pit lakes as a whole" – advice that is often ignored by critics of mining (see for example Pilkey and Pilkey-Jarvis 2007; Van Loon 2013). Despite being a "worst-case" scenario in terms of mining legacy (Geller et al. 2013), there have been some positive outcomes from Berkeley Pit Lake:

- The pit lake is presently a tourist attraction, with a viewing platform that can be accessed for $2 per person.
- The extreme conditions in Berkeley Pit Lake has led some researchers to study the microbiology in an attempt to derive novel medicines (Stierle and Stierle 2005). Recently conducted research revealed unique strains of fungi (named Berkeleylactones) that may be combined to develop new antibiotics that can kill methicillin-resistant *Staphylococcus aureus* (Stierle et al. 2017).
- Copper has been commercially recovered from the monimolimnion (underlying layer of water) by pumping it to surface and passing it over scrap iron, which causes copper to precipitate in elemental form.
- Berkeley Pit Lake was one of the first pit lakes to be studied widely, and it provided many scientific advances that are relevant to the management of acidic pit lakes globally (see references above and additional references in Geller et al. 2013). More generally, the Berkely Pit Lake case study revealed the

importance of proper waste characterization, closure planning, prediction, and public consultation that is common today in most jurisdictions.

- The pit lake serves as a stark reminder to mine closure practitioners about the potential consequences of mining in the absence of a comprehensive mine closure plan or one in which the original conditions were not well characterized.

Figure 11: Aerial View of Berkeley Pit Lake and Butte, Montana

B-2.4 Natural Lakes in Canada that Contain Mine Waste

While there are no proposals by oil sands mines to use natural lakes to store mine waste, there are case studies within Canada and elsewhere of natural lakes that are used to store tailings. This practice is allowed under the Canada Fisheries Act, provided authorization is granted. As noted by Environment and Climate Change Canada (2017), "*the MMER, enacted in 2002, were developed under subsections 34(2), 36(5) and 38(9) of the Fisheries Act to regulate the deposit of mine effluent, waste rock, tailings, low-grade ore and overburden into natural waters frequented by fish. These regulations, administered by Environment Canada, apply to both new and existing metal mines. Schedule 2 of the MMER lists water bodies designated as tailings impoundment areas (TIAs).*"

Wabush Lake – Carol Tailings Management Project

One such example is the Carol Tailings Management Project, near Labrador City. Iron Ore Company has been mining since 1962 and has historically stored tailings within Wabush Lake in accordance with provincial

regulations. Iron Ore Company applied to have Wabush Lake designated as a TIA in 2006 to comply with Metal Mining Effluent Regulations (MMER). The lake was segmented into three sections by dyke, and one of those sections receives tailings. In 2004, the tailings were flocculated prior to deposition to eliminate the red hue of the lake that was caused by discharging untreated tailings. Within three months of flocculant addition, the lake had reverted back to a more natural hue (IOC 2006).

There are two case studies of mines in the Northwest Territories (NWT) that deposit tailings into natural lakes (Davé et al. 1996). The Polaris mine, located on Little Cornwallis Island, deposited tailings into Garrow Lake, which is a naturally meromictic lake. Tailings were deposited at a depth of 26 m, below the pycnocline. Similarly, Nanisivik Mine on Baffin Island stored tailings in West Twin Lake until 1991, at which time the storage capacity of the lake was exhausted. Tailings were stored in the lake to mitigate their high AMD potential.

Based on lessons learned at the natural lakes described above, as well as the four Ontario case studies described in Section APPENDIX B, Davé (2009) made the following observations about tailings disposal in natural waterbodies that are also applicable to pit lakes.

- "*Minimal or no risk of catastrophic failure".*
- *"Most suitable for long-term geotechnical and chemical stability".*
- *"Suitable for small headwater or isolated water bodies".*
- *"Economically attractive and predictable technology*".

Davé (2009) list eight other underwater tailings disposal sites in Canada, including Island Copper Pit Lake and Garrow Lake, described above. Davé (2009) also lists three submarine tailings disposal sites in Canada, included Island Copper Mine. Dold (2014) lists 38 submarine tailings disposal sites around the world, including the four in Canada.

APPENDIX C

References

Allen CR, Fontaine JJ, Pope KL, Garmestani AS. 2011. Adaptive management for a turbulent future. Journal of Environmental Management 92: 1339-1345.

Amezaga JM, Younger PL. 2004. ERMITE: supporting European policy making on mine waste and waters, in Mine Water 2004 – Proceedings International Mine Water Association Symposium 1, Newcastle upon Tyne (University of Newcastle), UK, A. P. Jarvis; B. A. Dudgeon and P. L. Younger (eds), pp. 41-46.

ANCOLD. 2012. Guidelines on Tailings Dams – Planning, Design, Construction, Operation and Closure. Australian National Committee on Large Dams Incorporated ANCOLD Inc, Melbourne, Australia.

ARCADIS. 2015. In-Pit Disposal of Reactive Mine Wastes: Approaches, Update and Case Study Results. Mine Environment Neutral Drainage (MEND) Report 2.36.1b. Available at: http://mend-nedem.org/wp-content/uploads/2.36.1b-In-Pit-Disposal.pdf

Arias MAA, Fernández JLD. 2008. Water Quality Models in Limeisa Mining Lake. – In: Rapantova, N. & Hrkal, Z.: Mine Water and the Environment. – p. 547-549; Ostrava (VSB – Technical University of Ostrava).

Axler RP, Larsen C, Tikkanen C, McDonald M, Yokom S, Aas P. 1996. Water quality issues associated with aquaculture: a case study in mine pit lakes. Water Environment Research 68: 995-1011.

Axler R, Yokom S, Tikkanen C, McDonald M, Runke H, Wilcox D, Cady B. 1998. Restoration of a mine pit lake from aquacultural nutrient enrichment. Restoration Ecology 6: 1-19.

Axler R, Henneck J, McDonald M. 2004. Mine Pit Aquaculture in Minnesota: Perspectives on the Environmental and Regulatory Issues, 1988-1999. Pit Lakes 2004 Conference, November 16-18, Silver Legacy Hotel, Reno, Nevada

Bailey BL, Smith LJ, Blowes DW, Ptacek CJ, Smith L, Sego DC. 2013. The Diavik Waste Rock Project: Persistence of contaminants from blasting agents in waste rock effluent. Applied geochemistry, 36:256-270.

Beckie R. 2016. A Ten-Year Waste-Rock Study: Lessons Learned from Multiple Scales and Impact on Prediction. Mine Environment Neutral Drainage (MEND) BC Conference. December 1, 2016. Vancouver, Canada.

Beddoes P, Herrell M, Vandenberg JA, Richards J, Millar R, McMahen K. 2016. Validation of Springer Pit Lake Water Balance and Water Quality Model, Mount Polley Mine, British Columbia, Canada. International Mine Water Association. July 11-15, 2016. Leipzig, Germany.

Benthaus FC, Uhlmann W. 2006. Die chemische Behandlung saurer Tagebauseen in der Lausitz – Erfahrungen zur Kalkschlammresuspension im Tagebausee Koschen, Wissenschaftliche Mitteilungen des Institutes für Geologie Nr. 31/2006, B. Merkel, H. Schaeben, C. Wolkersdorfer, A. Hasche-Berger eds, Technische Universität Bergakademie Freiberg, Freiberg, pp. 85–96.

Blum JS, McCann S, Bennett S, Miller LG, Stolz JR, Stoneburner B, Saltikov C., Oremland RS. 2015. A microbial arsenic cycle in sediments of an acidic mine impoundment: Herman Pit, Clear Lake, California. *Geomicrobiology Journal* 1-13.

Boehrer B, Schultze M. 2006. On the Relevance of Meromixis in Mine Pit Lakes. Poster paper presented at the 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I.

Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502.

Böhrer B, Heidenreich H, Schimmele M,. Schultze M. 1998. Numerical prognosis for salinity profiles of future lakes in the opencast mine Merseburg-Ost. Intern. J. Salt Lake Res. 7, 235-260.

Boehrer B, Schultze M, Liefold S, Behlau G, Rahn K, Frimel S, Kiwel U, Kuehn UB, Brookland I, Büttner O. 2003. Stratification of mining Lake Goitsche during flooding with river water. p. 223-231. In: Tailings and Mine Waste '03. Swets and Zeitlinger, Lisse.

Brenner FJ, Edmundson J, Werner M, McGrath T. 1987. Plankton, chlorophyll characteristics and fishery potential of surface coal mine lakes in western Pennsylvania. In Proceedings of the Pennsylvania Academy of Science (USA).

Brinker C. 1991. Lake creation and development at an Alberta foothills coal mine. Proceedings of the 15th Annual British Columbia Mine Reclamation Symposium in Kamloops, BC, 1991. The Technical and Research Committee on Reclamation.

Brinker CJ, Symbaluk MD, Boorman JG., 2011. Constructing habitat for a sustainable native fisheries in the Sphinx Lake end pit lake system. Mine Closure 2011. September 18-21, 2011. Lake Louise, Canada.

Burke MG. 1990. Seawater consumption and water economy of tropical feral goats, Biotropica, Vol. 22, pp. 416-419.

Buzzacott P, Paine D. 2012. Former mine pit dive parks. International Mine Water Association Annual Conference. Bunbury, Australia.

Castendyk DN, Eary LE. 2009. Mine pit lakes: characteristics, predictive modeling, and sustainability (Vol. 3). SME.

Castendyk DN, Webster-Brown JG. 2007a. Sensitivity analyses in pit lake prediction, Martha Mine, New Zealand 1: Relationship between turnover and input water density. Chemical Geology 244: 42-55.

Castendyk DN, Webster-Brown JG. 2007b. Sensitivity analysis in pit lake prediction, Martha Mine, New Zealand 2: Geochemistry, water-rock reactions, and surface adsorption. Chemical Geology 244: 56-73.

Čech M, Peterka J, Řiha M, Draštik V, Kratochvil M, Kubečka J. 2010. Deep spawning of perch (*Perca fluviatilis*, L.) in the newly created Chabařovice Lake, Czech Republic. Hydrobiologia 649: 375—378.

CEMA (Cumulative Environmental Management Association). 2012. End pit lakes guidance document 2012. Hrynyshyn J and Wylynko D. (Eds.). Fort McMurray, AB, CEMA Contract No. 2010-0016 RWG. 434 p.

Colarusso LA, Chermak JA, Priscu JC, Miller FK. 2003. Modeling pit lake water column stability using Ce-Qual-W2, Tailings and Mine Waste '03, Swets & Zeitlinger, Lisse, pp. 213–222.

Crusius J, Pieters R, Leung A, Whittle P, Pedersen T, Lawrence G, McNee JJ. 2003. Tale of two pit lakes: Initial results of a three-year study of the Main Zone and Waterline pit lakes near Houston, British Columbia, Canada. Mining engineering, 55(2):25-30.

CVRI (Coal Valley Resources Inc.). 2012. Robb Trend Project – Section F – Reclamation Plan. Available at https://open.alberta.ca/dataset/b92b11da-c31e-4d21-a158-0ba6c078e610/resource/857a9529-b8f2-49ca-b3b6-f685229323ed/download/07-Section-F---Reclamation-Plan.pdf

CVRI. 2014. Coal Valley Resources Inc. - Coal Valley Mine; Robb Trend Project; Preliminary Fish Compensation Outline Project Update & Revised Discussion Report. Available at http://www.ceaa.gc.ca/050/documents/p61436/100433E.pdf

Czop M, Motyka J, Szuwarzynski M. 2008. Chemical Composition of the Extremely Alkaline Water within "Górka" Pit Lake (Chrzanow Region, South Poland). – In: Rapantova, N. & Hrkal, Z.: Mine Water and the Environment. – p. 559-562; Ostrava (VSB – Technical University of Ostrava). Dowling, J., Atkin, S., Beale, G., and Alexander, G., 2004. Development of the Sleeper Pit Lake. Mine Water and the Environment, 23: 2–11

Davé N, Blanchette M, Giziewicz E. 1996. Role of ice, in the water cover option, and permafrost in controlling acid generation from sulphide tailings. Mine Environment Neutral Drainage (MEND) Report 1.61.1. 96 pp.

Davé N. 2009. Disposal of Reactive Mining Waste in Man-made and Natural Water Bodies; Canadian Experience. Marine and Lake Disposal of Mine Tailings and Waste Rock. Egersund, Norway, Sept. 7-10, 2009

Davis A, Ashenberg D. 1989. The aqueous geochemistry of the Berkeley pit, Butte, Montana, USA. Applied Geochemistry, 4(1):23-36.

DDMI (Diavik Diamond Mines Inc.). 2010. Interim Closure and Reclamation Plan – Version 3.1. December 2010. Available at http://registry.mvlwb.ca/Documents/W2007L2-0003/W2007L2-0003%20-%20Diavik%20-%20ICRP%20-%20Version%203.1%20-%20Part%201%20-%20Main%20Report%20-%20Dec%2022_10.pdf.

Denimal S, Bertrand C, J. Mudry J, Y. Paquette Y, M. Hochart M, and M. Steinmann M. 2005. Evolution of the aqueous geochemistry of mine pit lakes – Blanzy-Montceau-les-Mines coal basin (Massif Central, France): origin of sulfate contents; effects of stratification on water quality. Appl. Geochem. 20, 825-839.

Dessouki TC, Hudson JJ, Neal BR, Bogard MJ. 2005. The effects of phosphorus additions on the sedimentation of contaminants in a uranium mine pit-lake. Water Research, 39(13):3055-3061.

DIIS. 2016. Leading Practice Sustainable Development Program for the Mining Industry - Preventing Acid and Metalliferous Drainage Handbook Department of Industry, Innovation and Science DIIS, Canberra, Australia.

DITR. 2007. Leading Practice Sustainable Development Program for the Mining Industry - Tailings management. Department of Industry, Tourism and Resources, Canberra, Australia.

DMP and EPA 2015. Guidelines for preparing mine closure plans. Western Australian Department of Mines and Petroleum (DMP), Environmental Protection Authority of Western Australia (EPA), Perth, Australia. 115p.

DOIR 1997. Safety bund walls around abandoned open pit mines, by Department of Mines and Petroleum, Perth, Western Australia. pp.

Dold B. 2014. Submarine tailings disposal (STD)—A review. Minerals, 4(3):642-666.

Doley D, Audet P. 2013. Adopting novel ecosystems as suitable rehabilitation alternatives for former mine sites. Ecological Processes 2: 1-11.

Donald S, Welch D, Holl N, Landine P. 1997. “Recent Hydrogeological Developments in Uranium Mine Tailings Management in Canada: The Key Lake Experience”, Proceedings International Symposium on Engineering Geology and the Environment, Organized by the Greek National Group of IAEG, Athens, Greece, 23-27 June, 1997, Balkema, Rotterdam, 1997, pp 2371-2377.

Doyle GA, Runnells DD.1997. Physical limnology of existing mine pit lakes. Mining Engineering 49, 76-80.

Dunson WA 1974. Some aspects of salt and water balance of feral goats from arid islands, American Journal of Physiology, Vol. 226, pp. 662-669.

Duthe, D.M, Mahoney, J.J., Shchipansky, A.A., Terrell, C.L. 2011. Assessment of the Process of Pit Lake Formation and Associated Geochemistry in Open Pits – Mupane Gold Mine, Botswana. – In: Rüde, R. T., Freund, A. & Wolkersdorfer, Ch.: Mine Water – Managing the Challenges. - p. 511 – 515; Aachen, Germany.s

ELUMTAEAP (Elliot Lake Uranium Mine Tailings Areas Environmental Assessment Panel). 1996. Decommissioning of Uranium Mine Tailings Management Areas in the Elliot Lake Area. Report of the Environmental Assessment Panel. June 1996. 69 pp.

EPLWG (End Pit Lake Working Group). 2004. Guidelines for Lake Development at Coal Mine Operations in Mountain Foothills of the Northern East Slopes, Report # ESD/LM/00-1, Alberta Environment, Environmental Service.

Environment and Climate Change Canada. 2017. Guidelines for the Assessment of Alternatives for Mine Waste Disposal. Available at http://www.ec.gc.ca/pollution/default.asp?lang=En&n=125349F7-1

ERCB (Energy Resources Conservation Board). 1994. ERCB Decision D 94-5; Syncrude Continued Improvement and Development Project Mildred Lake Oil Sands Plant. 50 pp. Calgary, Canada.

Ericsson B, Hallmans B. 1994. Treatment and disposal of saline wastewater from coal mines in Poland. Desalination 98: 239-248.

Faulkner BB, Wyatt G, Chermak JA, Miller FK. 2005. The Largest Acid Mine Drainage Treatment Plant In The World? Proceedings 26th Annual West Virginia Surface Mine Drainage Task Force Symposium, 19 April, Morgantown, USA, viewed 18 February 2009, http://wvmdtaskforce.com/proceedings/05/Faulkner.pdf.

Fisher TSR. 2002. Limnology of the meromictic Island Copper pit lake. Ph.D. thesis, University of British Columbia, Vancouver, BC.

Fisher TSR, Lawrence GA. 2006. Treatment of acid rock drainage in a meromictic mine pit lake. Journal of Environmental Engineering 132:515-526.

Flambeau Mining Company 2009. Annual report. USA.

Fleischhammel P, Menendez L, José A. 2010. Post-mining lakes – various types and their integration in river basin landscapes according to the European Water Framework Directive. – In: Wolkersdorfer, Ch. & Freund, A.: Mine Water & Innovative Thinking. – p. 533 – 537; Sydney, Nova Scotia (CBU Press).

Fox F. 2004. A return to beauty. Mining Environmental Management 14-16.

Fritz W, Tropp P, Meltzer A. 2001. A Remediation and reclamation strategy for disused brown coal mines in the Geiseltal area, Surface Mining – Braunkohle & Other Minerals 53, pp. 155–166.

Gammons CH, Wood SA, Jonas JP, Madison JP. 2003. Geochemistry of the rare-earth elements and uranium in the acidic Berkeley Pit lake, Butte, Montana. Chem. Geol. 198, 269-288.

Gammons CH, Duaime TE. 2006. Long term changes in the limnology and geochemistry of the Berkeley pit lake, Butte, Montana. Mine Water and the Environment. 25(2):76-85.

Gammons CH. 2009. Subaqueous oxidation of pyrite in pit lakes. In, Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability Chap. 12. In: Castendyk, D. & Eary, T. Society for Mining, Metallurgy, and Exploration SME, Colorado, USA, 137-145pp.

Garcia DH. 2008. Overview of international mine closure guidelines, in Meeting of the American Institute of Professional Geologists, Arizona Hydrological Society, and 3rd International Professional Geology Conference, Flagstaff, Arizona, USA, American Institute of Professional Geologists, pp. 1-9.

Geller W, Schultze M, Kleinmann RLP, Wolkersdorfer C. 2013. *Acidic Pit Lakes - Legacies of surface mining on coal and metal ores.* Springer, Berlin, Germany.

Godwin AL, Lee PF, Conly AG, Goold AR. 2010. Predicting toxicity of future combined pit lakes at the former Steeprock Iron Mine near Atikokan, Ontario. – In: Wolkersdorfer, Ch. & Freund, A.: Mine Water & Innovative Thinking. – p. 343 – 347; Sydney, Nova Scotia (CBU Press).

Goldcorp. 2013. 2012 Sustainability Report; Closed Sites in Honduras, Mexico, the United States and Canada. Available at http://csr.goldcorp.com/2013/_docs/Closed%20Sites%20Sustainability%20Report%202012.pdf

Golder (Golder Associates Ltd.). 1996. Geotechnical issues in Connection with Waste Dumping in Apirsa's Open Pit Mine, Aznalcollar, Spain. Report to Boliden Apirsa, S.L. September, 1996.

Golder. 2011. Design Report for the Quinsam 2 South Pit PAG CCR Storage Facility. Prepared for Hillsborough Resources Limited. 92 pp.

Government of Alberta. 2009. Environmental management of Alberta's oil sands, by Government of Alberta,, Calgary, Canada. 26 pp.

Hamaguchi BA, Larratt HM, Freberg M. 2009. The development of an aquatic ecosystem in Trojan Tailings Pond, Highland Valley Copper. British Columbia Mine Reclamation Symposium. University of British Columbia. Vancouver, Canada.

Hamblin PF, Stevens CL, Lawrence GA. 1999. Simulation of vertical transport in mining pit lake. Journal of Hydraulic Engineering. 125(10):1029-38.

Hatfield (Hatfield Consultants). 2008. Coal Valley Mine: An Evaluation of Existing End-Pit Lakes. Prepared for Coal Valley Resources Inc. February 2008. 72pp.

Hatfield. 2011. Coal Valley Mine: An Evaluation of Existing End-Pit Lakes. Prepared for Coal Valley Resources Inc. September 2011. 57pp.

Hatfield. 2014. Macrophyte and bathymetry surveys in end-pit lakes in the coal valley mine area. Prepared for Coal Valley Resources Inc. February 2014. 35pp.

Halir J, Zizka L. 2008. Residual Mining Pits in Central Part of North Bohemian Brown Coal Basin. International Mine Water Association Annual Congress. Ostrava, Poland.

Hao C, Wei P, Pei L, Du Z, Zhang Y, Lu Y, Dong H. 2017. Significant seasonal variations of microbial community in an acid mine drainage lake in Anhui Province, China. Environmental Pollution 223: 507-516.

Hildebrandt L, Noton LR, Anderson WJ. 1982. Lake development and fish habitat enhancement at Coal Valley, Alberta. Prepared for Luscar, Ltd. 83pp.

Hoekstra, G. 2014. 49 'dangerous occurrences' at B.C. mine tailings ponds in past decade: ministry data. Vancouver Sun. August 28, 2014.

Horn C, Metzler P, Ullrich K, Koschorreck M, Boehrer B. 2017. Methane storage and ebullition in monimolimnetic waters of polluted mine pit lake Vollert-Sued, Germany. Science of the Total Environment 584–585: 1-10.

IAEA (International Atomic Energy Agency). 2004. The long term stabilization of uranium mill tailings; Final report of a co-ordinated research project; 2000–2004. Report IAEA-TECDOC-1403. Vienna, Austria. 309pp.

INAP (International Network for Acid Prevention) 2014. Global Acid Rock Drainage Guide GARD Guide, http://www.gardguide.com/. Accessed: 18 February 2014.

Ingle DA. 2002. Newmont Waihi operations - an overview. Proceedings of the AusIMM 2002 Annual Conference. Auckland, New Zealand. 1-4 September, 105-109pp.

IOC (Iron Ore Company). 2006. IOC Carol Project; Revised Tailings Management Project; Registration/Referral. Submitted to Environment Canada. February 9, 2006. 50 pp.

Jonas J. 2000. Current seasonal limnology of the Berkeley Pit-Lake. p. 359-366. In: Proceedings Fifth International Conference on Acid Rock Drainage. Society of Mining, Metallurgy, and Exploration (SME), Littelton.

Jones, H. 1996. Minesite closure - a government perspective. In, AMPLA Yearbook, 464-474pp.

Jones H, McCullough CD. 2011. Regulator guidance and legislation relevant to pit lakes. In, Mine Pit lakes: Closure and Management, McCullough, C. D. Australian Centre for Geomechanics, Perth, Australia, 137-152pp.

Karakas G, Brookland I, Boehrer B. 2003. Physikal characteristics of Acidic Mining Lake 111. Aquat. Sci. 65, 297-307.

Kalin M, Cao Y, Smith M, Olaveson MM. 2001. Development of the phytoplankton community in a pit-lake in relation to water quality changes. Water Research, 35(13):3215-3225.

Koch C, Graupner B, Werner F. 2008. Pilotversuch zur Wasserbehandlung im Tagebausee Burghammer unter Verwendung von CO2 und Braunkohlenfilterasche, Wissenschaftliche Mitteilungen des Institutes für Geologie Nr. 37/2008, B. Merkel, H. Schaeben, A. Hasche-Berger eds, Technische Universität Bergakademie Freiberg, Freiberg, pp. 31–38.

Koch T, Preuß V, Schöpke R, Koch R. 2008 Pilotversuch zur kombinierten Förderung und Aktivierung alkalischer Sedimente mittels Drucklufttheber Airlift und CO2-Einsatz, Wissenschaftliche Mitteilungen des Institutes für Geologie Nr. 37/2008, B. Merkel, H. Schaeben, A. Hasche-Berger eds, Technische Universität Bergakademie Freiberg, Freiberg, pp. 39–46.

Kosík M, Cadková Z, Prikryl I, Seda J, Pechar L, Pecharová E. 2011. Initial succession of zooplankton and zoobenthos assemblages in newly formed quarry lake Medard (Sokolov, Czech Republic). – In: Rüde, R. T., Freund, A. & Wolkersdorfer, Ch.: Mine Water – Managing the Challenges. - p. 517 – 521; Aachen, Germany.

Kriváckova O, Cížková H. 2008. Sandpit Lakes in the Trebon Basin Biosphere Reserve (Czech Republic). – In: Rapantova, N. & Hrkal, Z.: Mine Water and the Environment. – p. 583-586; Ostrava (VSB – Technical University of Ostrava).

Kuznetsov P, Kuznetsova A, Foght JM, Siddique T. 2015. Oil sands thickened froth treatment tailings exhibit acid rock drainage potential during evaporative drying. Science of the Total Environment, 505:1-10.

Lane JC. 2000. In-pit tailings disposal Marymia gold operation – Case History: in Proceedings of the Goldfields Land Rehabilitation Group Workshop on Environmental Management in Arid and Semi-arid Areas, Kalgoorlie, May 2000.

Larratt HM, Freberg M, Hamaguchi BA. 2007. Developing tailings ponds and pit lakes as bioreactors and habitat cost-effective successes at Highland Valley Copper. British Columbia Mine Reclamation Symposium 2007. Squamish, Canada. BiTech Publishers Ltd., British Columbia, Canada.

Levy DB, Custis KH, Casey WH, Rock PA. 1997. The Aqueous Geochemistry of the Abandoned Spenceville Copper Pit, Nevada County, California. *Journal of Environmental Quality* 26: 233-243.

Lewis NM, Wangerud KW, Park BT, Fundingsland SD, Jonas JP. 2003. Status of in situ treatment of Anchor Hill Pitt lake, Gilt Edge Mine Superfund site, South Dakota, USA. p. 779-788. In: Farrell, T. and G. Taylor (eds.): Sixth International Conference on Acid Rock Drainage, 14-17 July 2003, Cairns, Queensland, The Australian Institute of Mining and Metallurgy Publication Series No 3/2003. The Australian Institute of Mining and Metallurgy, Carlton Victoria.

Lu M. 2002. Aqueous Geochemistry of Pit Lakes - Two Cases Studies at Ravlidmyran and Udden, Sweden. Licentiate Thesis, Department of Environmental Engineering, Division of Applied Geology, Lulea University of Technology, Lulea, Sweden.

Lu M. 2004. Pit Lakes from Sulphide Ore Mining, Geochemical and Limnological Characterization before Treatment, after Liming and Sewage Sludge Treatments. Doctoral Thesis, Department of Environmental Engineering, Division of Applied Geology, Lulea University of Technology, Lulea, Sweden.

Lund MA, McCullough CD, Kumar NR. 2012. The Collie Pit Lake District, Western Australia: an overview. Proceedings of the International Mine Water Association (IMWA) Congress. Bunbury, Australia. International Mine Water Association (IMWA), 287-294pp.

Luscar Ltd. 1991. Development of sport fisheries in lakes created by coal mining operations in the eastern slopes. Progress Report #1: Development, characteristics, and management of surface coal mine lakes. Available at Government of Alberta Library. 64pp.

Luscar Ltd., Luscar-Stereo (1977) Ltd, Cardinal River Coals Ltd., Pisces Environmental Consulting Services Ltd. and Bighorn Environmental Design Ltd. 1994. Development of sport fisheries in lakes created by coal mining operations in the eastern slopes. 162 pp.

Mackenzie S, de Kever N, Smedley E Gregory S. 2016. Mine waste characterisation — complexities with assessing the physical properties of rock. Proceedings of the International Mine Closure 2016 Congress. Perth, Australia. Fourie, A. B. & Tibbett, M. (eds.), Infomine, 671-684pp.

Madison JP, Gammons CH, Poulson SR, Jonas JP. 2003. Oxidation of pyrite by ferric iron in the acidic Berkeley pit lake, Montana, USA. p. 1073-1078. In: Farrell, T. and G. Taylor (eds.): Sixth International Conference on Acid Rock Drainage, 14-17 July 2003, Cairsn, Queensland, The Australian Institute of Mining and Metallurgy Publication Series No 3/2003. The Australian Institute of Mining and Metallurgy, Carlton Victoria.

Maiss H, Walz V, Zimmermann, MIlmberger J, Kinzelbach W, Glässer W. 1998. Experimentelle Tracerstudien und Mdellierungen von Austauschprozessen in einem meromiktischen Restsee (Hufeisensee). UFZ-Bericht 1/1998. UFZUmweltforschungszentrum Leipzig-Halle GmbH, Leipzig, Germany.

Mallo JC, De Marco SG, Bazzini SM, del Río JL. 2010. Aquaculture: an Alternative Option for the Rehabilitation of Old Mine Pits in the Pampasian Region, Southeast of Buenos Aires, Argentina. Mine Water and the Environment 29: 285-293.

Mara S, Deák S, Deák G, Stefanescu L, Vlad SN. 2008. Salt Mining Lake Pits in Romania, a Sustainable Heritage. – In: Rapantova, N. & Hrkal, Z.: Mine Water and the Environment. – p. 595-598; Ostrava (VSB – Technical University of Ostrava).

Martin J, Sulatyky T, Fraser B, Parker R, Rodgers B, Nicholson R. 2016. The Owl Creek Pit Part 1: Relocating Mine Rock from Surface Stockpiles to the Pit to Mitigate Acid Drainage. Mine Environment Neutral Drainage (MEND) BC Conference. December 1, 2016. Vancouver, Canada.

Mäkinen J. 2007. Seasonal Variation in Lake Sediment Geochemistry in an active Mine Area (Pyhäsalmi, Finland). - In: Cidu, R. & Frau, F.: Water in Mining Environments. - p. 89-91, 1 fig., 2 tab.; Cagliari (Mako Edizioni).

McCullough CD, Marchand G, Unseld J. 2013a. Mine closure of pit lakes as terminal sinks: best available practice when options are limited? Mine Water and the Environment 32: 302-313.

McCullough CD, Ballot E, Short D. 2013b. Breach and decant of an acid mine lake by a eutrophic river: river water quality and limitations of use. Proceedings of the Mine Water Solutions 2013 Congress. Lima, Peru. Infomine Inc., 317-327pp.

McCullough, C.D., Lund, M.A., May, J.M. 2008. Field scale trials treating acidity in coal pit lakes using sewage and green waste. Proceedings of the 10th International Mine Water Association (IMWA) Congress. Karlovy Vary, Czech Republic. Rapantova, N. & Hrkal, Z. (eds.), 599-602pp.

McCullough CD, Marchand G, Unseld J, Robinson M, O'Grady B. 2012a. Pit lakes as evaporative 'terminal' sinks: an approach to best available practice mine closure. Proceedings of the International Mine Water Association IMWA Congress. Bunbury, Australia. International Mine Water Association IMWA, 167-174pp.

McCullough CD, Kumar NR, Lund MA, Newport M, Ballot E, Short D. 2012b. Riverine breach and subsequent decant of an acidic pit lake: evaluating the effects of riverine flow-through on lake stratification and chemistry. Proceedings of the International Mine Water Association IMWA Congress. Bunbury, Australia. 533-540pp.

McCullough CD, Lund MA, Zhao LYL. 2010. Mine Voids Management Strategy I: Pit lake resources of the Collie Basin. Department of Water Project Report MiWER/Centre for Ecosystem Management Report 2009-14, Edith Cowan University, Perth, Australia. 250p. Unpublished report to Department of Water.

McCullough CD, Lund MA. 2006. Opportunities for sustainable mining pit lakes in Australia. Mine Water and the Environment, 25(4):220-226.

McCullough CD, Schultze M. 2015. Riverine flow-through of mine pit lakes: improving both mine pit lake and river water quality values? Proceedings of the joint International Conference on Acid Rock Drainage ICARD/International Mine Water Association IMWA Congress. Santiago, Chile. 1903-1912pp.

McCullough CD, Van Etten EJB. 2011. Ecological restoration of novel lake districts: new approaches for new landscapes. Mine Water and the Environment 30: 312-319.

McCullough CD. 2011. Mine Pit Lakes: Closure and Management. Australian Centre for Geomechanics (ACG), Perth, Australia. 183p.

McCullough CD. 2016. Key mine closure lessons still to be learned. Proceedings of the International Mine Closure 2016 Congress. Perth, Australia. Fourie, A. B. & Tibbett, M. (eds.), Infomine, 319-332pp.

McPhail G, Rye C. 2008. Comparison of the erosional performance of alternative slope geometries. Rock dumps 2008: proceedings of the first international seminar on the management of rock dumps, stockpiles and heap leach pads. Perth, Australia. Fourie, A. ed. Australian Centre for Geomechanics, CSIRO, Curtin University and the University of W.A., 15pp.

McNaughton KA. 2001. The limnology of two proximal pit lakes after twenty years of intense flooding. Master's Thesis, Department of Biology, Lakehead University, Thunder Bay, Ontario.

McNee JJ, Crusius J, Martin AJ, Whittle P, Pieters R, Pedersen TF. 2003. The Physical, Chemical and Biological Dynamics of Two Contrasting Pit Lakes: Implications for Pit Lake Bio-Remediation. Mining and the Environment Conference, Sudbury/Canada, May 25-28, Laurentian University, Sudbury.

McPhail G, Rusbridge S. 2006. Erosion control, how practical is it – really? Proceedings of the 2006 Workshop of Environmental Management, Goldfields Environmental Management Group. Kalgoorlie, Australia. 24pp. Miller LL, Rasmussen JB, Palace VP, Sterling G, Hontela A. 2013. Selenium bioaccumulation in

stocked fish as an indicator of fishery potential in pit lakes on reclaimed coal mines in Alberta, Canada. Environmental management, 52(1):72-84.

MEM (B.C. Ministry of Energy and Mines). 1998. Guidelines for Metal Leaching and Acid Rock Drainage at Minesites in British Columbia. Victoria, Canada. 92 pp.

MEM. 2017. Health, Safety and Reclamation Code for Mines in British Columbia. Victoria, Canada. 361 pp.

Morgenstern NR, Vick SG, Van Zyl D. 2015. Independent expert engineering investigation and review panel report on Mount Polley tailings storage facility breach. Available at: https://www.mountpolleyreviewpanel.ca/

Mhlongo SE and Amponsah-Dacosta F. 2014. Assessment of Safety Status of Open Excavations and Water Quality of Pit Lake at Abandoned Nyala Mine in Limpopo Province of South Africa. In: Sui, Sun and Wang. An Interdisciplinary Response to Mine Water Challenges, China University of Mining and Technology Press, Xuzhou, pp. 395-399.

Miller D. 2008. Using aquaculture as a post mining land use in West Virginia. Mine Water and the Environment. 27:122-126

Miller LL, Rasmussen JB, Palace VP, Sterling G, Hontela A. 2013. Selenium bioaccumulation in stocked fish as an indicator of fishery potential in pit lakes on reclaimed coal mines in Alberta, Canada. Environmental management.52(1):72-84.

Miot J, Lu S, Morin G, Adra A, Benzerara K, Küsel K 2016. Iron mineralogy across the oxycline of a lignite mine lake. Chemical Geology 434, 28-42.

Mudroch A, Stottmeiste, U, Kennedy C, Klapper H. 2002. Remediation of Abandoned Surface Coal Mining Sites: a NATO-project. Springer, Germany.

Muldoon J, Schramm LL. 2009. Gunnar Uranium Mine Environmental Remediation: Northern Saskatchewan. In ASME 2009 12th International Conference on Environmental Remediation and Radioactive Waste Management (pp. 621-632). American Society of Mechanical Engineers.

Neumann C, Beer J, Blodau C, Peiffer S, Fleckenstein JH. 2013. Spatial patterns of groundwater-lake exchange – implications for acid neutralization processes in an acid mine lake. Hydrological Processes 27: 3240-3253.

Neuner M, Smith L, Blowes DW, Sego DC, Smith LJ, Fretz N, Gupton M. 2013. The Diavik waste rock project: Water flow through mine waste rock in a permafrost terrain. Applied geochemistry, 36:222-233.

Ngalang Boodja Enterprises Pty Ltd. 2013. Mine lake aquaculture proposal - Ngalang Boodja Enterprise Project Prospectus. Ngalang Boodja Enterprises Pty Ltd, Collie, Australia. 16pp

Niccoli WL. 2009. Hydrologic characteristics and classifications of pit lakes. In, Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability Chap. 4. Castendyk, D. and Eary, T. Society for Mining, Metallurgy, and Exploration (SME), Colorado, USA, 33-43pp.

Nicholson A, Rudnick D, Willliams L, Ortega J. 2013. Spatial and temporal assessment of ecological risks at a gold mine pit lake. Proceedings of the International Mine Water Association (IMWA) Conference. Golden CO, USA. 30 September - 4 October, Wolkersdorfer, C.; Brown, A. & Figueroa, L. (eds.), 59-62pp.

Nixdorf B, Lessmann D, Deneke R 2005. Mining lakes in a disturbed landscape: application of the EU Water Framework Directive and future management strategies., Ecological Engineering, Vol. 24, pp. 67-73.

Otchere FA, Veiga MM, Hinton JJ, Farias RA, Hamaguchi R. 2004. Transforming open mining pits into fish farms: Moving towards sustainability. In Natural Resources Forum (Vol. 28, No. 3, pp. 216-223). Blackwell Publishing Ltd.

Otchere F, Veiga M, Hinton J, Hamaguchi R. 2002. Mining and Aquaculture: A Sustainable Venture. In Proceedings of the 26th BC Mine Reclamation Symposium (pp. 191-203). Dawson Creek, Canada.

Parsons Brinckerhoff. 2002. Perch mining area. In-pit tailings risk assessment: for Barrick Gold unpublished.

Paulson O, Harrington J. 2004. Status update on the bioremediation of the Sweetwater pit lake—Four years following treatment. In Proceedings of the US EPA meeting: Pit Lakes 2004, November 16–18, Reno, Nevada.

Pearman G. 2009. 101 things to do with a hole in the ground. Post-Mining Alliance in association with the Eden Project, UK.

Pelletier CA, Wen M, Poling GW. 2009. Flooding pit lakes with surface water. In, Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability Castendyk, D.; Eary, T. and Park, B. (eds.) Society for Mining Engineering (SME), Kentucky. 187-202pp. 978-0-87335-305-2.

Peterka J, Cech M, Draštík V, Juza T, Frouzová J, Prchalová M, Kubecka J. 2011. Ten years of fish community succession in post-mining lake Milada-Chabarovice. – In: Rüde, R. T., Freund, A. & Wolkersdorfer, Ch.: Mine Water – Managing the Challenges. - p. 535 – 539; Aachen, Germany.

Pieters R, Coedy W, Ashley KI, Lawrence GA. 2014. Artificial circulation of a mine pit lake. Canadian Journal of Civil Engineering 42: 33-43.

Pieters R, Lawrence GA. 2014. Physical processes and meromixis in pit lakes subject to ice cover. Canadian Journal of Civil Engineering, 41(6), pp.569-578.

Pilkey OH, Pilkey-Jarvis L. 2007. Useless arithmetic: why environmental scientists can't predict the future. Columbia University Press. New York, USA.

Pisces (Pisces Environmental Consulting Services Ltd.). 2013. Aquatic monitoring program for end pit lakes in the headwaters of the Embarras River, 2011-12.

Pellicori DA, Gammons CH, Poulson SR. 2005. Geochemistry and stable isotope composition of the Berkeley pit lake and surrounding mine waters, Butte, Montana. Appl. Geochem. 20, 2116-2137.

Poling GW, Ellis DV, Murray JV, Parsons TR, Pelletier CA. 2002. Underwater tailing placement at Island Copper Mine, Society for Mining, Metallurgy, and Exploration, Inc., Littleton, CO.

Poling GW, Pelletier CA, Muggli D, Wen W, Gerits J, Hanks C, Black K. 2003. Field studies of semipassive biogeochemical treatment of acid rock drainage at the Island Copper Mine pit lake. Proc., 6th Int. Conf. on Acid Rock Drainage, Cairns, Australia, 549–558.

Pollock R. 2008. Tailings and Waste Rock Management; Best Practice at AREVA's McClean Lake Operation. Presentation at IAEA-WNA Technical Meeting on the Implementation of Sustainable Global Best Practices in Uranium Mining and Processing. October 15-17, 2008. Vienna, Austria.

Puhalovich AA, Coghill M. 2011. Management of mine wastes using pit/underground void backfilling methods: current issues and approaches. In, Mine Pit Lakes: Closure and Management, McCullough, C. D. Australian Centre for Geomechanics, Perth, Australia, 3-14pp.

Ramsey D, Martin J. 2009. Subaqueous disposal of sulfide tailings - reclamation of the Sheriddon orphan mine site, Manitoba, Canada. Proceedings of the International Mine Water Conference. Pretoria, South Africa. 19-23 October, International Mine Water Association, 746-755pp.

Rescan. 2012. EKATI Diamond Mine: Water Quality Modelling of the Koala Watershed. Prepared for BHP Billiton Canada Inc. by Rescan Environmental Services Ltd.: Yellowknife, Northwest Territories.

Robins RG, Berg RB, Dysinger DK, Duaime TE, Metesh JJ, Diebold FE, Twidwell LG, Mitman GG, Chatham WH, Huang HH, Young CA. 1997. Chemical, physical and biological interaction at the Berkeley Pit, Butte, Montana. p. 529-541. In: Tailings and Mine Waste '97. Balkema, Rotterdam.

Rodgers B, Sulatyky T, Fraser B, Parker R, Martin J, Nicholson R. 2016. The Owl Creek Pit Part 2: Pit Water Quality 25 Years After Backfilling with Acid Generating Rock. Mine Environment Neutral Drainage (MEND) BC Conference. December 1, 2016. Vancouver, Canada.

Roman-Ross G, Charlet L, Tisserand D, Glemme M. 2005. Redox processes in a eutrophic coal-mine lake. Mineralogical Magazine 69: 797.

Rowson J, Tremblay MAJ. 2005. Tailings management best practice: a case study of the McClean Lake JEB Tailings Management Facility. Canadian Nuclear Society Bulletin, 26(2), pp.17-23.

Rücker JA, Fyson R, Deneke, Packroff G. 1999. Meromiktische Seen mit saurem Mixolimnion - eine Besonderheit der Lausitzer Bergbaufolgelandschaft. p. 239-243. In: DGL-Tagungsbericht 1998 (Klagenfurt). Eigenverlag der DGL, Tutzing.

Rytuba JJ, Enderlin D, Ashley R, Seal R, Hunerlach MP. 2000. Evolution of the McLaughlin Gold Mine pit lakes, California. In Proc. 5th International Conf. on Acid Rock Drainage (pp. 367-375).

Salmon SU, Oldham C, Ivey GN. 2008. Assessing internal and external controls on lake water quality: limitations on organic carbon-driven alkalinity generation in acidic pit lakes. Water Resources Research 44: W10414.

Sanchez-España J, López-Pamo E, Diez M, Santofimia E. 2009. Physico-chemical gradients and meromictic stratification in Cueva de la Mora and other acidic pit lakes of the Iberian Pyrite Belt. Mine Water and Environment 28: 15-29.

Sánchez-España J, Yusta I, López GA. 2012. Schwertmannite to jarosite conversion in the water column of an acidic mine pit lake. Mineralogical Magazine 76: 2659.

Schäfer W, Matthias A, Bauer M, Söll T, Peiffer S. 2016. Quantification of Acidity Deposition in the Sediment of a former lignite mining lake in the Wackersdorf Mining District (Eastern Bavaria). In: Drebenstedt, C. & Paul, M.: Proceedings IMWA 2016. Freiberg/Germany. 236-243.

Schimmele M 1999. Ausbildung von Meromixie durch physikalische und chemische Einflüsse am Beispiel von Bergbauseen. p. 234-238. In: DGL-Tagungsbericht 1998 (Klagenfurt). Eigenverlag der DGL, Tutzing, Germany.

Schramm LL. 2012. Cleaning-Up Abandoned Uranium Mines in Saskatchewan's North. Canadian Nuclear Society Bulletin, 33(2), pp.17-23.

Schreck P. 1998. Environmental impact of uncontrolled waste disposal in mining and industrial areas in Central Germany. Environ. Geol. 35, 66-72

Schroeter A. 1997. Modellhafte Sanierung von Altlasten am Beispiel des Tagebaurestloches Großkayna, Umweltbundesamt, Berlin, 723 p.

Schultze M, Boehrer B. 2008. Development of Two Meromictic Pit Lakes – a Case Study from the Former Lignite Mine Merseburg-Ost, Germany. Proceedings of the 10th International Mine Water Association (IMWA) Congress. Karlovy Vary, Czech Republic. Rapantova, N. & Hrkal, Z. (eds.).

Schultze M. 2012. The filling and remediation of pit lakes in former open cast lignite mines thesis, der Technischen Universität Carolo-Wilhelmina zu Braunschweig, 134pp.

Schultze M, Boehree B, Duffek A, Herzsprung P, Geller W. 2005. Introduction of river water as a tool to manage water quality in pit lakes. – In: Loredo, J. & Pendás, F.: Mine Water 2005 – Mine Closure. – p. 273-279, 5 fig., 1 tab.; Oviedo (University of Oviedo).

Schultze M, Friese K, Sánchez J, López E. 2006. The Aznalcóllar Pit Lake – Water Quality and Options of Control: ICARD 2006 7. – p. 1927-1935 [CD-ROM], 1 fig., 1 tab.; St. Louis (Proceedings, International Conference of Acid Rock Drainage [ICARD]).

Schultze M, Boehrer B, Friese K, Koschorreck M, Stasik S, Wendt-Potthoff K. 2011. Disposal of waste materials at the bottom of pit lakes. Mine Closure 2011: Proceedings of the Sixth International Conference on Mine Closure. Lake Louise, Canada. Fourie, A. B.; Tibbett, M. & Beersing, A. (eds.), Australian Centre for Geomechanics (ACG), Perth, Australia, 555-564pp.

Schultze M, Hemm M, Geller W, Benthaus FC. 2013. Pit lakes in Germany: Hydrography, water chemistry and management. In, Acidic Pit Lakes - Legacies of surface mining on coal and metal ores, Geller W, Schultze M, Kleinmann, RLP & Wolkersdorfer, C. Springer, Berlin, Germany, 265-291pp.

SENES (SENES Consultants Limited). 1995. Review of In–Pit Disposal Practices for the Prevention of Acid Drainage – Case Studies, Final Report, Volume 1 of 2. Prepared for Mine Effluent Neutral Drainage (MEND) Program, Canadian Centre for Mineral and Energy Technology (CANMET), September, 1995.

SERM (Saskatchewan Environment and Resource Management). 1993. Environmental Monitoring Investigation of the Flooded D-Pit at Cluff Lake Saskatchewan. Mineral Industry Environmental Branch.

Shaw S, Martin J, Meiers G, O'Kane M, Wels C. 2006. Characterization of the waste rock and pit walls at the Jundee gold mine site in Western Australia and implications for long-term issues. 7th International

Conference on Acid Rock drainage ICARD St Louis. Lexington: American Society of Mining and Reclamation.

Skousen J, Ziemkiewicz P, Yang JE. 2012. Use of coal combustion by-products in mine reclamation: review of case studies in the USA. Geosystem Engineering 15: 71-83.

Smith LJ, Moncur MC, Neuner M, Gupton M, Blowes DW, Smith L, Sego DC. 2013. The Diavik Waste Rock Project: Design, construction, and instrumentation of field-scale experimental waste-rock piles. Applied geochemistry, 36:187-199.

Sonderegger JL, Duaime TE, Noble RA, Ohguchi T. 1987. Butte mine flooding and the Berkeley Pit. In: Montana bureau of mines and geology open file report 195, Butte, MT, USA.

Sonnenberg R. 2011. Development of Aquatic Communities in High-altitude Mine Pit Lake Systems of West-central Alberta. Prepared for School of Graduate Studies of the University of Lethbridge in partial fulfillment of the requirements for the degree, Master of Science. Lethbridge, AB. 175pp + App.

Sperling EV, Grandchamp CAP. 2008. Water Quality of a Deep Pit Lake: Case Study of Aguas Claras, Brazil. – In: Rapantova, N. & Hrkal, Z.: Mine Water and the Environment. – p. 615-618; Ostrava (VSB – Technical University of Ostrava).

SRK (SRK Consulting, Inc.). 2008. Environmental Assessment; Gap Analysis; Gunnar Mine Site Rehabilitation Project. Report Prepared for Saskatchewan Research Council. February 2008. 71pp.

Stierle AA, Stierle DB. 2005. Bioprospecting in the Berkeley pit: bio active metabolites from acid mine waste extremophiles. Studies in natural products chemistry. 32:1123-75.

Stierle AA, Stierle DB, Decato D, Priestley ND, Alverson JB, Hoody J, McGrath K, Klepacki D. 2017. The Berkeleylactones, Antibiotic Macrolides from Fungal Coculture. Journal of Natural Products. 80(4):1150-1160.

Stockinger, NF, Hays HA. 1960. Plankton, Benthos and Fish in Three Strip-Mine Lakes with Varying pH Values. Transactions of the Kansas Academy of Science. 63(1):1-11.

Stellmacher 2004. Der Moritzteich bei Döbern - Analogon für die Sanierung saurer Bergbaugewässer? Hydro- und Sedimentgeochemie eines meromiktischen Restsees. Masterthesis, Technical University Bergakademie Freiberg, Germany

Stephens FJ, Ingram M. 2006. Two cases of fish mortality in low pH, aluminium rich water. Journal of Fish Diseases 29: 765-770.

Stevens, CL, Lawrence, GA. 1998. Stability and meromixis in a water-filled mine pit. Limnology and Oceanography, 43(5), pp.946-954.

Stottmeister U, Glässer W, Klapper H, Weissbrodt E, Eccarius B, Kennedy C, Schultze M, Wendt-Potthoff K, Frömmichen R, Schreck P, Strauch G. 1999. Strategies for remediation of former opencast mining areas in eastern Germany. p. 263-296. In: Azcue, J.M. (ed.): Environmental impacts of mining activities. Springer, New York.

Sumer S, Pitts L, McCulloch J, Quan H. 1995. Alberta lake re-established after draining to mine coal: Mining Engineering, November 1995, p. 1015-1019.

Suncor (Suncor Energy Inc.). 2003. South Tailings Pond Environmental Impact Assessment. Volume 3; Water Quality Baseline. Prepared by Golder Associates Ltd. December 2003. 44 pp.

Suncor. 2016. Suncor Base Plant Application for the Draft Tailings Directive. Submitted to Alberta Energy Regulator April 14, 2016.

Svoboda I, Pecharova E, Prikryl I, Kasparova I. 2008. The Development of Future Lakes in Opencast Mine Residual Pits in the Krušné Mountain Region of the Czech Republic. – In: Rapantova, N. & Hrkal, Z.: Mine Water and the Environment. – p. 619-622; Ostrava (VSB – Technical University of Ostrava).

Tones PI. 1982. Limnological and fisheries investigation of the flooded open pit at the Gunnar uranium mine. Saskatchewan Research Council Publication No. C-805-10-E-82, Saskatoon, Canada.

Tourism Canmore. 2017. Quarry Lake. Available at http://www.tourismcanmore.com/things-to-do/quarry-lake. Retrieved April 8, 2017.

Tuttle S, Sisson R. 1998. Closure plan for the proposed millenium project, In, Mine planning and equipment selection, R. K. Singal (ed) A. A. Balkema,, Rotterdam, The Netherlands, pp. 747-760.

Uhlmann W, Gröschke A, Arnold I, Rolland W. 2007. Wirkung von Eisenhydroxidschlämmen aus der Grubenwasseraufbereitung auf die Gewässerchemie von Tagebauseen in der Lausitz, Management bergbaubedingten Säurepotentials, C. Drebenstedt, M. Struzina eds. Technische Universität Bergbauakademie Freiberg, Freiberg, pp. 109–121.

Uhlmann W, Zimmermann K, Mix S, Nixdorf B, Totsche O. 2016. Causes of a distinct metalimnic oxygen gradient in the pit lake Senftenberger See in summer 2013 as a case study. In: Drebenstedt, C. & Paul, M.: Proceedings IMWA 2016. Freiberg/Germany. 261-268.

Unger-Lindig Y, Merkel B, Schipek M. 2010. Carbon dioxide treatment of low density sludge: a new remediation strategy for acidic mining lakes? Environmental and Earth Sciences 60, pp. 1711–1722.

Van Etten EJB, McCullough CD, Lund MA. 2012. Importance of topography and topsoil selection and storage in successfully rehabilitating post-closure sand mines featuring pit lakes. Mining Technology 121: 139-150.

Van Loon. J. 2013. Toxic Lakes From Tar-Sand Projects Planned for Alberta. Bloomberg. November 22, 2013.

Vandenberg JA, Beddoes P, Litke S. 2016. Beneficial use of Springer Pit Lake at Mount Polley Mine. Mine Environment Neutral Drainage (MEND) BC Conference. December 1, 2016. Vancouver, Canada.

Vandenberg JA, Herrell M, Faithful JW, Snow AM, Lacrampe J, Bieber C, Dayyani S, Chisholm V. 2015a. Multiple Modeling Approach for the Aquatic Effects Assessment of a Proposed Northern Diamond Mine Development. Mine Water and Environment. 1-9. http://dx.doi.org/10.1007/s10230-015-0337-5

Vandenberg JA, Litke S. *Submitted to Mine Water and Environment*. Beneficial use of Springer Pit Lake at Mount Polley Mine.

Vandenberg JA, McCullough CD, Castendyk D. 2015. Key issues in mine closure planning related to pit lakes. Proceedings of the joint International Conference on Acid Rock Drainage ICARD/International Mine Water Association IMWA Congress. Santiago, Chile. Brown, A.; Figueroa, L. & Wolkersdorfer, C. eds., International Mine Water Association IMWA, 1852-1861pp.

Verburg R, Bezuidenhout N, Chatwin T, Ferguson K. 2009. The global acid rock drainage guide (GARD Guide). Mine Water and the Environment, 28(4), pp.305-310.

von Rohden C, lmberger J. 2001. Tracer experiment with sulfur hexafluoride to quantify the vertical transport in a meromictic pit lake. Aquatic Sciences 63, 417-431.

Wen MEAP, Pelletier C, Norlund K, Wolff WR, Berthelot DS., 2015. Phytoremediation to improve pit lake water quality. Mine Closure 2015. June 1-3, 2015. Vancouver, Canada.

Whisson G, Evans L. 2003. Aquaculture as a relinquishment option for final mining voids. ACARP Final Report C9027. Curtin University of Technology, Perth. 157pp.

Williams RD. 2009. Regulatory Issues, In, Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability D. Castendyk; T. Eary and B. Park (eds) Society for Mining Engineering (SME), Kentucky, USA, pp. 13-17.

Wyatt G, Miller F, Chermak J. 2006. Innovative water treatment plant utilizing the South Mine Pit at the Copper Basin mining site in Tennessee, USA, in Proceedings 7th ICARD, R.I. Barnhisel ed, 7th International Conference on Acid Rock Drainage ICARD, 26–30 March, St. Louis, USA, American Society of Mining and Reclamation ASMR, Lexington, pp. 2529–2539.

Yokum S, Axler R, McDonald M, Wilcox D. 1997. Recovery of a mine pit lake from aquacultural phosphorus enrichment: model predictions and mechanisms. Ecological Engineering 8: 195-218.

Younger PL. 2005. Westfield pit lake, Fife (Scotland): the evolution and current hydrogeological dynamics of Europe's largest bituminous coal pit lake. – In: Loredo, J. & Pendás, F.: Mine Water 2005 – Mine Closure. – p. 281-287, 3 fig., 2 tab.; Oviedo (University of Oviedo).

Younger PL, Mayes WM. 2014. The potential use of exhausted open pit mine voids as sinks for atmospheric CO2: Insights from natural reed beds and mine water treatment wetlands. Mine Water and the Environment. 34(1): 112-120.

Yucel DS, Yucel MA, Baba A. 2014. Change detection and visualization of acid mine lakes using time series satellite image data in geographic information systems (GIS): Can (Canakkale) County, NW Turkey. Environmental Earth Sciences 72: 4311-4323.

As a global, employee-owned organisation with over 50 years of experience, Golder Associates is driven by our purpose to engineer earth's development while preserving earth's integrity. We deliver solutions that help our clients achieve their sustainable development goals by providing a wide range of independent consulting, design and construction services in our specialist areas of earth, environment and energy.

For more information, visit golder.com

Africa	+ 27 11 254 4800
Asia	+ 86 21 6258 5522
Australasia	+ 61 3 8862 3500
Europe	+ 44 1628 851851
North America	+ 1 800 275 3281
South America	+ 56 2 2616 2000

solutions@golder.com
www.golder.com

Golder Associates Ltd.
102, 2535 - 3rd Avenue S.E.
Calgary, Alberta, T2A 7W5
Canada
T: +1 (403) 299 5600

Golder Associates