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Physical, chemical and ecological performance of Syncrude Canada Ltd's Base Mine Lake

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Abstract

Base Mine Lake (BML), the first commercial demonstration of water-capped tailings technology (WCTT) in the mineable oil sands in Alberta, Canada, was commissioned in December 2012, following seventeen years of transfer of fine tailings (FT) into West-in-pit. BML's design basis is that over time, the FT will be physically isolated due to self-weight consolidation, the lake's water quality will improve, and the lake will ultimately achieve targeted closure outcomes. Since commissioning, the lake has been intensively monitored to track the physical, chemical, and ecological parameters of the FT and the water cap in order to demonstrate the viability of WCTT in reclaiming FT. The FT is consolidating as predicted by finite-strain consolidation theory, reflected by increasingly distinct mudline and profile density increases with time. The water chemistry of BML is improving with decreasing concentrations of many key constituents below both acute and chronic protection of aquatic life guidelines. The lake's ecosystem is developing, with the establishment of an aquatic invertebrate community. An adaptive management approach helps steward BML towards desired short and long-term objectives. Adaptive management actions have included alum treatment to address water turbidity, and removal of bitumen mats from the FT surface. Improvements observed in the trajectory of the physical, chemical, and ecological parameters for BML are consistent with its short-term objectives. Ongoing monitoring and adaptive management of BML will continue to ensure its long-term closure objectives are met.

Keywords: *base mine lake, water-capped tailings technology, oil sands, fine tailings, aquatic closure*

1 Background

In 1995, Syncrude Canada Ltd (Syncrude) secured the regulatory approval to reclaim fine tailings (FT) below grade using water-capped tailings technology (WCTT) at its Mildred Lake oil sands surface mining operations in Northern Alberta. Base Mine Lake (BML) was subsequently commissioned in December 2012 following seventeen years (1995 to 2012) of FT transfer into a mined-out pit called 'West In-Pit' (WIP). At commissioning, the total volume of FT in BML was ~ 196 Mm^3. The FT was thereafter capped with a mixture of fresh and oil sands process water (OSPW). Since then, the lake has been maintained as a flow-through system, with inflow of fresh water from the adjacent Beaver Creek Reservoir, BCR (Figure 1) and pumping out of lake water as required. This has helped maintain the lake at a constant elevation and contributes to dilution of the water cap. This flow-through system will continue until the lake is integrated into the closure watershed in the long term. BML (Figure 1) is the first commercial demonstration of WCTT in the Canadian mineable oil sands region and is underpinned by several decades of research related to WCTT at Syncrude (COSIA 2021).

Fine tailings is a by-product of the bitumen extraction process, comprising of fine solids (with particle size less than 44 microns), sands (with particle size greater than 44 microns), OSPW, and residual hydrocarbons. WCTT is one of several current commercial-scale technologies for reclaiming FT from mineable oil sands operations. WCTT targets reclaiming FT into an aquatic closure landform that can be integrated into the final mine closure landscape. Other technologies (such as FT centrifugation, in-line flocculation, tailings thickening, composite tailings, non-segregated tailings, tailings filtration etc) produce treated FT that can be stabilized and incorporated into the closure landscape as terrestrial landforms. WCTT is a relatively lower energy-intensive technology for reclaiming FT in a pit lake and is a best practice in various mining jurisdictions globally.

BML is currently in the commercial demonstration phase and an extensive research and monitoring program has been ongoing since the lake was commissioned. A key purpose of the BML monitoring and research programs is to continue to support the adaptive management of the lake towards both the short and long-term objectives. The monitoring and research program is designed to assess lake performance against key performance indicators and evaluate the need for management interventions. The initial focus of the research program is to support the demonstration of the WCTT and to provide a body of scientific evidence which demonstrates that BML is on a trajectory to become integrated into the reclaimed landscape and will ultimately receive reclamation certification. The outcomes from the BML monitoring and research program will be used to inform the design and management of future pit lakes, including those that may contain treated or untreated tailings. At the same time, the program establishes a baseline of biophysical data to assess the changes in the lake through time, including water quality and other lake processes.

In the short term, to validate WCTT, BML should demonstrate 2 key results: (a) the fines are physically isolated below the water cap, and; (b) the water quality trajectory is improving over time. Key performance indicators (KPIs) that support the validation of WCTT include the following:

- The lake should have all solids in place and be filled to design elevation with a water cap sufficient to prevent wind-driven resuspension of fines.
- The fine tailings should be settling as it dewaters with time.
- Although total suspended solids (TSS) in the water column is expected to fluctuate seasonally with mixing events, TSS should show improvements over time or be in the range of natural variability.
- The water cap should not be acutely toxic, as demonstrated by appropriate standard acute lethality tests described in Environment Canada Biological Test Methods and Guidance Documents (Government of Canada).
- The water cap should pass appropriate Canadian Water Quality (acute) Guidelines for the Protection of Aquatic Life (CCME 2014c) and Environmental Quality (acute) Guidelines for Alberta Surface Waters (AEP 2018).

This paper summarizes the short-term trajectories in the physical, chemical, and ecological parameters observed or predicted for BML since commissioning. Longer-term performance related to reclamation certification of BML is beyond the scope of this paper and can be found elsewhere (Syncrude 2022). The physical parameters relate to the fines being physically isolated below the lake's water cap, including during lake mixing events. The chemical parameters relate to the trajectory in the water quality of the lake over time. Ecological parameters relate to the increasing abundance and diversity of biological components of the lake. In this paper, two examples of management interventions are briefly highlighted. These interventions demonstrate the application of the adaptive management approach in stewarding BML towards the intended performance outcomes.

Figure 1 BML showing adjacent structures and Beaver Creek Reservoir (BCR)

2 Base Mine Lake – Performance Monitoring

Monitoring the physical parameters of the lake involved tracking the settlement of the FT, characterizing the geotechnical parameters of the FT, and measuring the total suspended solids (TSS) of the water cap with time. Details regarding monitoring and characterizing the FT are published by Dunmola et al. (2023). The physical parameters are linked to the chemical and ecological performance of the lake as they influence the water, chemical and energy fluxes within the lake, subsequently impacting its ecological evolution.

The chemical parameters are being monitored to understand the temporal changes of the lake's water chemistry. The chemical constituents are monitored to ensure that the water cap is not acutely toxic in the short term, and show a trajectory of improvement over time. Details of the water quality monitoring program can be found in Syncrude (2022). The lake's water balance is driven by the inflows and outflows into the lake as well as the pore water release due to self-weight consolidation of the FT as detailed in Syncrude (2022).

The ecological parameters help in assessing the state and capacity of the lake to support ecological structure and functions. These parameters include whole-water assessments of acute and chronic toxicity of the water cap, using standard tests (Environment Canada, 2000a and 2000b). Acute guidelines and toxicity assessments help characterize the short-term improvement in the lake's water quality. A variety of biological communities are assessed in the lake, including phytoplankton, zooplankton, aquatic vegetation, and benthic macroinvertebrates.

3 Performance Trajectory Results

The following sections summarize the key results related to the short-term trajectory of the physical, chemical, and ecological parameters of BML since commissioning in late 2012. The highlighted parameters are required to validate WCTT's capacity for the remediation of oil sands FT in the short term. In the long term, the parameters are also crucial to the lake's capacity to be certified as an aquatic landform within the overall mine closure landscape.

3.1 Physical performance trajectory

Physical performance monitoring results indicate that the fines in BML are physically isolated below the water cap. The lake's water cap depth has been consistently maintained above the minimum design water cap depth (6 m) that can prevent wind-driven resuspension of the fines. The water cap depth has been greater than 9 m since May 2015 (Lawrence et al. 2016). As reflected by the seasonal cycling of the turbidity in the water cap (Figure 2), BML undergoes conventional boreal lake dimixis, including ice-on and ice-off periods, summer thermal stratification, spring and fall turnover, and winter reverse thermal stratification (Table 1 as per Syncrude 2022). Also, as discussed later in this paper, the TSS in the water cap has been decreasing, especially following the adaptive management intervention that involved alum addition to the water cap (Figure 9). Hence, since commissioning, there has been no evidence of wind-driven fines resuspension in the lake. The increasing water cap depth, along with the densification of the FT due to self-weight consolidation is expected to sustain this trajectory (Dunmola et al. 2023).

Since commissioning, the FT has been settling as indicated by the lowering of the mudline over time (Figure 3). The volume of FT has decreased from ~ 196 Mm^3 in October 2012 to 167.7 Mm^3 as of September 2022, a 14.4% volumetric deformation. The FT settlement in BML is spatially variable, with cumulative settlement (2012 to 2022) ranging between 0.3 and 7.6 m (Figure 3). The least settlements were recorded in areas close to the shoreline where the initial FT thickness was lowest. The greatest cumulative settlement magnitudes are generally observed for areas of the lake where the initial FT thickness was largest. The FT settlement observed in the lake is driven by self-weight consolidation (Figure 4) as shown by the general agreement between field data and numerical predictions based on the finite-strain consolidation theory (Dunmola et al. 2023). Also, profiles of effective stresses were successfully measured and well predicted within the FT using the finite-strain consolidation theory as discussed in Dunmola et al. (2023). In addition, the FT settlement is complemented by an increase in the profiles of solids content (Figure 5), as well as increasingly more distinct transition at the FT-water cap interphase (mudline) with time (Figure 6).

Table 1 Summary of ice-on, ice-off, whole lake stratification and turbidity extremes measured from moored sensors installed on a floating platform at BML

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021
Winter Min. (NTU)	-	*180*	*169*	53	2	23	28	28	18[c]
Ice-off	-	May 1	Late April	April 27	May 5	May 5	April 20	May 6	May 6
Spring Max. (NTU)	*99*[a]	*177*	221	153	55	70	55	70	24[d]
Stratification Onset	Late May[b]	May 30	June 9	June 23	May 26	May 10	May 17	June 9	May 28
Summer Min. (NTU)	*5*	*10*	36	16	3	6	7	6	4
Fall Turnover	Early Sept.	Sept. 7	August 28	August 27	Sept. 3	Sept. 3	August 21	August 30	Sept. 14
Fall Max. (NTU)	*260*	*138*	308	40	100	100	51	30	27
Ice-on	Nov. 10	Nov. 11	Nov. 20	Nov. 18	Nov. 8	Nov. 8	Nov. 11	Nov. 10	Nov. 21

[a] Italics mark turbidity measured from bottle samples before the continuous moored turbidity loggers were installed.

[b] Estimate only

[c] Based on platform 2 at 2.5m (the instrument at P3 drifted off of calibration)

[d] Based on Hatfield YSI ProDSS profiler data collected June 2 (Spring maximum) at P3 at 2.5m. [f] Intermittent sensor communication may have resulted in missed peak, to be updated at next instrument access.

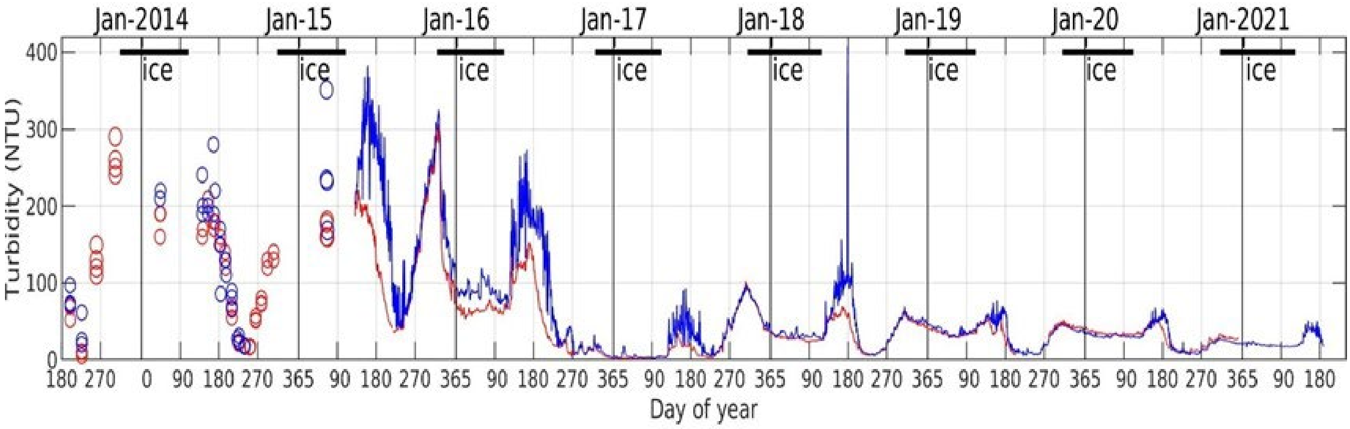


Figure 2 Turbidity measured from June 2013 to June 2021 at BML

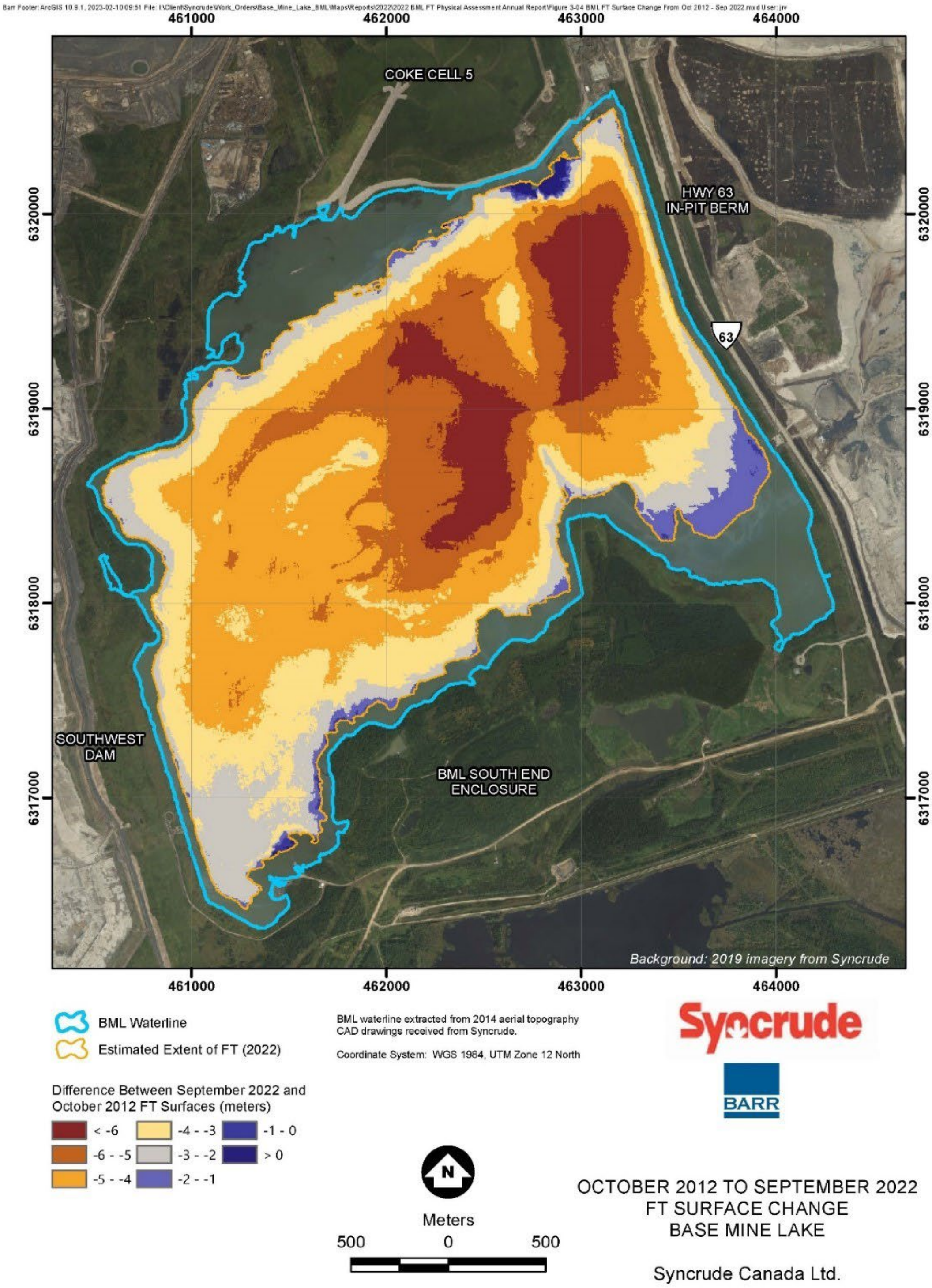


Figure 3 **Change in surface elevation of fine tailings in BML between October 2012 and September 2022**

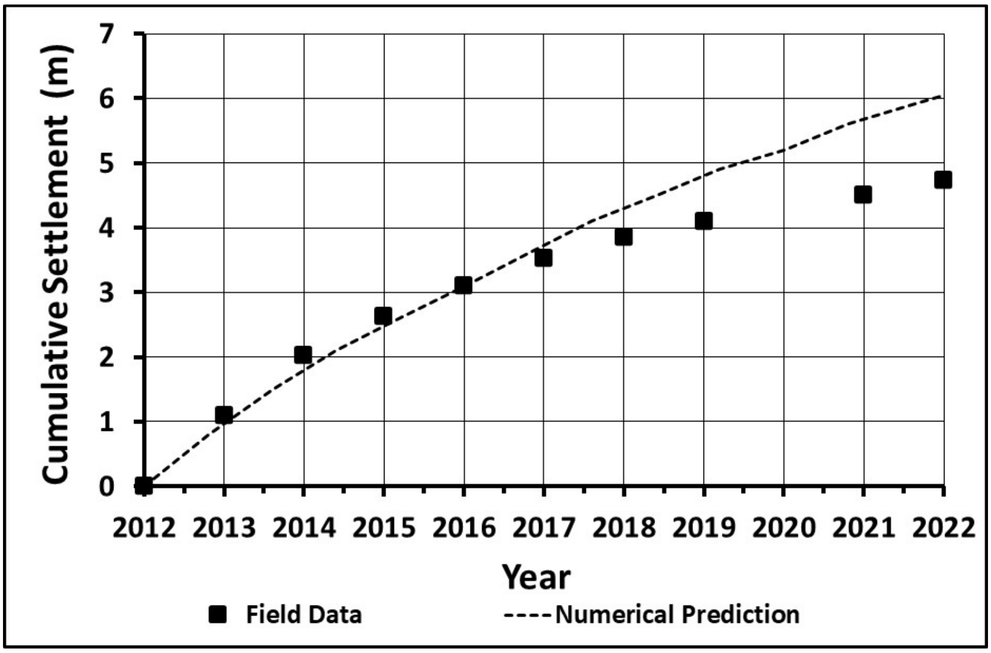


Figure 4 Cumulative settlement of FT observed compared with numerical prediction using finite-strain consolidation theory (after Dunmola et al. 2023)

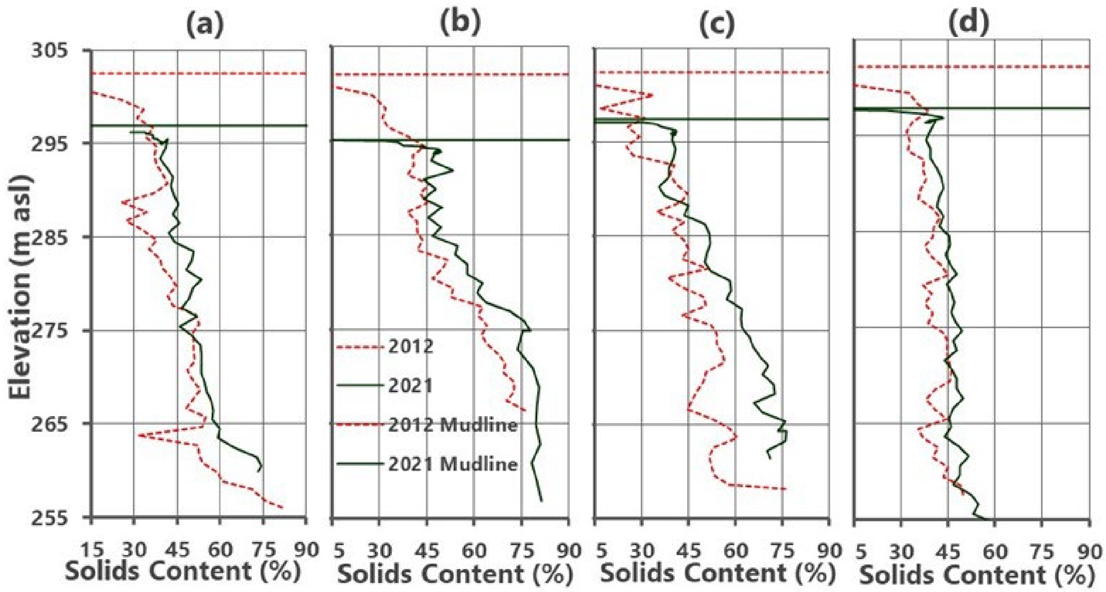


Figure 5 Profiles of solids content of FT measured in 2012 and 2021 in BML at sampling locations: (a) D11; (b) Platform 2; (c) D08, and (d) D38

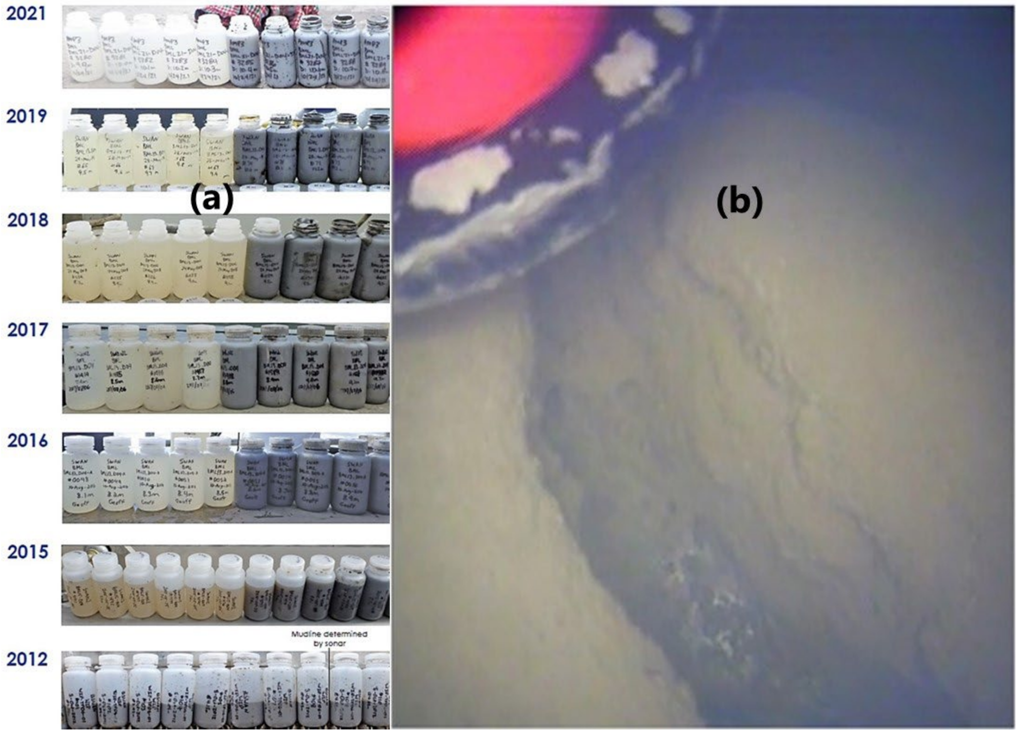


Figure 6 Photograph of: (a) fluid samples taken at 10 cm intervals across the BML mudline from 2012 to 2021, and; (b) the mudline taken underwater in September 2019 as detailed in Zhao et al. 2021

3.2 Water quality performance trajectory

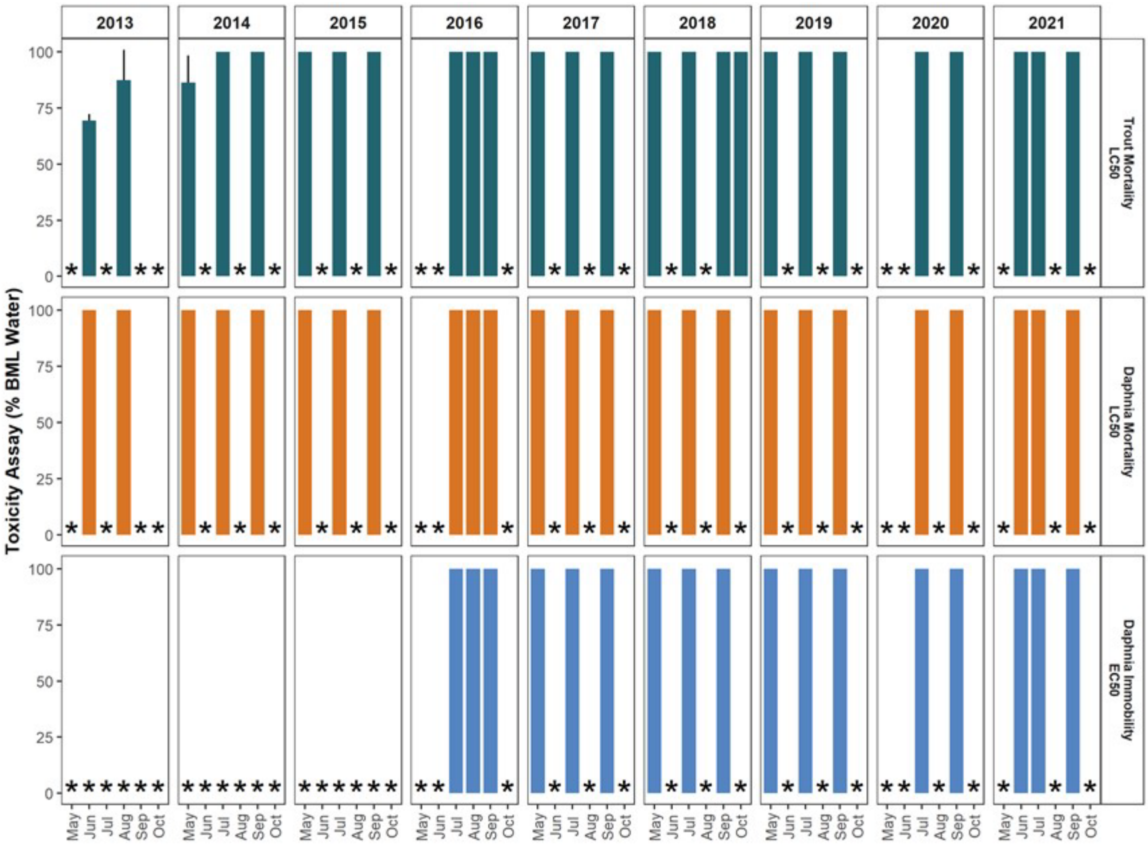
A comparison of all 185 parameters measured in the water cap at BML to the acute Protection of Aquatic Life (PAL) guidelines showed that only the F2 hydrocarbon concentration was exceeded. Details of the water quality parameters and trajectories for BML are not included here as they are provided in Syncrude (2022). The F2 hydrocarbon guideline is an interim guideline derived from soil studies, hence its relevance to aquatic closure landforms is currently the subject of study for the oil sands industry (Syncrude 2022).

The lake's water has elevated concentrations of chloride and sodium, compared to fresh water, with a slightly alkaline pH. All major ions, cations, total dissolved solids (TDS), total suspended solids (TSS), conductivity and metals have generally shown decreasing concentration since 2013 when monitoring began. Petroleum-based organics such as naphthenic acids (NAs), Polycyclic aromatic hydrocarbons (PAHs), F2 and F3 hydrocarbons continue to be measurable in BML, while most volatile organics (such as benzene, xylene and toluene) were near or below their respective detection limits. It is expected that concentrations of measured parameters will improve with time. The freshwater inflow from Beaver Creek Reservoir dilutes the OSPW in the BML water cap. Also, over time, the contribution of porewater advection from the FT into the water cap will decline due to decreasing rate of consolidation (Dunmola et al., 2023). There is also evidence that organic constituents in the water cap can be degraded via bio- or photo-degradation.

3.3 Ecological performance trajectory

A key measure of the ecological performance of the lake is the water chemistry and toxicity. Since May 2014, the BML water has consistently passed the 96-hour static acute test on rainbow trout (*Oncorhynchus mykiss*), with no adverse effect on survival rate (Figure 7). Similarly, the BML water has consistently passed the 48-hour acute *Daphnia magna* test since monitoring started in 2013 (Figure 7). Hence, both acute toxicity tests have shown no evidence of acute toxicity of the water in BML since early 2014 (Figure 7). Chronic toxicity has been observed for some organisms since 2013. Additional details regarding the chronic toxicity tests are beyond the scope of this paper but are discussed in Syncrude (2022).

Although Base Mine Lake is a young aquatic system, there is evidence that conventional boreal flora and fauna are establishing in the lake. BML supports a phytoplankton community, and that community is still developing. The most abundant phytoplankton community components are genera typical of natural boreal lakes and should be able to support complex aquatic food webs. An assessment of littoral zone vegetation in 2019 detected 14 different wetland and aquatic plants (Table 2). The benthic invertebrate community is dominated by chironomid midge larvae (Diptera: Chironomidae), but other taxa have been detected in the lake including freshwater shrimp, dragonflies, damselflies, water boatmen, beetles and caddisflies. Fish screens are in place at the inflow from Beaver Creek Reservoir, which prevents fish from entering BML.



Shown are pooled averages of toxicity assay results across BML platform stations, with standard deviations shown as error bars where applicable.
LC50 is the concentration of BML water, diluted by non-toxic medium, estimated to cause 50% mortality in exposed test organisms.
EC50 is the concentration of BML water, diluted by non-toxic medium, estimated to cause immobility in 50% of the test organisms.
Seasons without toxicity assay results for these endpoints are marked with asterisks.

Figure 7 Acute toxicity test results (Rainbow trout and Daphnia magna) for BML's whole water from 2013 to 2021

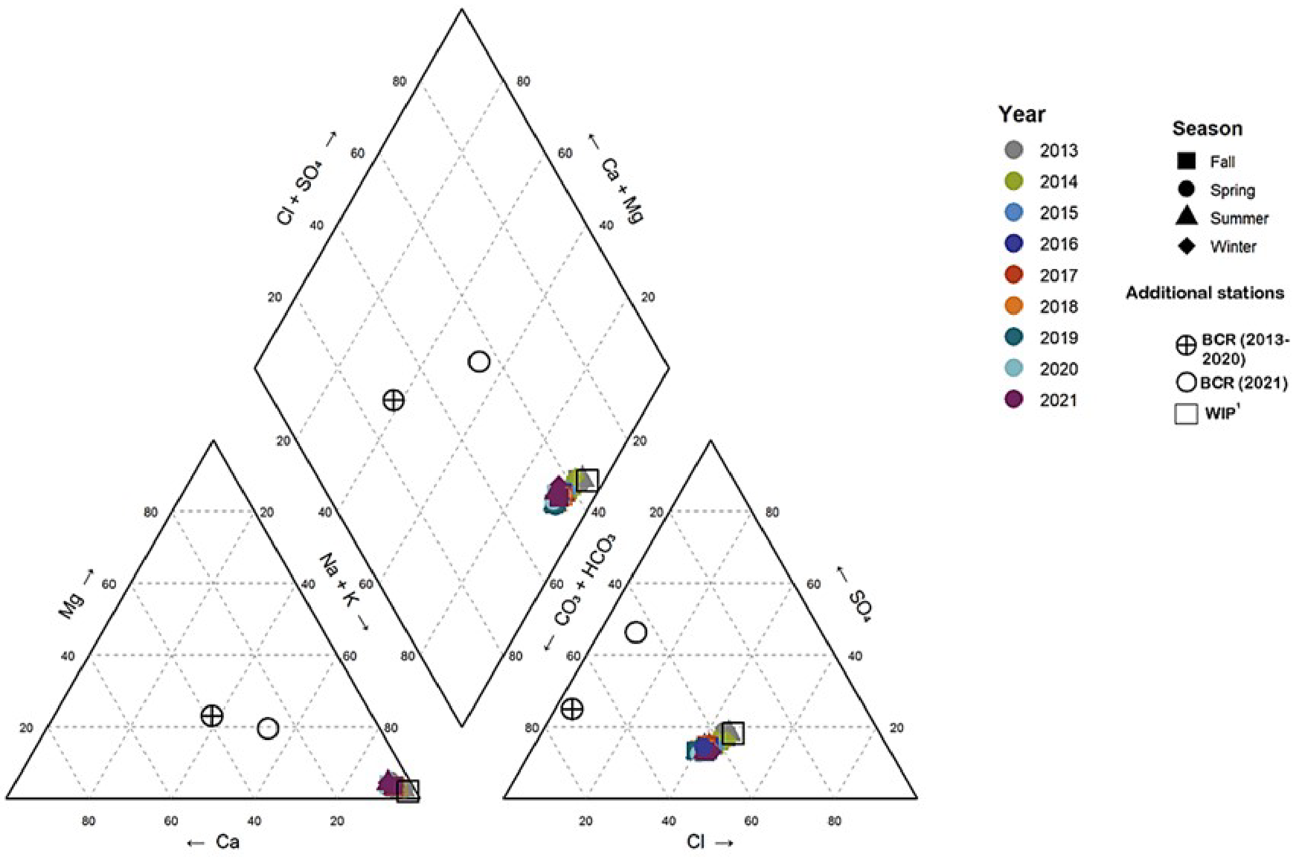
Table 2 Aquatic plant species identified in the littoral zone of BML in 2019

Scientific Name	Common Name
Equisetum arvense	Common horsetail
Stuckenia filiformis	Thread-leaved pondweed
Potamogeton gramineus	Various-leaved pondweed
Sparganium angustifolium	Narrow-leaved bur-reed
Schoenoplectus tabernaemontaini	Common great bulrush
Typha latifolia	Common cattail
Utricularia intermedia	Flat-leaved bladderwort
Phalaris arundinacea	Reed canary grass
Carex aquatilis	Water sedge
Hordeum jubatum	Foxtail barley
Salix spp.	Willow
Chara spp.	Stonewort
Euglena spp.	*Euglena* algae
Stigeoclonium spp.	*Stigeoclonium* algae

4 Discussion

As presented in this paper, the field observations and model predictions from BML show that the fine tailings in BML is isolated below the water cap, while the water quality is improving over time. There is evidence that typical boreal lake ecological communities are developing in the lake. This pattern is consistent with the short-term goal of demonstrating the viability of WCTT as a technology for reclaiming oil sands fine tailings into an aquatic closure landform. The FT in the lake is consolidating and dewatering as predicted by finite-strain consolidation theory. The water released from FT consolidation constitutes an integral part of the water, thermal and chemical fluxes from the underlying FT into the water cap. The consolidation trajectory is complemented by an increase in the profile density of the FT, and reflected in the progressively more distinct transition between the water cap and the FT at the mudline. Though the lake undergoes seasonal dimixis that is characteristic of conventional boreal lakes, the turbidity of the lake has improved with time. Since commissioning, there has been no evidence of wind-driven resuspension of the FT. This is attributed to maintaining sufficient water cap depth (above the design depth) as well as the consolidation-driven dewatering and densification of the underlying FT which prevents fines from resuspending from the FT into the water cap.

Overall, the chemical composition of BML water is comparable to that of OSPW from WIP during FT deposition. The water quality is different from that of freshwater from adjacent Beaver Creek Reservoir (Figure 1). However, BML's water quality has improved over the years from the ionic signature of the OSPW during fine tailings placement in WIP (Figure 8). Also, field data have confirmed the development of viable aquatic biota in the lake. The lake has not exhibited any whole-water acute toxicity response since 2014. Several standard tests also show no chronic toxicity response. However, there remains some residual chronic toxicity. Conventional boreal lake floral and faunal communities are establishing in the lake. This developing aquatic ecosystem reflects the improvement in the turbidity, oxygen availability and improved water quality observed over time for the lake. More details can be found in Syncrude (2022).



Note: Oil sands process-affected water from the West-In Pit (OSPW WIP) presented as mean ionic composition pre-commissioning, 2001 to 2012.

Figure 8 Piper plots of major ionic composition in BML from 2013 to 2021. Shown are the respective plots of OSPW from West in-pit (WIP) and fresh water from adjacent Beaver Creek Reservoir (BCR)

As per the principles of adaptive management, through the BML's research and monitoring program, the lake's performance is continuously assessed against the stated key performance indicators, both for the short and long terms. If the trajectory of a performance indicator is deemed to be off track, management intervention is undertaken to steer the lake towards achieving the candidate indicator both in the short and long terms. For BML, two of such interventions relate to addressing the lake's water turbidity and hydrocarbon sheen issues. BML had high levels of turbidity in the water cap for the first four years after commissioning, with the turbidity driven by fine mineral particles suspending in the water column during FT deposition. Although there were year-over-year improvements in turbidity, a decision was made to intervene to increase the pace of turbidity improvements. Having a clear water column is important for the biological (especially algal community) development and oxygenation status of the lake. In September 2016, during the lake's fall turnover, alum solution was added to the water cap from a boat-mounted system. This resulted in substantial improvement in the lake's water turbidity (Figure 9). The lake's water turbidity has remained low ever since.

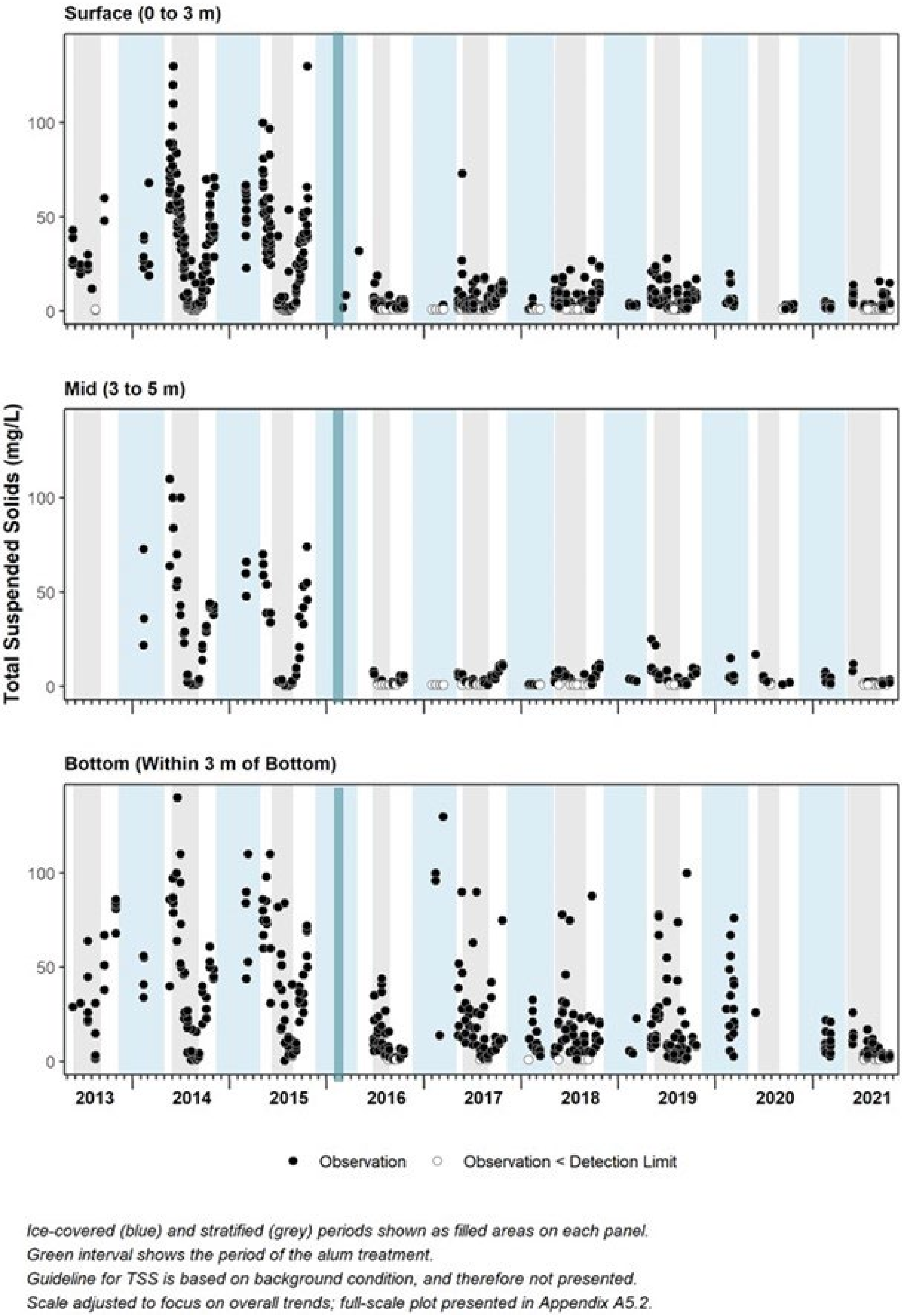


Figure 9 Temporal pattern in total suspended solids (TSS) in BML's water cap from 2013 to 2021. Shown are three profile intervals within the water cap

The second intervention was related to the formation of bitumen mats during the placement of FT into WIP (Syncrude 2022). Residual bitumen makes up a relatively small component of the fine tailings. When FT was placed in the mined-out pit, some residual bitumen separated from the FT, resulting in bitumen mats forming on the surface of the FT. The bitumen mats were primarily located in areas of the pit where tailings was discharged. As detected by the BML monitoring program, some residual bitumen is also present as a hydrocarbon sheen on the water surface, some of which accumulated along the shoreline. This sheen is a result of methanogenic bacterial consumption of residual hydrocarbon in the bitumen mat producing methane bubbles with attached bitumen being released at the air-water interface.

Sonar acoustic imagery, 'Ponar' grab sampling of the mudline, and visual observations of bitumen on the water surface and at the FT surface were used together to determine the location and extent of bitumen mats. Sampling efforts identified bitumen mats on the surface of the FT in areas of the lake where the FT was discharged, and evidence indicates these mats are not very thick (in the order of centimeters). These areas are important sources of bitumen to the water column, and it was determined that removal of these mats could lead to a significant improvement in the long-term performance of BML.

Hence, in 2018 and 2019, a horizontal auger dredge was deployed at BML to remove bitumen mats on the FT surface. This preliminary dredging effort has provided valuable information to design and develop a more efficient dredging operation using a mechanical clam-shell environmental dredge that was piloted in 2021. Efforts are currently on-going to develop in-situ monitoring techniques (such as ice core and gas detection techniques) to assess the effectiveness of the bitumen dredging operations in mitigating the hydrocarbon sheen that can negatively impact the ecological functions of the lake. Preliminary assessment indicates that the dredging operations may be effective in the bitumen mat removal and may help to reduce bitumen liberation to the lake water surface (Syncrude 2022). Technology development efforts are underway to develop more effective tools for detecting bitumen mats and monitoring gas-driven liberation of bitumen from the mats.

5 Conclusion

This paper presents the field data and numerical predictions to demonstrate that WCTT is a viable technology for the reclamation of oil sands tailings as an aquatic closure landform. It was successfully demonstrated that BML is meeting the short-term performance metrics of fines isolation and the water quality improving with time. Two adaptive management interventions related to managing the lake turbidity and sheen formation from bitumen mats were shown to be successful in stewarding the lake towards an acceptable short and long-term reclamation outcome. Research and monitoring of the parameters required to ascertain the longer-term closure and certification objectives of the lake (details in Syncrude 2022) are currently on-going. Also, a comprehensive and inter-disciplinary research program is on-going to better understand the evolving physical, chemical and ecological state of BML. Learnings from this research program will continue to inform future adaptive management interventions aimed at stewarding the lake towards achieving its long-term closure and certification goals. These learnings would also help to inform the design and operations of future water-capped tailings at Syncrude in particular and the Canadian mineable oil sands region in general.

Acknowledgement

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