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Pit Lakes: A Surface Mining Perspective

Tailings Environmental Priority Area (EPA)

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Executive Summary



Surface mining, which accounts for approximately half of all oil sands production, leaves large pits which must be reclaimed. Mining companies around the world reclaim mine pits as pit lakes by filling them with water, tailings, and other solid mine waste. When properly designed and planned, pit lakes are considered a best practice in global mine reclamation, and there are many successful pit lakes in Canada and around the world.

Oil sands mine reclamation will use a suite of tailings reclamation options, including pit lakes. Pit lakes can serve multiple functions in the reclaimed landscape and will support the overall reclamation of mine sites. As of November 2018, 23 pit lakes were planned in the Alberta oil sands mining region; these lakes will be filled with freshwater or a mixture of freshwater and oil sands process-affected water, and may or may not contain treated or untreated tailings. The proposed oil sands pit lakes vary in size and shape.

The size and shape of a lake, the materials placed in and around it, and the resulting physical dynamics will affect the water chemistry of the lake. Deep pit lakes that are influenced by higher density saline water can become permanently stratified, isolating the saline water at the bottom of the lake. If tailings are placed in the lake, porewater release can affect the lake water chemistry, but this effect will be diminished with time. In either case, how the water chemistry changes over time should be considered when predicting biological community development in the lake.

The oil sands industry has been conducting research, from laboratory to full scale demonstrations, on pit lakes for over 40 years, and a large body of evidence exists to support the use as features in the closure landscape Syncrude's Base Mine Lake is the first full scale pit lake in the oil sands industry. There are pilot scale demonstration lakes including Suncor's Lake Miwasin (previously called the Suncor Demonstration Pit Lake), and Syncrude Demonstration Pond. The large body of research to date indicates that pit lakes are a viable strategy to reclaim oil sands mine pits, and that pit lakes will become an integral part of a successful closure landscape.

Document Purpose:

This document provides information about pit lakes as reclamation features in the closure landscape for oil sands mining, how they are successfully used in other mining industries around the world, and that tailings treatment is only one of many purposes that pit lakes serve.

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1. Pit Lakes in the Global Mining Industry

Key Points

- Open pit mining creates pits that need to be reclaimed.
- Pit lakes are commonly used around the world to reclaim mine pit(s), and can be filled with just water, or water above a layer of tailings or other mining by-products.
- Pit lakes require planning, of which several key elements can include an understanding of the surrounding hydrology, hydrogeology, and geochemistry of the materials in and around the pit.
- Adaptive management systems are used to steward pit lakes to acceptable outcomes.
- Many successful examples of pit lakes exist in Canada and around the world.
- Pit lakes globally have a diverse range of end land use targets.

This section is a broad overview of pit lakes from mining industries around the world. It introduces general concepts about pit lakes: planning, adaptive management, potential functions and descriptions of some lakes. Some of these concepts, including mitigations to manage potential challenges of each lake may or may not be applicable to the oil sands situation.

Open pit mining extracts resources from the earth, creating mined-out pits that can be as large as the entire mined area or as small as the last pit mined. The initial mine pits are often backfilled with overburden or in the case of oil sands lakes, can be filled with oil sand tailings as mining progresses. Regardless of size, these pits need to be reclaimed after mining is complete, and, one reclamation strategy is to transform a mine pit into a pit lake.

Pit lakes can also be used to manage tailings or mine waste, where mine waste generally refers to overburden or waste rock that is removed to access the ore. Tailings refers to mineral waste from an ore or oil sands processing plant, usually mixed with water and transported as a slurry (OSRIN, 2010). Both mine waste and tailings can also be stored in above-grade waste deposits.

The global mining industry produces a variety of solid and fluid mine wastes, which must be integrated into the closure landscape. Tailings-containing pit lakes from other mining industries have similarities to oil sands pit lakes, as well as some differences. For example, mine wastes placed below grade in the mine pit can be covered with a water cap, which physically isolates these materials.

Planning and adaptive management for pit lakes. The success of pit lakes around the world is directly linked to the extent and quality of reclamation research and closure planning and design. Closure plans integrate the entire mining operation, including mine and tailings plans and water management. Mine reclamation in Canada is closely regulated by governments, and pit lakes are designed based on research and predictive modelling. The goal is to build a landform that is a safe and functional part of the closure landscape. To understand how a pit lake will perform, small and medium-scale tests can be followed by full-scale demonstrations, and monitoring data are regularly compared to target outcomes through an established adaptive management process (Castendyk & Vandenburg 2013). All of this information is used to design and construct future pit lakes.

Adaptive management is a decision-making process for natural resource management that emphasizes learning through management and allows for adjustments as outcomes from management actions and other events are better understood (Walters 1986, Allen *et al.* 2011,

and others). This allows for learning from experience and modifying actions based on that experience (Stankey *et al.* 2005). It also permits management action in the face of the uncertainty inherent in complex ecological systems. The process decreases ecological uncertainty and improves knowledge about potential management choices through direct comparisons of their performance in practice, allowing for flexible decision making (Walters 1986, Walters 2007). Intended outcomes of an environmental management system include: enhancement of environmental performance, fulfilment of compliance obligations, and, achievement of environmental objectives (ISO 2016). In very simple terms, adaptive management ensures that objectives are understood, activities are planned and executed to achieve the objectives, results are measured to see what is working or not working, and information is used to make informed decisions on whether to implement additional actions to achieve the objectives and desired outcomes (Jones 2009).

The iterative decision-making process is cyclical (Figure 1-1). Adaptive management is a "learn by doing" approach, not a "trial and error" approach. There are four key components to the cycle: Plan, Do, Evaluate & Learn, and Adjust. The cycle is continuous, allowing information gathered during the actual performance of the lake to be fed back into the design and operation, ensuring improved performance in the future (Alberta Energy Regulator (AER) 2018).

Potential Functions of a pit lake

Placing mine waste in pit lakes is considered to be a best practice around the world. Pit lakes can perform a range geotechnical and geochemical functions in a reclaimed landscape (Golder Associates 2017). Not all functions listed below will apply to every lake in the oil sands region. The function of any particular lake will be dependent on the target outcome for that lake, and is accommodated through pit lake design.

Regulate surface water flows. A pit lake will receive runoff from the surrounding reclaimed watershed, and this runoff can have variable flow. The large volume of a pit lake can moderate the flow of water from the lake into the environment.

Prevent unwanted geochemical reactions. Some mine waste, particularly in the global metal mining industry, contains reduced sulfur compounds like iron sulfide, which can be oxidized by bacteria to generate acidic runoff. This acidic runoff can leach metals out of the waste rock, creating even poorer water quality. Pit lakes containing acid-generating materials can be designed to be meromictic, meaning the denser salty and cold water near the bottom does not mix with the surface water.[1] This bottom layer of water has no oxygen (because it has no contact with the atmosphere) preventing oxidation of the waste at the bottom of the pit lake.

Trap sediment and provide water treatment. In the global metal mining industry, pit lakes can improve water quality before release by allowing suspended particles in mine water effluent to settle, and can also neutralize and dilute acid drainage.

Provide aquatic habitat. Pit lakes can provide a range of opportunities for aquatic biodiversity and unique wildlife habitat in the closure landscape.



Figure 1: The adaptive management cycle (after Jones 2005)

Figure 1-1: The adaptive management cycle (after Jones 2005)

[1] See Appendix 1 for more information on lake stratification and meromictic lakes.

1.1. Examples of pit lakes in Canada

There are many pit lakes in Canada and around the world. Some have met their reclamation objectives and are deemed successful, others have required extensive management, and some will require ongoing management to meet their reclamation objectives. A more complete survey of pit lakes can be found elsewhere (Golder Associates 2017). Four successful pit lakes in Canada are described below. These examples demonstrate that clear reclamation objectives can ensure pit lakes are designed and managed successfully.

1.1.1. Sphinx Lake, Alberta

Sphinx Lake in Alberta is constructed in a coal mine (Figure 2A). The pit is up to 50 m deep and mostly filled with waste rock. Reclamation objectives included restoring water flow through Sphinx Creek and establishing healthy fish habitat.

During reclamation, shallow shoreline areas were created by re-contouring the waste rock and covering it with soil, and the pit was filled from Sphinx Creek. Selenium is the only element of concern in the lake elevated above water quality guidelines (CCME 2007), and it is declining with time. Fish have colonized the lake, including rainbow trout and bull trout. Biological communities are similar in structure and function to natural systems, despite differences in water chemistry (Golder Associates 2017).

1.1.2. Highland Valley Copper Mine Pit Lakes, British Columbia

Trojan Pond is a former copper mine tailings pond operated by Highland Valley Copper (Figure 2B). It is 26 ha in size with a 10 m water cap. When reclamation began in the early 1990s, reclamation objectives included improving the water quality and making the pond productive for wildlife and fish.

High metal concentrations were removed by fertilizing the pond to stimulate algae and plant growth.[2] Microbial biofilms, invertebrates, and submerged plants were transplanted from nearby ponds, and shoreline areas were planted with shrubs and trees. Rainbow trout were introduced throughout the 1990s. Fish populations in Trojan Pond are now considered to be self-sustaining, and the pond is an important location for fishing derbies. A variety of wildlife use the area around the pond, including bald and golden eagles, black bear, moose, deer, and coyotes (Hamaguchi *et al.* 2008).

1.1.3. Owl Creek, Ontario

The Owl Creek Mine near Timmons, Ontario, was an active gold mine from 1981 to 1989 (Figure 2C). A decade after the mine opened, acid runoff from a waste rock deposit was discovered (Golder Associates 2017). One reclamation objective for this mine was to produce water acceptable for release to the environment. To manage the acid runoff, the waste rock was buffered with crushed limestone and moved into the mine pit, and then capped with soil. The pit was then filled rapidly from the Porcupine River.

The pit lake is approximately 20 m deep and permanently stratified (meromictic).[3] This isolates the saline and acidic water at the bottom of the pit, and surface water is acceptable to release to the Porcupine River, meeting the reclamation objectives for Owl Creek Mine.

1.1.4. Island Copper Pit Lake, British Columbia

Some pit lakes require multiple and ongoing interventions to ensure their success. One example is the Island Copper Mine Pit Lake (Figure 2D). The main objective of the pit lake reclamation was to remediate acid drainage coming from the waste rock piles surrounding the mine pit.

Island Copper Pit lake was designed to be meromictic so the bottom layers would remain unmixed and have no oxygen, preventing the generation of acid drainage. In 1996, the pit was flooded rapidly with seawater and capped with freshwater. The oxygen content of the layers was monitored, and in 2000, the lake was fertilized to increase algae growth, which in turn increased biodegradation and oxygen consumption. As of 2015, the lake is on its way to meeting the design objectives (Golder Associates 2017).

[2] Plants and algae absorb metals, which are then sequestered in the sediments when the plants die and sink.
[3] See Appendix 1 for more information on lake stratification.

A)



B)



C)



D)



Figure 2.
A) Sphinx Lake, Alberta. B) Trojan Pond, British Columbia.
C) Owl Creek, Ontario. D) Island Copper Mine, British Columbia.[4]

[4] Image credits: A) https://www.teck.com/news/stories/2016/reclamation-example--making-a-mine-pit-into-an- aquatic-habitat.
B) Hamaguchi, *et al.*, 2008. C) Google Earth. D) https://vlms.ca/history-of-island-copper-mine/

2. Characteristics of Pit Lakes in the Oil Sands

Key Points

- Pit lakes planned for the oil sands region could be filled with freshwater or a mixture of oil sands process-affected water and freshwater, and may or may not contain treated or untreated tailings.
- Most lakes in the oil sands will have water columns mixing in the spring and the fall (dimictic), just like natural boreal lakes.
- Pit lakes can be designed to prevent annual mixing (meromictic). This happens in very deep pits with very saline water at the bottom. The absence of mixing isolates the saline water in the bottom of the pit.
- Tailings placed at the bottom of the pit lake could affect the lake water chemistry. As the rate of tailings settlement decreases over time, this effect will diminish.
- The chemistry of the lake water, and how it will change over time, must be considered when predicting how the ecology in a pit lake will develop.

As of 2018, two types of pit lakes have been proposed by the oil sand mining operators: lakes containing only water, and lakes containing water over tailings. Although each pit lake will be unique, it is possible to make general statements about these two types of pit lakes and compare them to other pit lakes from the global coal and metal mining industries.[5]

First, oil sands pit lakes tend to be shallower than those created within metal mines, which means they may have different mixing behavior. The water-only lakes currently planned for the oil sands region are an average water depth of 26.8 m, and cover an average area of 8.2 km2. Oil sands pit lakes containing tailings are shallower than metal mine lakes (average water depth 15.8 m) and are slightly bigger in surface area (average 10.5 km2) than a typical metal mining pit lake (Golder Associates 2017).

Second, some oil sands pit lakes will contain oil sands tailings material rather than waste rock material found

	Average Water Depth (Range)	Average surface area (Range)
Oil sands pit lakes (water only)	26.8 m (5.7–44.6 m)	8.3 km^2 (2.1–26.5 km^2)
Oil sands pit lakes (with tailings)	15.9 m (2.5–40 m)	10.5 km^2 (2.3–22.0 km^2)
Metal mining pit lakes	96 m (6.0–275 m)	0.3 km^2 (up to 1.2 km^2)
Coal/lignite mining pit lakes	34 m (2.5–203 m)	2.0 km^2 (up to 13 km^2)

Table 1: Depth and surface area of planned oil sands pit lakes, compared to that of global metal mine and coal mine pit lakes (Golder Associates 2017).

[5] This document does not address Compensation lakes, which are lakes constructed if mining activities are expected to impact fish habitat

in some coal and metal mine pit lakes. The tailings solids could be a combination of treated or untreated fluid tailings[7] (FT, also known as fluid fine tailings or FFT), or other tailings materials such as sand. Tailings will be placed at some designed depth. Over time the tailings will settle, releasing porewater into the water cap. This will have an impact on both the water cap depth and water cap chemistry over time. The rate of porewater flux will decrease with time depending on the expected rate of tailings settlement.

Third, the water that will enter and flow from the oil sands pit lake will have different chemistry than what is typically seen in metal mines. Although the methods used to fill oil sands pit lakes—pumping in oil sands process-affected water (OSPW[8]), dewatering tailings, diverting surface water flow from reclaimed areas of the mine, and importing water from surrounding natural water bodies—are similar to metal mining pit lakes, the chemistry of this water will be different primarily due to differing geology of the oil sands. Generally, the water will be alkaline. For a description of OSPW see Mahaffey & Dube (2017) and Schramm *et al.* (2000).

Every oil sands mining company has a Life of Mine Closure Plan (LMCP) to ensure that the land disturbed by mining is returned to a self-sustaining ecosystem, and to meet regulatory requirements under the Environmental Protection and Enhancement Act (EPEA, Government of Alberta 2018a). The LMCP includes designs for terrestrial and aquatic (i.e. wetlands and pit lakes) landforms that are integrated into the surrounding ecosystem by surface and groundwater connections. Each closure option for mine reclamation, including aquatic closure, is assessed by the mining company to compare the impacts to progressive reclamation, environmental net effects, the flexibility of the operation, and the ability to meet closure requirements. The information regarding the design and performance of pit lakes is reported through the LMCP following the process outline in the AER's Special Enactment Directive 003 (SED-003) (AER 2018).

2.1. Stratification and mixing

Stratification (either permanent or temporary with annual turnover) will affect the chemical, geochemical and ecological processes occurring in the lake.[9] Lakes can either be thermally stratified (conventional boreal lakes and most oil sands pit lakes), or chemically stratified (usually due to very high salinity differences). In a permanently stratified (meromictic) lake, the bottom layer of water will never mix with the top layer. Deep oil sands pit lakes with no tailings are more likely to become meromictic if they receive groundwater containing elevated salts (CEMA 2012). This is not expected to be a common feature in oils sands pit lakes. Pit lakes in metal mining are often designed to be meromictic so the mine waste at the bottom of the lake is prevented from reacting with oxygen to form acid. Meromictic lakes do occur naturally but they are rare; two natural meromictic lakes are Deadmoose Lake and Waldsea Lake in Saskatchewan (CEMA 2012).

Whether a pit lake is designed to mix or not is dependent on the objectives for that particular lake. If the lake is intended to isolate the underlying saline water, it can be designed to promote meromixis (Canadian Natural Resources Limited 2018). If the oil sands pit lake is intended to support the biodegradation of dissolved organics, the lake will be designed with a water cap that mixes completely at least once a year, which helps to replenish oxygen concentrations. (Golder Associates 2017).[10]

2.2. Fluid tailings

Some oil sands pit lakes will have fluid tailings (FT) or other mine waste below the water cap. These may be untreated FT (e.g. Syncrude's Base Mine Lake (BML)), or treated FT (e.g. Suncor's Upper Pit Lake (UPL)). FT consist primarily of fine sand, silt, clay, residual bitumen and OSPW. Treated FT is FT mixed with chemicals (e.g. polymer flocculant, gypsum, alum, etc.) to increase the rate of settlement. As the solids settle, porewater

[7] Fluid tailings (FT) are defined as a thin slurry (more than 5% solids by mass) with an undrained shear strength of less than 5 kilopascals (AER 2017). FT may also contain fine sand, silt, clay, water, and residual bitumen from the extraction process.

[8] OSPW from each operator will have a different chemical signature, but generally has higher salts, organic compounds, and suspended solids than natural waterbodies. (Mahaffey & Dube 2017).

[9] See Appendix 1 for more information on lake stratification.

[10] Oxygen allows microbes to more efficiently degrade organic contaminants, prevent the release of reduced gases (methane and hydrogen sulfide) to the atmosphere, and will also help the lake to develop ecologically.



is released into the lake, and the salts or organic compounds present in the FT porewater are released into the water cap and will affect water chemistry. The rate and amount of porewater released will decline over time and become negligible as the tailings settle.

2.3. Water chemistry and toxicity

All pit lakes will receive local runoff and shallow groundwater from the surrounding reclaimed and natural watershed. If the pit lake contains FT, porewater will be released into the lake as the tailings slowly settle. Because of the influence of porewater from FT and runoff from reclaimed areas, oil sands pit lakes may have elevated salts and dissolved organics compared to natural freshwater waterbodies in the region.

Undiluted, fresh OSPW can be acutely toxic[11] to a variety of aquatic organisms, but acute toxicity decreases within several months when it is left undisturbed in the environment (Boerger and Aleksiuk 1987; Allen 2008; Nix & Martin 1992). This phenomenon has been clearly demonstrated by long-term field studies at Syncrude's test ponds (Section 3.1 and Appendix 3) and Base Mine Lake (Section 3.2 and Appendix 4). Chronic toxicity[12] of OSPW persists for longer but also decreases over time.

The large volume and long residence[13] time in pit lakes provides passive treatment for the organics in OSPW, while also providing enough dilution to reduce salt concentrations. The water chemistry and toxicity are monitored in the lake to ensure it meets established water quality guidelines.

[11] Acute toxicity is measured using widely accepted standard techniques by testing the survival of different types of organisms in the water. The test organisms can include bacteria, Daphnia (water fleas), and fish such as rainbow trout.

[12] Chronic toxicity is measured by exposing the same types of aquatic organisms as for acute toxicity tests to the test water for a longer time, and observing if there are longer term effects on growth or reproduction. The organisms may grow more slowly or lay fewer eggs when exposed to the test waters, among other effects.

[13] Residence time refers the length of time water spends in the lake before flowing out. This is a function of the volume of water in the lake, how quickly it mixes, and the rates of inflow and outflow.

3. Oil Sands Pit Lake Research

Key Points

- Research on oil sands pit lakes has been ongoing for the last 40 years, including laboratory and field experiments, modelling, and long-term monitoring of field pilots.
- Research indicates that oil sands pit lakes are a viable strategy to reclaim oil sands mine pits and FT.
- FT will strengthen over time as porewater is released and solids settle. Transport of OSPW constituents, including salts, into the water cap will continue but slow over time. Eventually the FT will be fully settled.
- FT has a low permeability to water, as do overburden clays and lean oil-sands deposits. Modelling and monitoring indicates there will be negligible groundwater movement from the pit lakes.
- Once oil sands process-affected water (OSPW) is removed from an active tailings pond, under aerobic conditions, the acute toxicity dissipates.
- There are local algae, zooplankton, and invertebrates that are tolerant of the initial elevated salinities in OSPW porewater. There is evidence that some species can acclimate to elevated salts and/or naphthenic acid concentrations in porewater.
- Oxygen in the water cap is important for the breakdown of naphthenic acids.
- Over time the lake water cap can be diluted with inflows of freshwater (from natural flows including streams, run-off from reclaimed land and precipitation).

The oil sands industry has been conducting research into pit lakes for over 40 years, and a large body of evidence exists to support the successful use of pit lakes in reclamation. Conceptual and numerical models have guided the construction of lab and field pilots. Much of this research has focused on how FT affects water quality and how the lake ecology develops over time. The outcomes have been published extensively in peer-reviewed journals and are summarized in this section.

Oil sands companies have worked, and are currently working with a number of collaborative organizations including the Cumulative Environmental Management Association (CEMA), the Regional Aquatic Monitoring Program (RAMP), the Oil Sands Leadership Initiative, the Oil Sands Tailings Consortium (OSTC), and most recently COSIA to address the use of pit lakes in oil sands reclamation. Operators will continue to refine pit lake plans based on findings from these research programs, as expected by the principles of adaptive management.

The oil sands industry recognizes that there will be phases in the development of pit lakes. First, treated or untreated tailings may be deposited in the empty mined out pit, and then the water cap is added. There is an interim phase where the lake is adaptively managed to ensure that the lake progresses as expected, after which the lake is expected to achieve closure targets.

3.1. Syncrude: Historical water capping research program (1982-2012)

When Syncrude first started to develop the concept of water-capped FT in pit lakes, which is the physical isolation of FT in a mine-pit beneath a water cap, some key questions were addressed through laboratory- and field-scale experiments, modelling, and long-term monitoring. For decades, Syncrude has been working with a number of collaborative organizations including COSIA, CEMA, the Oil Sands Tailings Consortium (OSTC), Canadian Oil Sands Network of Research and Development-Environmental Reclamation Research Group (CONRAD ERRG) to develop and study water capping of FT and to advance industry's understanding of pit lake design, modelling, prediction and monitoring.

In 1982, Syncrude initiated work to determine if clay particles in the FT at the bottom of a pit lake would be re-suspended into the water column. This work was followed by a series of laboratory-scale experiments to understand OSPW detoxification. Laboratory experiments are still used to complement both the field-scale pilots and full-scale demonstration (Base Mine Lake) during the entire pit lake research program.

The field pilots, also known as the Syncrude Test Ponds, were initiated in 1989 (Figure 3). Seven small ponds (each 0.05 ha in size, containing approximately 3 m FT, and capped with either freshwater or OSPW) were constructed in 1989, and four larger ponds (three 1 ha, one 4 ha) were constructed in 1993. The test ponds were regularly monitored and used in a wide variety of research programs focused on water chemistry, toxicity, and biological development until approximately 2012.

This research program, along with modelling activities around the same time, provided the answers to a number of questions, and helped to validate the technology and inform the design of Syncrude's Base Mine Lake (Section 3.3). Some of the research findings for each study area are outlined below.[14]

Stability of the layers. For the design considerations of Base Mine Lake, the lake must be at least 5 m deep and less than 4 km long to prevent FT resuspension by storm-generated waves. The physical limnological dynamics of each pit lake configuration should be examined to determine the right water cap depth to prevent mixing of FT (Lawrence *et al.* 1991). This has been validated at the full-scale demonstration because after six years



Figure 3: Syncrude's test ponds

of settlement, Base Mine Lake has an average water cap thickness of 10 m and there is no indication of wave generated fines re-suspension of the underlying FT.

Flux across the water cap–FT interface. Salts, dissolved organics, ammonia, and organic compounds are released with porewater from FT into the water cap (Eckert *et al.* 1996). Naturally occurring bacteria break down many of these compounds, such as ammonia, dissolved organics, PAHs, and sulfate (Herman *et al.* 1994; Scott *et al.* 2005). Salts are not degradable and need to be diluted to reduce their concentration.

Shallow shoreline area development. The quality of the sediment along the shoreline is critical for plant growth. The best substrates are sand or clay amended with peat. Fertilizing with nitrogen and phosphorus does not improve the long-term success of the plant communities (CEMA 2014).

Aquatic toxicity. The acute toxicity of undiluted OSPW or water-capped FT is mainly due to naphthenic acids (NAs). The acute toxicity dissipates naturally within several months (Boerger & Aleksiuk 1987, Allen 2008, Han *et al.* 2009, Clemente *et al.* 2004).

Chronic toxicity was observed in fish living in the water-capped FT test ponds (reproductive stress, altered embryonic development, and reduced disease resistance), and may be due to the higher salt concentrations of these small ponds in addition to the effects of naphthenic acids. (Leung *et al.* 2003). Salts and NAs can have an additive effect on fish toxicity (Nero *et al.* 2006).

[14] See Appendix 3 for a list of publications from Syncrude's historical water capping research.

Ecological development. The water-capped FT test ponds were colonized within one year by microbes, macrophytes, phytoplankton, zooplankton, and benthic invertebrates. These communities were initially less diverse when salts or dissolved organics were high (Bendell-Young *et al.* 2000), but after four to five years exhibited a diversity similar to natural reference systems (Leonhardt 2003).

3.2. Syncrude: Base Mine Lake (BML) Demonstration (2012-present)

With a surface area covering approximately 800 ha, Base Mine Lake (BML) is the first full scale demonstration pit lake in the oil sands region and is located in the former Base Mine of the Syncrude Mildred Lake operation (Figure 4).

Following a regulatory hearing in 1993, Syncrude committed to developing the Base Mine Lake Demonstration, a full-scale demonstration of the water-capped tailings technology. Once mining of the Base Mine was finished in 1995, Syncrude started to transfer FT from other tailings storage areas into the mine pit, creating a tailings pond called West In-Pit (WIP). WIP was used as an active tailings pond as part of the recycle water system until BML was commissioned on December 31, 2012.

At commissioning, approximately 45 m of FT was at the bottom of the pit, and no tailings solids have been added or removed since then. During 2013, freshwater and OSPW were added to the water cap of BML until it reached the designed water elevation. The lake is operated as a flow-through system. Water is currently pumped into BML from the Beaver Creek Reservoir, and water pumped out of BML is used in Syncrude's recycle water system. Adding freshwater to BML dilutes the OSPW in the water cap over time. (Syncrude Canada, Ltd. 2019). BML is the first commercial scale demonstration of Water Capped Tailings technology. WCTT is the physical isolation of FT beneath a water cap. Based on previous research and modelling (described in Section 3.1), Syncrude expects that water quality in BML will improve over time, and the FT will remain physically isolated below the water cap.

Since 2013, Syncrude has executed a comprehensive monitoring and research program on BML, the only full-scale demonstration of a pit lake in the oil sands.

Syncrude is collecting data through the BML Monitoring and Research Program, and will use this data to demonstrate that oil sand pit lakes containing tailings can be included in the closure landscape. The results and conclusions from BML will provide information to support the design of other oil sand pit lakes containing treated or untreated tailings. The Monitoring Program tracks the trends in the lake through time, and the Research Program investigates why those changes are occurring.



Figure 4: Syncrude's Base Mine Lake. Photo courtesy of Syncrude Canada, Ltd.

3.2.1. Base Mine Lake (BML) Monitoring Program

The specific objective of the Base Mine Lake (BML) Monitoring Program is to provide information to support the validation of Water Capped Tailings Technology (WCTT) as a viable tailings management and reclamation option. In the early stages, the BML Monitoring Program will demonstrate that fluid tailings are sequestered and that the water quality in the lake is improving. The monitoring program is designed to do this by tracking the physical, chemical and biological changes in BML. The program captures these changes both temporally and spatially, and eventually in the context of regional climate cycles. The monitoring program supports regulatory compliance, but also informs adaptive management of BML.

Demonstrating the physical isolation of fines beneath the water cap of BML is a key performance outcome related to the validation of Water Capped Tailings Technology. Results so far indicate that the FT is settling as expected by model predictions, the mudline is declining in elevation year over year, the water cap is increasing in depth, and although the turbidity in the

water cap fluctuates seasonally, there is generally a decrease in the suspended solids concentration over time, especially in the upper layers of water.

Surface water quality has been improving with time in Base Mine Lake as expected, to demonstrate Water Capped Tailings Technology. The lake water is not acutely toxic[15]. All parameters measured are below Alberta Surface Water Quality short term guidelines for the Protection of Aquatic Life, except for F2 hydrocarbons.

Some selected performance results are summarized below.

Fluid Tailings Settling. The top of the FT is not flat, and generally follows the original pit topography. FT is settling as expected, up to 6 m between October 2012 and October 2018. The FT-water interface is fairly sharp and transitions from water to FT over less than 20 cm.

Physical Limnology. BML undergoes the same physical processes as natural lakes, including summer thermal stratification, spring and fall turnover, reverse thermal stratification in winter, and mixing of the water column by wind. Turbidity has a strong seasonal cycle, increasing during the fall, decreasing under ice, increasing during the spring, and decreasing again during the summer.

Water Quality. Surface water quality in Base Mine Lake has improved since 2013, and currently most of the almost 180 parameters measured are within Environmental Quality Guidelines for Alberta Surface Waters. (Government of Alberta 2018b). Some parameters (ammonia, nitrate, chloride, total boron, total phenolics and F2 hydrocarbons[16]) frequently exceed (>50% of observations) the chronic, or long-term, guidelines for the protection of aquatic life. Dissolved oxygen saturation can reach 100% in shallow depths in early summer. Oxygen concentrations in the winter are lower under ice because oxygen is consumed by biological activities, but not replenished by photosynthesis or exchange with the air as is typical in boreal lakes. However, oxygen is not always completely used up under the ice.

Aquatic Biology. The diversity of algae has generally increased every year since Base Mine Lake was commissioned, however the amount of algae growth is variable over time. Zooplankton (microscopic animals floating in the water column) are present and their diversity has increased over time. BML has a variety of benthic invertebrates (small insects living at the bottom of a lake), and they are predominantly chironomid larva (midges, red worms) however, a range of invertebrates including dragonfly and damselfly larvae, fresh water shrimp, diving beetles, water beetles and water boatmen have been observed in the lake.

Water Toxicity. Base Mine Lake has not been acutely toxic to bacteria, zooplankton, fathead minnow, or rainbow trout since 2014. The lake water has not shown chronic toxicity in fathead minnow tests since 2013. Chronic toxicity is observed in some of the organisms tested, including growth inhibition of freshwater algae, decreased frond numbers in the seven-day macrophyte tests, inhibition of bioluminescence in a bacterial test, and reproduction of *C. dubia*.

3.2.2. Base Mine Lake Research Program

The Base Mine Lake Research Program uses a multi-university, multi- and inter- disciplinary approach that focuses on the analysis and interpretation of monitoring data, hypothesis driven research activities, and integration and collaboration among and between research programs. Research results are integrated with monitoring results on an ongoing basis, with the ultimate goal of identification and quantification of the processes and properties in BML that are responsible for the trends observed in the Monitoring Program.
The various components comprising the BML Monitoring and Research Program are closely linked.

The current focus of the Research Program is to support the demonstration of the WCTT. The program also provides supporting information about key processes fundamental to the progression of BML towards a functional component of the closure landscape.
The current research programs were focused on key parameters influencing early BML development.

The program has two overarching themes. The first theme is validating the WCTT. Several research programs will determine the potential fluxes from the FT to the water column, including chemical, geochemical, mineral,

[15] The toxicity tests conducted are the following: Biological Test Method: Reference Method for Determining Acute Lethality of Effluents to Rainbow Trout (Environment Canada 2000b); and Biological Test Method: Reference Method for Determining Acute Lethality of Effluents to Daphnia magna (Environment Canada 2000a,).

[16] F2 hydrocarbons are a fraction of the total petroleum compounds and include hydrocarbons with 10 to 16 carbon atoms.

gases and heat. Physical, biological and chemical mechanisms are being investigated. The second key (and related) theme relates to the oxygen dynamics in the lake. The programs focus on understanding the oxygen balance and process of oxygen consumption (e.g. methanotrophy) and oxygen production (photosynthesis).[17]

3.3. Suncor: Aquatic Closure Development Program (2016-present)

Suncor's Aquatic Closure Development Program began in the 1990s with the construction of two demonstration pit lakes known as the Sustainability Ponds. The Sustainability Ponds were designed to test the water capping of untreated FT. Since then, Suncor has been working with a number of collaborative organizations including COSIA, CEMA, the Oil Sands Tailings Consortium (OSTC), and the Oil Sands Leadership Initiative (OSLI) to investigate water capping of treated FT and to address remaining pit lake research priorities. Priority information for building pit lakes over treated FT are being addressed by Suncor's aquatic closure development program which include the following:

- Is the treatment working? What are the characteristics and behavior of treated FT under an aquatic cover?
- What are the environmental risks posed by the treated FT in the aquatic landform?
- What are the closure and reclamation outcomes, including the safe return of water to the environment?

Suncor has assessed several closure options for the Suncor Base Plant site, including aquatic closure, to compare their impacts to progressive reclamation, and determine their environmental net effects and operations flexibility. A new in-pit treatment area, Dedicated Disposal Area 3 (DDA3), uses the Permanent Aquatic Storage Structure (PASS) FT treatment technology. The PASS technology uses an inline treatment process where coagulant and flocculant are added to treat more FT at the Suncor Base Plant and is expected to accelerate the timeline to meet water quality objectives.

3.3.1. Lake Miwasin (Suncor Demonstration Pit Lake) design

Suncor initiated the Lake Miwasin program (previously the Suncor Demonstration Pit Lake program) in 2016.

The design of the 18-hectare Lake Miwasin was based on Suncor's site-wide reclamation and closure plan. The Base Plant closure plan includes Upper Pit Lake (UPL), which incorporates DDA3 and its surrounding watershed. Lake Miwasin is a scaled-down pilot of DDA3/UPL which considers both surface area and timeline of operational phases. Lake Miwasin uses the new PASS process to treat FT, which improves the release water quality. Research and monitoring results from Lake Miwasin will be used to inform and adjust the Base Plant closure plan, where needed, to ensure that the area develops into a self-sustaining, locally common boreal forest integrated into the regional ecosystem. DDA3/UPL are expected to transition through a number of phases on the way to becoming a sustainable pit lake, and the Lake Miwasin project will also go through these phases but on a faster time scale due to its smaller size (i.e. 2017 to ~2023 for DPL vs. 2018 to ~2063 for DDA3). Wherever possible, the same scaling factors and process operating conditions that will be used for DDA3/UPL are used to build and operate Lake Miwasin.

Lake Miwasin's water depth was initially 3.5 m and the estimated final depth will be 5 m. It will have 15% littoral area, a 9:1 ratio of watershed to lake surface area, and will contain treated FT. Various littoral and riparian zone slopes will be tested, and the upland, riparian, and aquatic revegetation prescriptions were based on the CEMA Riparian Classification and Reclamation Guide guidance from local Indigenous knowledge holders and elders.

The water cap on Lake Miwasin is a combination of industrial wastewater (PASS release water and OSPW from an active tailings pond) and fresh runoff water. The target ratio of OSPW to freshwater is approximately 50:50, consistent with what is planned for the full-scale DDA3/UPL.
Lake Miwasin and the commercial scale DDA3/UPL will have the following lifecycle phases:

- Phase 1: FT treatment, deposition and dewatering (Q3 2017 for Lake Miwasin; 2018–2043 for DDA3)
- Phase 2: Aquatic cover placement and in situ organic treatment (Q3 2018 for Lake Miwasin; 2043–2053 for DDA3/UPL)
- Phase 3: Controlled water flow-through (~2019–2023 for Lake Miwasin; 2053–2060 for DDA3/UPL)
- Phase 4: Water return under natural flow (2024 onward for Lake Miwasin; 2060 onward for DDA3/UPL)

[17] See Appendix 3 for a list of Base Mine Lake research publications.

Table 2: Base Mine Lake research programs and key findings.

	Objectives	Summary of findings as of 2018
Physical limnology	To understand the circulation of BML and its potential for meromixis.	• The lake thermally stratifies during summer and turns over in the fall. • Turbidity decreases during summer stratification and increases at fall turnover. • Water becomes nearly anoxic under ice during the winter. • The surface hydrocarbon sheen may impact waves. • Meromixis is unlikely and not expected
Mass loading from FT into the water column	To identify how heat and chemicals are transferred between the tailings and water, how these change over time, and how the movement of these chemicals affect the cap water chemistry.	• Salts move from the FT porewater to the BML water cap through porewater release during FT settling. • Microbial processes like sulfate reduction can change the porewater chemistry.
Chemical flux across tailings-cap water interface	To understand how microbial activity and gas production affect movement of chemicals from the FT to cap water, to quantify the rate of chemical fluxes, and use these values to model pit lake development.	• In the laboratory, microbially-produced methane bubbles move out of the FT into the water cap, causing dissolved salts to move from the FT porewater into the cap water. • Microbial activity also changes the porewater chemistry, and causes faster FT settling and more porewater released to the cap water.
Cause and treatment of turbidity	To use laboratory columns to study the effect of gas production on water cap turbidity, and test various additives to reduce turbidity.	• Bubbling can resuspend the fine particles in FT and increase turbidity in laboratory settings. • Alum is more effective than $CaCl_2$ in reducing turbidity.
Oxygen consumption rates in the water cap	To determine the changes in oxygen concentrations in the BML water cap, the rate of oxygen consumption, and the primary biogeochemical processes which consume oxygen, and to identify long-term trends in the dissolved oxygen concentrations in BML.	• The BML water cap is thermally stratified and remains oxic down to the FT-water interface, which means oxygen is being replenished from the top of the water column. • FT is the main source of oxygen-consuming reactions, which cause lower oxygen concentrations near the FT-water interface. Oxidation of dissolved methane and ammonia coming out of the FT is the largest contributor to oxygen demand.
Microbial communities and methane oxidation	To study Biological Oxygen Demand (BOD) in the lake, especially methane oxidation and nitrification, and the role of methanotrophs in NA degradation.	• Methane oxidation makes up most of the BOD, and methane-oxidizing bacteria help to reduce the toxicity of OSPW. The exact mechanism is still being studied. • Microbial communities are highly variable over time, and do not show any clear trends.
Air-Water exchanges and water balance	To measure the water balance in BML, physical mechanisms controlling evaporation, and CH_4 and CO_2 release from BML.	• Runoff does not contribute to the water balance. • Evaporation was suppressed after BML commissioning; this may have been due to a hydrocarbon sheen. • Evaporation has increased through time and is now comparable to what is expected from a boreal lake.

3.3.2. Lake Miwasin Research and Monitoring Plan

A Research and Monitoring (R&M) Plan to evaluate the Lake Miwasin project was developed in collaboration with Indigenous communities, regulators, Alberta Innovates, industry, academics, and consultants. The goal of the Lake Miwasin R&M Plan is to monitor and evaluate if the PASS treatment process and the watershed management design for the Demonstration Pit Lake project will lead to the desired outcome—a self-sustaining boreal lake ecosystem on an accelerated timeframe. In addition, Suncor continues to use input from ongoing regional initiatives (i.e. Syncrude's Base Mine Lake) and participate in research conducted by COSIA (Vegreville Mesocosm Test Facility) to improve aquatic closure development at Suncor Base Plant.

Specific objectives of the R&M Plan are to: (1) test assumptions in the design of Lake Miwasin, and (2) identify critical gaps in the design. Monitoring and research activities will take place over a 15-year period (2018 to 2033), and an effectiveness monitoring design will determine if the goal and objectives of the Demonstration Pit Lake project are being met.

The focal areas for the Lake Miwasin R&M Plan are as follows:

- expressed porewater
- treated fluid tailing s settlement
- human and wildlife risk assessment
- water balance (quantity and quality)
- pit lake interactions with local groundwater aquifer
- biogenic gas
- treated fluid tailings-water interface stability
- bitumen stability/release
- ecological development
- performance criteria for certification
- treatment wetlands for water quality polishing
- water release off-site

3.3.3. Preliminary observations

Lake Miwasin was filled on October 6–8, 2017 with approximately 40,000 m3 of treated FT to a depth of 9.1 m (Phase 1). Samples were collected and tested to ensure that the FT was treated appropriately before deposition. This sampling confirmed that the key operating parameters (feed density, coagulant dose, flocculent dose) were all within the planned operating range for DDA3, so the treated FT in Lake Miwasin is representative of the future full-scale operation.

In 2018, Suncor executed Phase 2 of the Lake Miwasin project and placed the water cover on the treated FT deposit, planted the littoral zone, and reclaimed the uplands. Phase 3 of the Lake Miwasin project (controlled water flow-through) has been ongoing since October 2018.

Baseline and ongoing testing confirmed that Lake Miwasin was constructed in accordance with the proposed pit lake design. Observations of Lake Miwasin during and after filling with treated FT confirmed the predicted hydraulics, mixing relationships, deposit slopes and bitumen release. The treated FT deposit has settled by >2.5 m in one year. Treated FT and water quality conditions generally met performance expectations.

3.4. COSIA Demonstration Pit Lake Mesocosm study



Figure 5: COSIA Demonstration Pit Lake Mesocosm study at Innotech (Vegreville, AB). [18]

[18] Photo credit: innotechalberta.ca/research-facilities/mesocosm-test-facility-aquatic/

A mesocosm study, located at the InnoTech facility in Vegreville, AB, was initiated in 2017 to examine the response of the aquatic ecosystems to introduced test materials (Figure 5). OSPW and densified FT were added to the mesocosms, and a variety of variables, including toxicity, water chemistry, and diversity of zooplankton and invertebrates were monitored over time. This mesocosm experiment will help to improve the design of pit lakes in the oil sands.

3.5 CEMA: Oil sands pit lake model development (2004–2014)

Starting in 2004, CEMA supported the development of numerical computer models to help evaluate oil sands pit lake designs (Golder Associates 2004; Berger & Wells 2014). Currently, three phases of computer models have been developed by CEMA, with the most recent updates completed in 2014.[19]

Phase I of the modelling exercise focused on describing stratification and how the water would mix in the lake (Westcott & Watson 2007). Various combinations of different lake depths, surface areas, and water salinities were modelled to determine which conditions had the potential to cause permanent or seasonal stratification.

Phase II continued the investigation of lake mixing with a two-dimensional model (Vandenberg *et al.* 2009) and included the effect of FT on water quality.

Phase III of the model incorporated the biogeochemical changes that would occur if the pit lake contained FT, including gas bubbles moving from the FT into the water column (methane, carbon dioxide, and hydrogen sulfide), water released during FT settlement and a deepening lake bottom, and the rate of oxygen consumption by the lake sediment by both chemical and biological processes (Berger & Wells 2014). CEMA supported research to determine the sediment oxygen demand (Weisener 2015). All of these factors are important to predict the oxygen concentrations, which in turn will determine how quickly compounds like naphthenic acids (NAs) are degraded in the lake.

[19] See Appendix 4 for a list of publications from CEMA modelling activities.

4. Pit Lake Industry Research Priorities

Key Points

- Ongoing research will identify and prioritize research priorities with high-quality, peer-reviewed research.
- COSIA is engaging stakeholders to share information and research on pit lakes around the world, including in Canada and in the oil sands, and to identify and close research areas.

Although a 40-year body of knowledge exists on oil sands pit lakes, it should be recognized that like any lake, they are complex and dynamic systems. Adaptive management will be required to steward these lakes to closure targets, and ongoing research is required to support this process (CEMA 2012, Castendyk & Vandenburg 2013, Syncrude 2019). Along with the pilot activities discussed in this document, COSIA has undertaken several activities to identify and evaluate research priorities.

4.1. Addressing Industry Research Priorities

In 2013, COSIA facilitated a process to identify and evaluate industry research priorities, previously referred to as "gaps", described below and in Castendyk & Vandenburg (2013).

A list of research questions was compiled from a variety of sources, including the End Pit Lake Guidance Document (EPLGD, CEMA 2012), regulatory approvals for all oil sands operators, and industry research priorities identified by COSIA members based on their understanding of pit lakes. These research priorities help COSIA to plan pit lake research to assist all industry participants.

Adaptive management, industry-stakeholder workshops, industry partnerships through COSIA, peer-reviewed research, as well as bi-annual pit lake research reports as part of regulatory requirements, all provide the opportunity to address industry research priorities to support the advancement of the science of oil sand pit lake knowledge.

4.2. Pit lake workshop 2018

A COSIA pit lake workshop held in Edmonton in October 2018 included Indigenous community representatives, and regulators. A variety of stakeholders, including industry representatives, and provincial and federal government representatives, also participated. The workshop provided a review of global and North American pit lakes and an overview of oil sands pit lakes. A variety of topics were discussed, including how and why pit lakes are used in surface mining, case studies of successful and unsuccessful pit lakes, best practices and adaptive management.

Participants learned that globally, the planning process for pit lakes has changed over time. Early pit lakes from 50 or more years ago had no planning or research. This shifted to lakes constructed with basic planning and lab scale testing. Currently, global pit lakes, including those in the oil sands, are planned to be integrated into the whole mining process and undergo extensive research and pilot-scale testing (Castendyk 2018). Although participants agreed that oil sands pit lakes do undergo extensive research and testing, stakeholders identified the desire for more communication about the progress being made for pit lake development (personal communication, J. Brogly).

5. Conclusions

Surface mining leaves large pits which must be reclaimed, and the global pit lake experience has proven these lakes can be an environmentally sound and economical approach to reclaiming mine pits. They have been used widely in mine reclamation around the world over the last century, and extensive research has been conducted to ensure they are appropriate for the oil sands mining area.

Oil sands mine reclamation will use a suite of tailings reclamation options, including pit lakes. Pit lakes can serve multiple functions in the reclaimed landscape and will support the overall reclamation of mine sites to a locally common boreal forest environment. Pit lakes planned for the Alberta oil sands mining region could be filled with freshwater, or a mixture of OSPW and freshwater, and may or may not contain treated or untreated FT.

Pit lakes are designed based on decades of research, from small pilots to full-scale demonstrations. Base Mine Lake (Syncrude) is an example of a full-scale pit lake demonstration. Lake Miwasin (Suncor) and the Test Ponds (Syncrude) are two examples of field scale pilot demonstrations. Research, modelling and monitoring to date indicates that pit lakes are a viable strategy to reclaim oil sands mine pits and FT, where they will form a part of a successful closure landscape. Using an adaptive management framework will ensure that pit lakes are stewarded to acceptable closure outcomes.

The oil sands industry will continue to work with stakeholders, regulators, and Indigenous groups to ensure that oil sands mine sites are being reclaimed to meet their requirement of creating a self-sustaining, locally common boreal forest ecosystem, that is integrated with the surrounding area, and consistent with the values and objectives identified in local, regional, and sub-regional plans. In addition, COSIA continues to engage stakeholders to share information and research on pit lakes around the world, including in Canada and in the oil sands, and to identify and evaluate industry research priorities, and then address them through research and monitoring activities.

PIT LAKE GUIDE

LEAD

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6. Appendices

Appendix 1: Lake stratification (from Wetzel, 1983)

In temperate regions, lakes exhibit thermal stratification, which is the layering of water driven by temperature induced density differences. During warmer summer periods, the sun heats the surface water of the lake. This heating happens more rapidly than the heat can be distributed by the wind mixing the water. As a result, the surface waters warm up and become less dense (maximum density of water is at 4°C), and the wind is not strong enough to mix the surface and bottom waters together. The lake becomes layered (stratified) into 3 zones: the epilimnion, the hypolimnion, and the metalimnion. The epilimnion is the upper layer of warmer, less dense water that circulates with the wind. The hypolimnion is the lower layer of colder, denser and relatively quiescent water. The metalimnion is a relatively narrow layer of water between the epilimnion and hypolimnion, where the temperature changes rapidly between the two.

In the fall, as air temperatures and solar radiation declines, the surface waters cool and increase in density. Fall winds and convection currents are able to mix the upper and lower waters as their densities become more similar. Eventually, the entire water column can circulate. This is fall turnover, or mixis. As ice covers the lake, colder less dense water overlies warmer more dense water (nearer to 4°C) at the bottom of the lake. When the ice cover melts in the spring, the lake water is nearly all the same temperature, and wind energy can circulate the entire water column again. This is spring turnover or mixis. Lakes that undergo complete circulation in spring and fall, with thermal layering in the summer and winter are called dimictic lakes. This is typical of boreal lakes.

Lakes can also stratify as a result of salinity induced density differences. Some lakes with very high salinity can become permanently stratified, or meromictic, when the higher density saltwater stays at the bottom of the lake and resists mixing with the lower density freshwater on top (Figure A1.1b). The epilimnion and hypolimnion will still form in the summer months due to temperature differences, but the monimolimnion at the bottom of the lake, which has a different chemistry, will never or rarely mix with the surface layers.

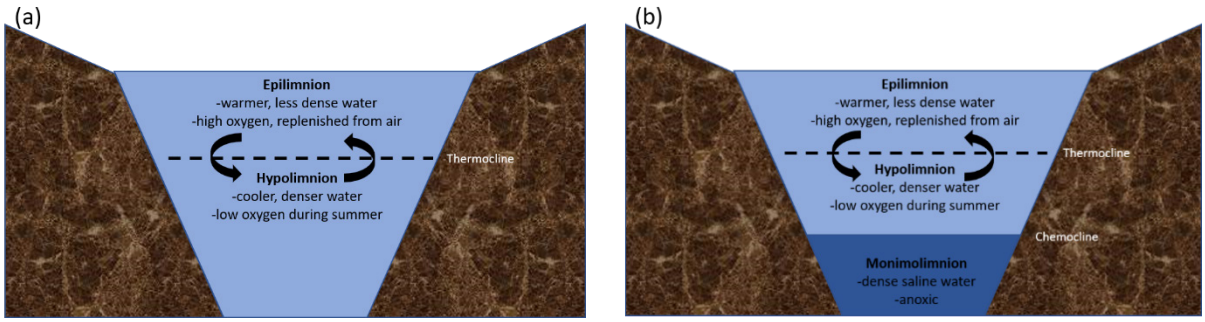


Figure A1.1: Two types of lake stratification. (a) Complete mixing, Dimictic pit lake. Stratification is due to water temperature and density differences, and the lake mixes twice per year. (b) Incomplete mixing Meromictic pit lake. Dense, high salinity water forms a permanent layer at the bottom of the pit, and does not mix during seasonal turnover. In both cases the epilimnion and hypolimnion mix at least once a year during spring and fall.

Appendix 2: Pit lakes planned for the oil sands region as of Q4 2018

Table A2.1. Planned Pit Lakes in the Oil Sands Region (provided to COSIA by Golder Associates, November 26, 2018).

Operator	Mine	Pit Lake Name	Water Volume (Mm3)	OSPW Volume (Mm3)	Untreated and Treated FT Volume (Mm3)	Total Volume (Mm3)	Surface Area (km2)	Mean Water Depth (m)	Filling Period (start– end year)		Source
Teck Resources	Frontier	CPL	725	112	0	725	26.5	33.0	2066	2080	a
		NPL	92.4	0	0	92	3.6	36.1	2063	2080	
		SPL	290.7	0	0	291	11.4	33.7	2066	2081	
Canadian Natural	Horizon	EPL1	208	0	0	208	4.7	44.6	2057	2069	b
		EPL2	188	26	177	365	9.4	20.0	2057	2064	
		EPL3	186	26	0	186	4.5	41.2	2057	2066	
	Jackpine and Expansion	NEPL	540	>0	>0	540	23.7	22.8	2050	2065	c
		NWPL	158	0	0	158	6.4	24.9	2060	2065	
		SCPL	204	0	0	204	7.4	27.6	2050	2065	
		SPL	52	0	0	52	2.1	24.8	2050	2056	
	Muskeg River	MRM EPL	25.8	0	31	57	2.6	9.9	-	-	d
		SKB EPL	6	0	17	23	2.3	2.6	-	-	
Suncor Energy	Fort Hills	NPL	63.3	0	0	63	6.5	9.7	2075	2081	e
		SPL	49.3	18	439	488	8.1	6.1	2075	2081	
		East Pit lake	12	0	0	12	2.1	5.7	2075	2081	
	Millennium	Upper PL	138.3	40	283	343	7.6	25.9	2043	2050	f
		Lower PL	80.1	0	0	80	4.5	14.8	2045	2057	
Syncrude Canada	Mildred Lake	MLX_W EPL	123	0	0	123	4.1	29.0	2037	2037	g
		North Mine Pit lake	40	25	200	240	5.2	7.7	2041	2050	h
		BML	119	40	183	302	9.9	12.0	2012	2015	i
	Aurora North	EPL	50	0	190	240	20.0	2.5	2040	2052	j
	Aurora South	Aurora South EPL	689	45	48	746	22.0	32.0	2044	2065	k
Imperial Oil	Kearl	EPL	740	30	125	865	18.2	40.0	2056	2066	l

NOTES:

PL = Pit Lake, EPL = End Pit Lake, NPE = North Pit Extension, MLX_W = Mildred Lake Mine Extension, BML = Base Mine Lake, NSE = North Steepbank Extension, CPL = Central Pit Lake, NPL = North Pit Lake, SPL = South Pit Lake, NEPL = Northeast Pit lake, NWPL = Northwest Pit Lake, SCPL = South Central Pit Lake, MRM = Muskeg River Mine, SKB = Shakebite Mine

a. Teck (Teck Resources Ltd.) 2015. Frontier Oil Sands Mine Project – Project Update. Submitted June 15, 2015 to Alberta Energy Regulator and Canadian Environmental Assessment Agency by Teck Resources Ltd. Volume 3 section 7

b. Canadian Natural Resources Limited. 2018. Horizon Oil Sands Mine North Pit Extension Integrated Application and Environmental Impact Assessment. Submitted to the AER April 30, 2018. Volume 3, Section 7.8.

c. Shell 2012. Supplement to the December 2007 Application for Approval of the Jackpine Mine Expansion & Pierre River Mine Project: Pre-Development Scenario and Updated Planned Development Case Mar 2012. Section 3.5.4.3

d. (1) BGC Engineering Inc. 2016. Muskeg River Mine-Life of Mine Closure Plan EPEA and water Act Approval Renewal Application. Submitted Dec 2016 by Shell Canada Limited Section 4.2.4 (2) tailing volumes from: Shell. 2016. Muskeg River Mine-Closure landscape Plan. Appendix E, Tables E-1 and E-2, Shell Planning volume. Submitted June 2016 by BGC Engineering Inc.

e. Suncor 2017. 2017 Fort Hills Mine Amendment Application. Submitted to Alberta Energy Regulator. February 2017. Section 10.3.2 Table 10-3

f. Suncor 2018. Base Plant operations 2018 Reclamation and Closure Plan. Appendix M Of: Environmental Protection And Enhancement Act Approval No. 94-02-00 Renewal Application. Submitted to Alberta Energy Regulator April 2018. Section 5.2.3 Table 5.3

g. Syncrude 2014. Mildred Lake Extension Project. Submitted December, 2014 to Alberta Energy Regulator and Canadian Environmental Assessment Agency by Syncrude Canada Ltd. Vol 1. Section 9.4.6

h. Syncrude 2006. Mildred Lake Mine Conceptual Closure Drainage Plan. Prepared by Golder Associates Ltd. for Syncrude Canada Ltd. Submitted to Alberta Environment. March 2006. 2) For OSPW volume: Syncrude 2014. Mildred Lake Extension Project. Submitted December, 2014 to Alberta Energy Regulator and Canadian Environmental Assessment Agency by Syncrude Canada Ltd., Vol 1, Section 6, Table 6.4-2 (RCW volume)

i. Syncrude 2016. Syncrude 2016 EPEA Approval Renewal Application. Submitted to Alberta Energy Regulator. December 21, 2016. Section 5.5.5 for FT volume. 2) For OSPW volume: Syncrude 2014. Mildred Lake Extension Project. Submitted December, 2014 to Alberta Energy Regulator and Canadian Environmental Assessment Agency by Syncrude Canada Ltd., Vol 1, Section 6, Table 6.4-2 (RCW volume)

j. Syncrude 2016. Tailings Management Plan Application, Syncrude Aurora North Mine. Submitted October, 2016 to Alberta Energy Regulator by Syncrude Canada Ltd. Section 3.5 Figure 3.17.

k. Syncrude 2009. Aurora South Mine 2009 Project Update. Submitted to the Energy Resources Conservation Board. December 2009. Appendix 9A Table 9A-2

l. Imperial Oil 2017. Kearl Oil Sands Renewal Application. Submitted to Alberta Energy Regulator. October, 2017. Appendix I, Section 4.3.3

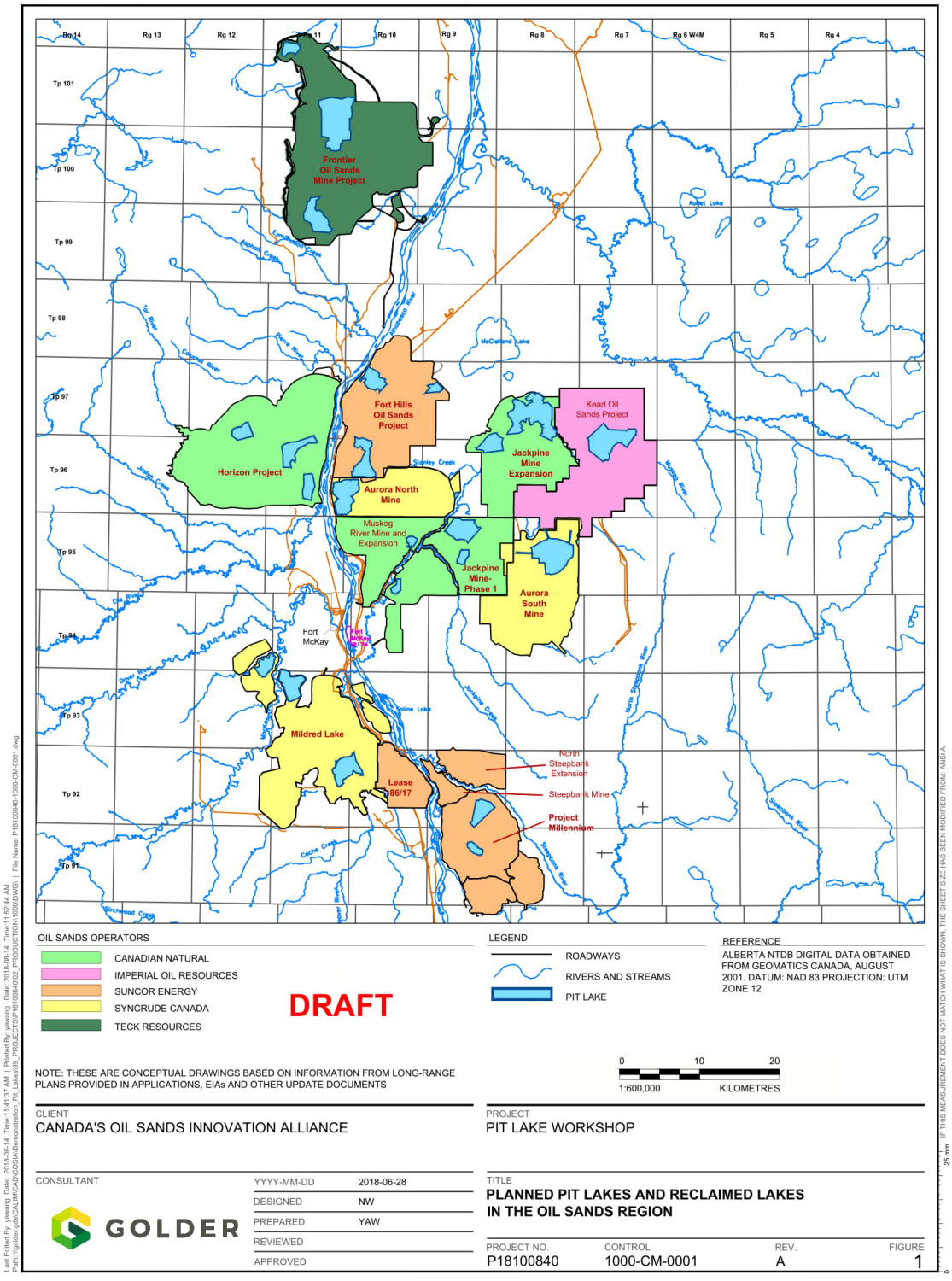


Figure A2.1: Map of the pit lakes planned for the oil sands region. (provided by Golder Associates, November 26, 2018.)

Appendix 3: Syncrude's historical water capping research publications

Armstrong SA. 2008. Dissipation and phytotoxicity of oil sands naphthenic acids in wetland plants. PhD Thesis. Saskatoon, SK: University of Saskatchewan. http://hdl.handle.net/10388/etd-07082008-115622

Bataineh M, Scott AC, Fedorak PM, Martin JW. 2006. Capillary HPLC/QTOF-MS for characterizing complex naphthenic acid mixtures and their microbial transformation. *Analytical Chemistry* 78: 8354-8361. DOI: 10.1021/ac061562p

Boerger H, Aleksiuk M. 1987. Natural detoxification and colonization of oil sands tailings water in experimental pits. In *Oil in freshwater: chemistry, biology, countermeasure technology*, Vandermeulen JH, Hrudey SE, editors. New York: Pergamon Press. p. 379-387DOI: 10.1016/B978-0-08-031862-2.50031-9

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Appendix 4: Syncrude Base Mine Lake Demonstration publications

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