Syncrude

June 27, 2019

By e-mail only: EPEA.Reports@aer.ca

Alberta Energy Regulator
2nd Floor, Provincial Building
9915 Franklin Avenue
Fort McMurray, Alberta
T9H 2K4

Attention: Charles MacDonald
Mining Authorizations, Manager Oil Sands West

Subject: Base Mine Lake Monitoring and Research Summary Report
Clause 6.1.98, EPEA Approval No. 26-02-00 (as amended)

Dear Sir,

The attached Base Mine Lake Monitoring and Research Summary Report is provided to the Alberta Energy Regulator (AER) by Syncrude Canada Ltd. (Syncrude) in accordance with clause 6.1.98 of *Environmental Protection and Enhancement Act* (EPEA) Approval No. 26-02-00 (as amended).

Please contact me if you have any questions regarding this submission.

Regards,

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2019 Base Mine Lake Monitoring and Research Summary Report: Results from 2013-2018

Environmental Protection and Enhancement Act Approval No. 26-02-00, as amended, clause 6.1.98

Submitted to:
Alberta Energy Regulator

Submitted by:
Syncrude Canada Ltd.

June 27, 2019

LIMITATIONS:

This report is provided by Syncrude Canada Ltd. to the Alberta Energy Regulator.

Findings and interpretations found in this report are superseded by any future Base Mine Lake report. This report represents the data and interpretations from data collected from BML commissioning (December 31, 2012) up to and including the year of the report. In future years, as more data are collected, understanding and interpretation of results may change. Please use the most current report for the most up-to-date information.

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1. INTRODUCTION

1.1. Regulatory Overview

1.1.1. Approval History

Pursuant to the *Oil Sands Conservation Act* (OSCA), in September 1992 Syncrude Canada Ltd. (Syncrude) submitted Application No. 921321 to the former Energy Resource Conservation Board (ERCB) to amend Mildred Lake Approval No. 5641. The application included plans for fluid fine tailings reclamation and identified water-capped fine tails as the preferred fluid tailings treatment option. The water-capped tailings technology (WCTT) was selected based on several years of research and development, including laboratory studies beginning in 1985 and a series of seven test ponds constructed in 1989, each containing approximately 1000 m^3 of fluid fine tailings.

In the response for additional information regarding Application No. 921321 issued by the ERCB on January 7, 1993, Syncrude indicated that a larger scale demonstration was under development which would more closely resemble the final water-capping scenario. The pilot plan included construction of a 200,000 m^3 demonstration pond into which 120,000 m^3 of fluid fine tails would be transferred.

During the hearing for Application No. 921321 in 1993, some stakeholders questioned whether the 200,000 m^3 demonstration pond would be large enough to provide the necessary information to verify and implement the water-capped tailings technology at full scale. In response to stakeholder concerns, Syncrude proposed a commercial scale test, which included the development of a lake containing roughly 150 Mm^3 of fluid fine tailings with a 5m water cap. This test became known as the Base Mine Lake (BML) demonstration.

In July 1994, Syncrude received the decision report for Application No. 921321 (Decision 94-5) from the ERCB, which was followed by OSCA Approval No. 7550 in November later that year. In the decision report, the ERCB indicated that it supported the full scale Base Mine Lake demonstration, as follows:

> *"The Board notes the considerable research and development work conducted by Syncrude in support of its water-capped fine tails reclamation concept. It is satisfied that the water-capped fine tails concept as proposed, appears to present a relatively low environmental risk and may represent the most cost effective method by which to address the reclamation of fine tails. While the Board finds that the work done to date is sufficient to satisfy it that the concept has a reasonable probability of success, the Board agrees with the interveners that additional development work is required to verify the performance of the technique and to work out some of the specific design parameters for the final lakes. The Board therefore supports the proposal by Syncrude to develop and implement a large scale demonstration lake as one of the means to dispose of fine tails produced from Syncrude's facility."*

Pursuant to the *Environmental Protection and Enhancement Act* (EPEA), in March 1995, Syncrude submitted Application No. 002-26 to the former Alberta Environmental Protection (AEP) to renew Mildred Lake Approval No. OS-1-78. The application included a conceptual life of mine closure and reclamation plan which included WCTT and the BML demonstration as key components, in alignment with the 1993 ERCB application and proceedings.

In December 1995, Syncrude received EPEA Approval No. 26-01-00 from AEP, which provided formal approval for the full-scale BML demonstration, as described below:

12.3.13 The Base Mine Lake described in the application is approved as a full-scale demonstration of the water-capped fine tails reclamation concept. Prior to June 30, 1996 the approval holder shall submit, for the approval of the Director of Land Reclamation, a detailed outline of a comprehensive research and monitoring program for the Base Mine Lake, addressing the objectives, methods and schedule of the program. The program shall be developed in consultation with all stakeholders.

1.1.2. Monitoring and Research

As required under clause 12.3.13 of EPEA Approval No. 26-01-00, Syncrude submitted a Base Mine Lake Research and Monitoring Plan to AEP on June 26, 1996. In November 2012, Alberta Environment and Sustainable Resource Development (AESRD) requested additional monitoring and research plans through the issuance of EPEA Approval No. 26-02-05, as follows:

6.1.91 The approval holder shall submit a Base Mine Lake Monitoring Plan to the Director by December 15, 2012, unless otherwise authorized in writing by the Director.

6.1.92 The approval holder shall submit a Base Mine Lake Research Plan to the Director by November 15, 2013, unless otherwise authorized in writing by the Director.

6.1.93 The objective of the Base Mine Lake Monitoring Plan and Base Mine Lake Research Plan referred to in subsections 6.1.91 and 6.1.92 is to determine, by information collected through monitoring and research, whether or not water capped fine tailings will be a viable tailings management, remediation and reclamation option at the Mildred Lake Plant Site.

Syncrude submitted the BML Monitoring Plan on December 14, 2012 pursuant to clauses 6.1.91, 6.1.93 and 6.1.94. Syncrude submitted the BML Research Plan on November 8, 2013 pursuant to clauses 6.1.92, 6.1.93, and 6.1.95. The plans have been executed annually since 2013.

1.1.3. Reporting

The issuance of EPEA Approval No. 26-02-05 required Syncrude to submit a biennial BML summary report, as follows:

> *6.1.98 The approval holder shall submit a Base Mine Lake Monitoring and Research Summary Report to the Director by March 31, 2015, and every two years thereafter, unless otherwise authorized in writing by the Director.*

This report is the third submission to satisfy this requirement. Pursuant to EPEA Approval 26-02-00 (as amended) the purpose of this report is to summarize key findings and interpretations from the BML Monitoring and Research Program (MRP) during the 2017 and 2018 seasons (October 31, 2016 to November 1, 2018) which are the fifth and sixth years of BML operation, post-commissioning. Monitoring results are presented in Section 5.0 and research results are presented in Section 6.0 of this submission.

Table 1-1 outlines the BML monitoring and research reporting requirements per clause 6.1.99 of EPEA Approval No. 26-02-00 (as amended) and the sections in this submission which satisfy the requirements.

Table 1-1: Concordance Table

Requirement	Section
The Base Mine Lake Monitoring and Research Summary Report referred to in subsection 6.1.98 shall include the following, unless otherwise authorized in writing by the Director:	
(a) a summary of the results of monitoring for the previous two years;	3.0 5.0
(b) a summary of the results of research for the previous two years;	6.0
(c) a description and presentation of trends across all timeframes;	3.0 4.0 5.0 6.0
(d) updates to the Base Mine Lake Monitoring Plan as necessary;	N/A
(e) updates to the Base Mine Lake Research Plan as necessary, including a description of research continuing and planned for the next five year period; and	2.2.2.2 6.0
(f) any other information as required in writing by the Director.	N/A

1.2. Water Capped Tailings Technology (WCTT)

BML is the first, and currently the only full-scale commercial demonstration of the end pit lake technology in the oil sands industry. An oil sands end pit lake (EPL) is an area where overburden and oil sand has been removed and is then filled with fluids prior to closure. An EPL contains water (from the process of oil sands extraction or freshwater or both) and may or may not contain treated or untreated fluid tailings (FT), or other solids (for example, coarse tailings sand, or overburden).

BML is located in the former West In-Pit (WIP) of the Syncrude Mildred Lake (Base Lease) operation (Figure 1-1). It consists of a mined out oil sands pit filled with untreated fluid fine tailings (FFT). Fluid fine tailings are comprised of silt, clay, process-affected water and residual bitumen. The FFT is physically sequestered below a combination of oil sands process-affected water (OSPW) and fresh water. This pit lake configuration is often referred to as Water Capped Tailings Technology (WCTT). Based on previous research and modelling, the prediction for WCTT is that with time, EPL water quality improves and the fluid tailings (or other tailings) will remain sequestered below the water cap.

Freshwater is pumped in to Base Mine Lake from the Beaver Creek Reservoir (BCR) and as required, water is pumped out of BML to the tailings recycle water system (RCW) where it is utilized in the bitumen extraction process. This flow through process dilutes the BML water cap over time and will be in place until a more substantial upstream surface watershed is reclaimed and connected to BML, and outflow is established into the Athabasca River. As the tailings continue to dewater over time, the lake water will get deeper.

Placement of fluid tailings began in 1995, was completed in late 2012, and BML was commissioned as of 31 December 2012. No tailings solids were added after this time. During 2013, fresh water and OSPW was added to the existing OSPW upper layer to attain the final water elevation.

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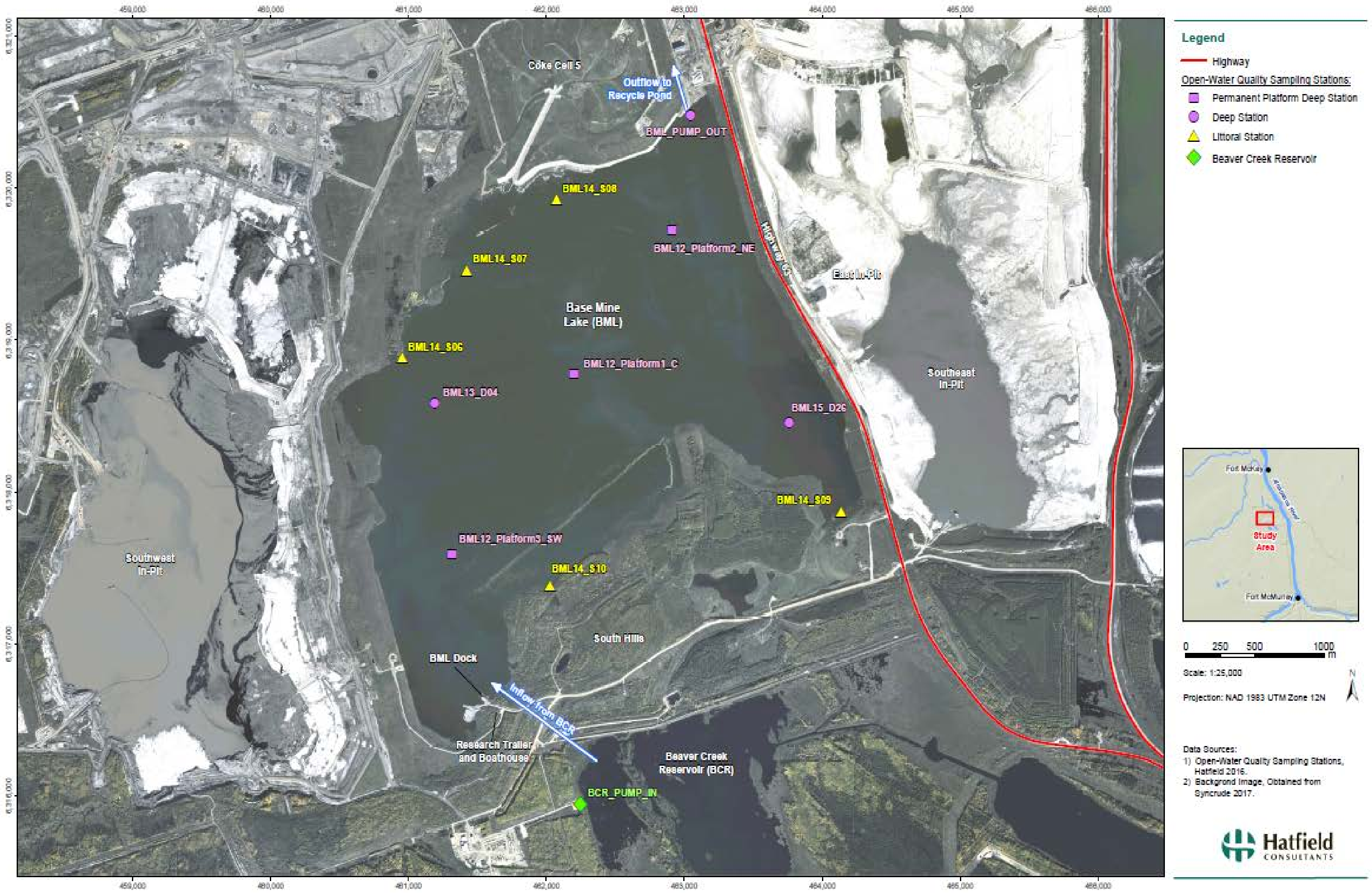


Figure 1-1: Base Mine Lake Overview

2. ADAPTIVE MANAGEMENT APPROACH FOR BML

2.1. Adaptive Management: A decision making framework

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 2-1). Adaptive management is a "learn by doing" approach, not a "trial and error" approach. There are 4 key components to the cycle: Plan, Do, Evaluate & Learn, and Adjust. Each of these will be described more specifically for Base Mine Lake in the following sections.

Figure 2-1: The adaptive management cycle (after Jones 2005)

2.2. Adaptive Management Approach for Base Mine Lake

The Adaptive Management approach for Base Mine Lake has allowed for flexible decision making and management actions to steward the lake to its closure outcomes. Some key components of the adaptive management framework as applied specifically to BML are described below.

2.2.1. Plan

The Plan component of the adaptive management cycle is key to success. We have defined management objectives, which are to validate Water Capped Tailings Technology, and ensure the lake becomes a functioning component of the closure landscape. Key outcomes and performance indicators are described in more detail below.

2.2.1.1. Key desired outcomes

In general, pit lakes will support ecological functions and lake specific wildlife habitat. The specific end land use goal for Base Mine Lake is that the lake will support lake ecological functions, including sustainable small-bodied fish populations (Syncrude 2016). Base Mine Lake is expected to support conventional boreal lake functions, with water quality capable of supporting typical lake algae, plants and macroinvertebrates. Small bodied fishes will be able to survive in the lake- there will be enough biomass (food) and dissolved oxygen to support small bodied fish populations (Syncrude 2016).

2.2.1.2. Performance indicators

In order to support the adaptive management cycle, it is important to identify performance indicators that will help guide management decisions. There are two key milestones for Base Mine Lake each with unique performance indicators. In the short term, performance indicators are associated with validation of Water Capped Tailings Technology, and in the longer term performance indicators for Certification are appropriate. It is important to identify longer term performance indicators at early stages so that management decisions are made with these progressive milestones in mind. Management decisions to achieve technology validation cannot come at the expense of longer term certification outcomes. The lake is expected to change over time, and performance expectations for each milestone are necessarily different.

2.2.1.2.1. Shorter term: Performance Indicators to Validate Water Capped Tailings Technology

Validation of Water Capped Tailings Technology will require demonstration that the lake water quality is improving with time and that the fines are physically sequestered beneath the water cap.

The water cap should not be acutely toxic, as demonstrated by appropriate standard Acute Lethality tests as described in Environment Canada Biological Test Methods. The water should also pass appropriate CCME Canadian Water Quality Acute Guidelines for the Protection of Aquatic Life

(CCME, 2014c), and Environmental Quality Acute Guidelines for Alberta Surface Waters (EQGASW) (AEP 2018). 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. Although TSS in the water column is expected to fluctuate seasonally with mixing events, TSS should show improvements over time.

2.2.1.2.2. Longer Term: Performance Indicators to Support Certification of BML

Certification of BML will require demonstration that the lake is a functioning component of the closure landscape with water quality appropriate to support the desired end land use and to provide lake specific wildlife habitat.

Existing guidelines that are appropriate as Performance Indicators to support certification of BML include: CCME Canadian Sediment Quality Guidelines for the Protection of Aquatic Life (CCME, 2014a), CCME Canadian Water Quality Chronic Guidelines for the Protection of Aquatic Life (CCME, 2014c), Environmental Quality Chronic Guidelines for Alberta Surface Waters (EQGASW) (ESRD, 2014), and CCME Canadian Tissue Residue Guidelines for the Protection of Wildlife that Consume Aquatic Biota (CCME, 2014b). The PAL water Quality Guidelines for Dissolved Oxygen will be particularly important for ensuring the lake can support small-bodied fish populations. Site specific standards for select parameters may need to be developed as provided for by the CCME and EQGASW (Syncrude 2016).

2.2.2. Do and Evaluate & Learn: BML Monitoring and Research Program

A key purpose of the BML Monitoring and Research Program (MRP) is to support the adaptive management framework. The BML MRP 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 water-capped tailings technology, and to provide a body of scientific evidence that demonstrates that BML is on a trajectory to become integrated into the reclaimed landscape. The outcomes from the BML MRP can be used to inform the design and management of future pit lakes, including those that may contain tailings materials, such as treated or untreated fluid tailings. At the same time, the program establishes a baseline of biophysical data to assess the changes in BML through time, and the state of the lake at certification, including water quality and other lake processes. The monitoring program is designed to track trends in the lake both seasonally and annually, and measure these trends against some key performance metrics as outlined above. The research program focuses on key scientific questions designed to elucidate the mechanisms and processes that govern the current state of BML, and explain changes detected by the monitoring program. In other words, the monitoring program tracks the trends in the lake through time, and the research program investigates why those changes are occurring.

Syncrude recognizes three categories of monitoring: 1) Compliance 2) Adaptive Management/Validation and 3) Continuous improvement research and monitoring. Components of the BML Monitoring Program fit into one or more of these categories. Each is described below.

1. *Compliance Monitoring*

   Compliance monitoring is data collection used to support compliance with regulatory approvals or other policy requirements (including certification assessments).

2. *Adaptive Management/Validation Monitoring*

   This refers to data collection to support plan stewardship and adaptive management actions and is critical to support technology validation. It also tracks rates of progress towards certification criteria and permits early intervention when there are performance deviations.

3. *Continuous Improvement Research and Monitoring*

   Continuous improvement research and monitoring involves a combination of monitoring, assessments, and focused studies. This includes the learnings from results of compliance monitoring, plan stewardship, and adaptive management monitoring.

These three components are integrated, such that lessons learned from research are used to inform future monitoring programs, as well as support validation and corrective/preventive measures. Trends and information obtained from the compliance monitoring program will guide priorities for the research program.

This integrated BML MRP supports the adaptive management of BML performance to ensure attainment of key desired outcomes. The BML MRP also provides knowledge and guidance valuable to the integration of other pit lakes in the region. The MRP is supported as a COSIA Joint Industry Project (JIP) under the Water Environmental Priority Area (WEPA). Industry partners that contribute to the BML MRP include Suncor Energy Inc., Canadian Natural Resources Limited, and Imperial Oil.

2.2.2.1. Base Mine Lake Monitoring Program

The specific objective of the BML Monitoring Program is to provide information to support the validation of WCTT as a viable tailings management and reclamation option. In the early stages, the BML Monitoring Program will demonstrate that fluid fine tailing 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. The physical, chemical and biological components of the program are summarized in the following table.

Table 2-1: BML Monitoring Program Components

Physical	Chemical	Biological
FFT Settlement	Water Balance Assessment	Aquatic Biology Assessment Surface Water Toxicity
FFT Geochemistry Assessment	Surface Water Quality Assessment	Sediment Toxicity
Physical Limnology Assessment	Groundwater Assessment	
Meteorological Monitoring	Chemical Mass Balance	
FFT Physical Assessment		

2.2.2.2. Base Mine Lake Research Program

The BML 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 Water Capped Tailings Technology (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 FFT to the water column, including chemical, geochemical, mineral, gases and heat. Physical, biological and chemical mechanisms are being investigated. Further details of this research are provided below.

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). The research programs, associated principal investigators (PIs) and participating universities are summarized in Table 2-2: BML

Research Program below. A list of peer reviewed publications and theses from the research programs is provided in Section 6.7.

Table 2-2: BML Research Programs

Research Component	Primary Objective	University	Researchers (PIs)
Physical limnology of BML and the potential for meromixis	*To understand the circulation of BML and its potential for meromixis*	*University of British Columbia*	*Greg Lawrence / Ted Tedford / Roger Pieters*
Characterization of controls on mass loading to an oil sands end pit lake	*To define mass loading to Base Mine Lake by characterizing the mechanisms and distribution of heat and mass transfer from the tailings column to the overlying water column.*	*University of Saskatchewan*	*Lee Barbour / Matt Lindsay*
Laboratory studies investigating chemical flux across tailings-cap water zones, simulating an end pit lake in the Athabasca oil sands region	*To quantify physical and biogeochemical processes in a laboratory system simulating an EPL*	*University of Alberta*	*Ania Ulrich / Morris Flynn / Tariq Siddique*
Laboratory studies investigating light penetration in Syncrude's Base Mine Lake water	*To understand water column turbidity and mitigation in laboratory mesocosms*	*University of Alberta*	*Ania Ulrich*
Field investigation of BML water cap oxygen concentrations, consumption rates and key BOD/COD constituents affecting oxic zone development.	*To establish temporal and spatial variability in in situ BML water cap oxygen concentrations, oxygen consumption rates and identify the biogeochemical processes linked to its consumption from the FFT-water interface to the BML water surface*	*University of Toronto / McMaster University*	*Lesley Warren / Greg Slater*

Research Component	Primary Objective	University	Researchers (PIs)
Microbial communities and methane oxidation processes in Base Mine Lake	*i) To study Biological Oxygen Demand (BOD) in the lake, ii) to examine a potential role of methanotrophs in the degradation of naphthenic acids (NAs), and iii) to examine the microbial community in BML, how the community changes over time with changes in lake chemistry, and the potential use of community analyses as an indicator of reclamation*	*University of Calgary*	*Peter Dunfield*
Understanding Air-Water Exchanges and the long-term hydrological viability of Base Mine Lake	*To measure and improve the understanding of the physical mechanisms controlling CH_4 and CO_2 fluxes across the air-water interface, to determine the factors that control evaporation from BML and to understand the long-term water balance of BML*	*McMaster University / Carleton University*	*Sean Carey / Elyn Humphreys*

2.2.3. Adjust: Examples of management actions

The adaptive management framework allows for adjustment to lake management when an evaluation and assessment of performance does not match expectations. These management actions are undertaken to steward the lake to key desired outcomes. To date, there have been two adaptive management actions taken to improve BML performance: application of alum to manage mineral turbidity, and hydrocarbon mitigation.

2.2.3.1. Alum application to reduce turbidity

Since commissioning, turbidity in the lake was dominated by mineral solids. In response to the results of the first four years of monitoring, alum was added to BML for the management of the mineral turbidity in the lake. This trial occurred in September 2016 during fall turnover to take advantage of lake mixis. Light penetration (water clarity) was determined to be an important parameter to track in the BML MRP, for several reasons. First, mineral turbidity in the lake is a result of suspended fine mineral particles, and clear water could indicate that residual fines left in the water column from pit filling have settled out of suspension. In addition, a clear water column allows sunlight penetration, which is critical for algal primary production in the lake.

Monitoring results indicate that the alum dosage was effective at reducing turbidity. The monitoring program will continue to track turbidity and the expectation is that turbidity will fluctuate with lake mixing events, but turbidity will continue to decline with time. If lake performance does not meet this expectation, further management actions may be considered as part of the ongoing adaptive management cycle presented previously in Figure 2-1.

2.2.3.2. Hydrocarbon mitigation

Residual bitumen is a minor component of the fluid fine tailings (FFT). When FFT was placed in the mined-out pit, some of this residual bitumen separated from the FFT, resulting in bitumen mats on the surface of the FFT, focused in areas of the lake where the tailings was discharged. Some residual bitumen is also present as an oily sheen on the water surface, some of which has accumulated on the shore. This was detected by the BML Monitoring Program.

During the winter of 2017/2018, efforts were undertaken to trial the removal of residual bitumen from the shoreline. An extensive sampling program indicated that the bitumen was sitting on the surface of the shoreline soils and was not imbedded throughout the soil. In January 2018, 300 metres of shoreline was the focus of bitumen removal activities. Equipment was used to strip the hydrocarbon from the surface of the soil without damaging the reclamation soils below. Both the timing of the removal (frozen conditions) and selection of smaller equipment minimized the effects on surrounding reclaimed shoreline and slopes.

To determine the extent and location of bitumen mats on the surface of the FFT, sonar acoustic imagery, ponar grab sampling of the mudline, and observations of bitumen on the water surface and at the FFT surface were used together to determine the location and extent of bitumen mats. Sampling identified bitumen mats on the surface of the FFT in areas of the lake where the FFT was poured, and evidence indicates these mats are not very thick (centimetres in thickness). 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. A horizontal auger dredge was deployed in the fall of 2018 to target removal of bitumen mats on the FFT surface. This preliminary dredging effort has provided valuable information to design and implement a more intensive dredging effort through the open water season of 2019. The BML MRP will help to determine the effects that bitumen mat removal through dredging have on lake performance in both the short- and the long-term.

3. KEY PERFORMANCE RESULTS FOR BML

The two key desired outcomes for BML that are important for the validation of the technology are the physical sequestration of the fine tailings below the water cap and water quality improvements over time. Key results demonstrating these two key outcomes are discussed below.

3.1. Physical sequestration of FFT

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 FFT 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.

3.1.1. FFT Settlement and Pore-water Release Projections

The rate and magnitude of settlement of the FFT within BML is an important driver for the rate and magnitude of advective transport of pore-water constituents from the FFT into the overlying water cap. In turn, this flux has direct implications for the chemistry and ecological evolution of the water column. Hence, a forward projection of this rate and magnitude is an important component of operating and adaptively managing BML to ensure successful stewardship to the desired closure outcomes.

In 2006/2007 a numerical prediction of the settlement and water release from the BML was completed (herein referred to as Carrier *et al.* 2007). This occurred prior to the complete in-filling of West In-Pit (WIP) and subsequent commissioning as BML. As a result, a number of assumptions were made, including the total tonnage of fluid fine tailings that would have been discharged into WIP at BML commissioning. It was forecasted that a total of 104.6 million dry tonnes (MT) of FFT would have been deposited at the end of filling of WIP. This would represent a perfect filling of the lake to an average elevation of 303.7 masl, based on an assumed average annual filling of 6.15 MT of FFT over a 17 year period (1995-2012).

BML was geometrically represented in the model as a 1-dimensional parallelepiped, with an equivalent surface footprint of 5.62 million m^2 and an effective bottom elevation at 264.5 masl. The prediction of settlement was completed for up to 40 years after the end of deposition (2052), and recently extended to 100 years (2112) after the end of deposition by Carrier and Shaw 2019. The material input parameters for the numerical model are shown in Figures 3-1 and 3-2. Both the compressibility (Figure 3-1) and hydraulic conductivity function (Figure 3-2) were based on a back-analysis of laboratory consolidation data and field observations of the FFT in WIP.

The resulting prediction of the settlement of the FFT is shown in Figure 3-3. A total average settlement of 17.5 m after 100 years is shown, with cumulative ultimate settlement of 19.7 m. A comparison of the numerical prediction of cumulative water release with measurements based on annual surveys of the FFT in BML is shown in Figure 3-4. The predicted cumulative water release is shown to be in agreement with corresponding field measurements from BML. A total of 98.5 million m^3 of water is projected to be released from the FFT after 100 years. Hence, it can be concluded that the assumptions and input parameters for the Carrier *et al*. 2007 predictions were reasonable, as the ensuing numerical predictions agree reasonably well with field measurements made from BML since 2012.

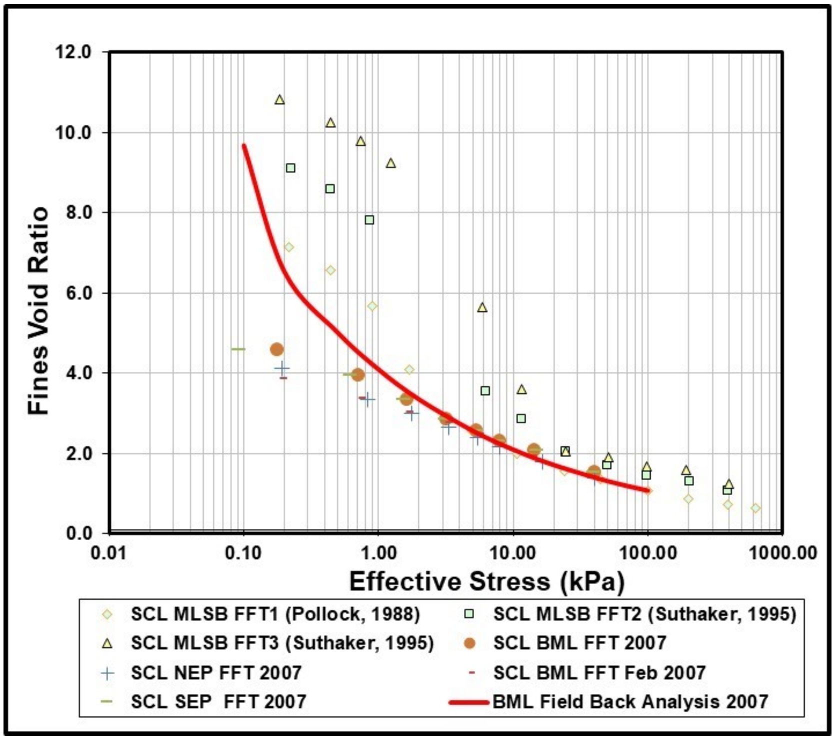


Figure 3-1: Compressibility of the FFT input into the Carrier *et al*. 2007 model. The red line represents the best fit to several analytical data of input FFT into BML.

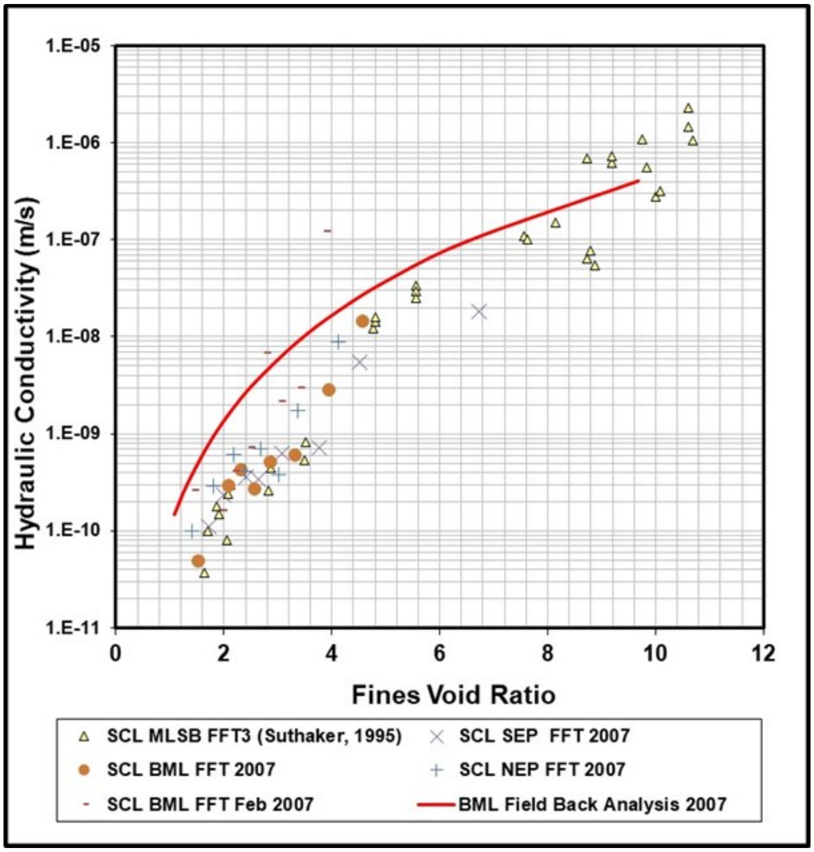


Figure 3-2: Hydraulic conductivity function of the FFT input into the Carrier *et al*. 2007 model. The red line represents the best fit to the numerous analytical data of input FFT into BML.

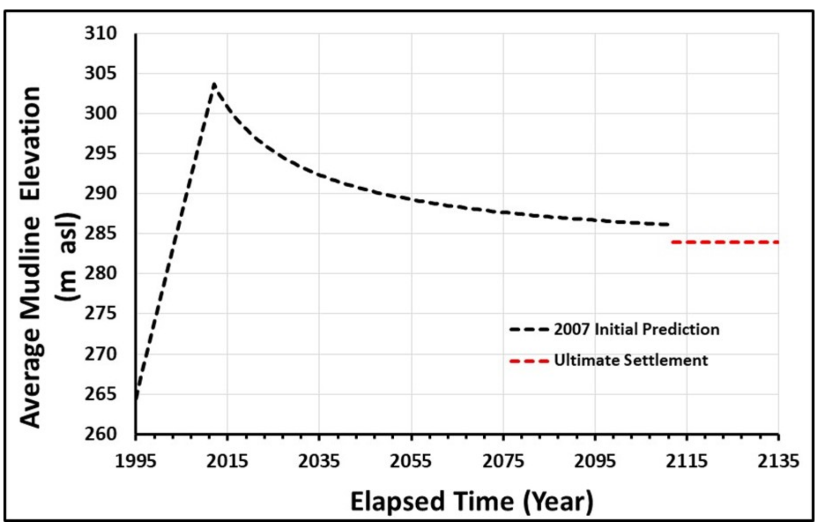


Figure 3-3: Settlement of the FFT over time as predicted by Carrier *et al*. 2007 model. The red line represents the ultimate settlement of the input FFT into BML.

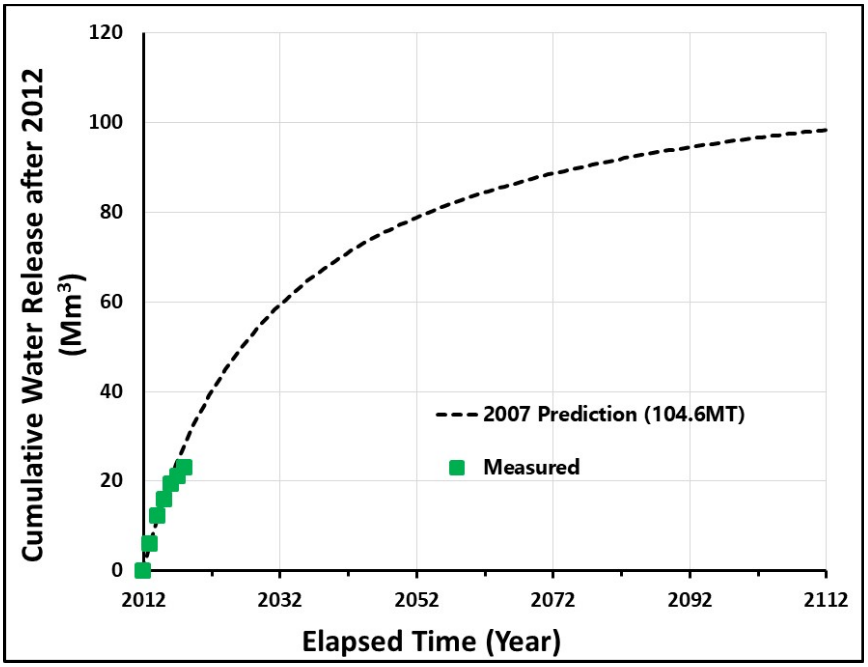


Figure 3-4: Cumulative water release from the FFT over time as predicted by Carrier *et al*. 2007 model compared to cumulative measurement based on annual surveys of the FFT in BML.

The Carrier *et al.* 2007 prediction was recently updated by Carrier and Shaw 2019. The update was necessary because the forecast tonnage input of 104.6 MT of FFT based on the Carrier *et al.* 2007 analysis was not the same as the actual total tonnage of FFT input to BML. A re-analysis of the 2012-2017 FFT sampling data estimates the tonnage input of FFT into BML at 94.8 MT. Consistent with the principle of continuous improvement, the Carrier *et al.* 2007 projection was then updated with the initial tonnage revised to 94.8 MT. All other input parameters, including the geometry and material properties (Figures 3-1 and 3-2), were kept unchanged.

The revised predicted cumulative settlement was determined to be 14.6 m after 100 years following the end of deposition (Figure 3-5). As expected, this is slightly lower than the Carrier *et al.* 2007 predicted cumulative settlement of 17.5 m due to the lower initial tonnage input into WIP. The corresponding cumulative water release predicted by Carrier and Shaw 2019 is shown to be 81 Mm^3 after 100 years, less than the 98.5 Mm^3 from the previous prediction (Figure 3-6). The predicted cumulative water release by both the Carrier *et al.* 2007 and Carrier and Shaw 2019 models are shown to agree well with the measured cumulative water, with the latter showing relatively better agreement (Figure 3-6).

In summary, the Carrier *et al.* 2007 model was based on an over-estimate of the fines tonnage input into WIP. This tonnage was revised in 2019, based on FFT profile sample data collected from BML from 2012 to 2017. The 2007 model was then revised with the new fines tonnage in 2019. Both the 2007 and 2019 models showed good agreement with the FFT settlement as well as the cumulative water released from the FFT into the water cap. Hence, it is concluded that the material properties of the FFT that form the basis of the numerical models in 2007 and 2019 are appropriate. Also, the FFT in BML is settling and releasing pore-water as expected.

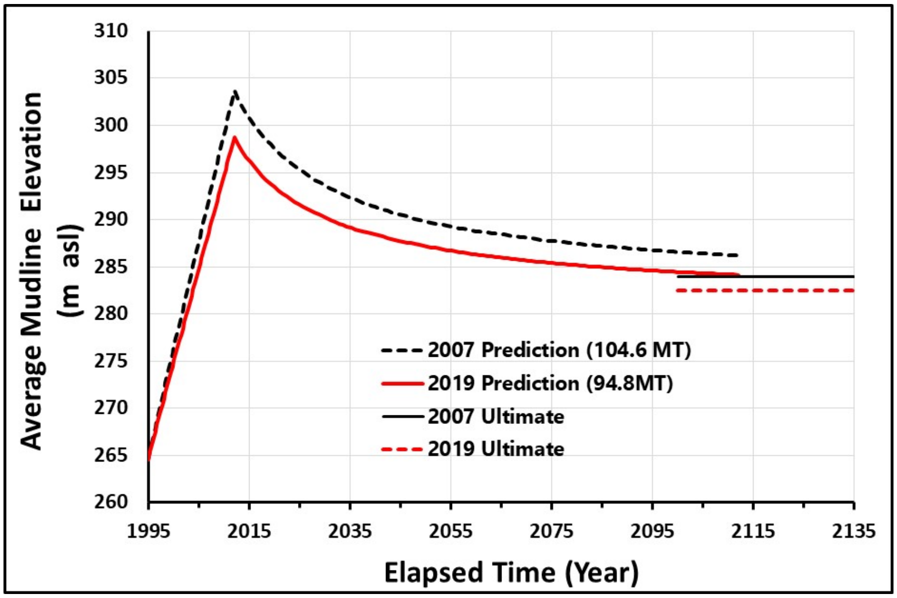


Figure 3-5: Settlement of the FFT over time as predicted by Carrier and Shaw 2019 compared to prediction by Carrier *et al.* 2007 model. The continuous black and dashed red lines represent the respective ultimate settlement of the input FFT into BML.

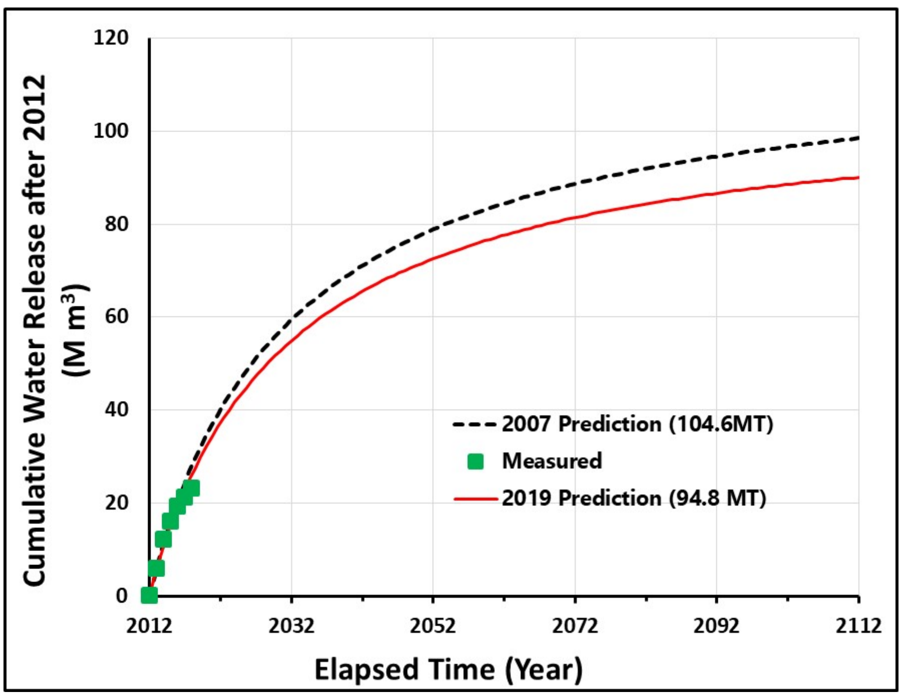


Figure 3-6: Cumulative water release from the FFT over time as predicted by Carrier *et al*. 2007 and Carrier and Shaw (2019) models compared to cumulative measurement based on the annual survey of the FFT in BML.

3.1.2. Physical Assessment of the FFT

A range of physical parameters of the FFT have been assessed in BML over time. Some key results that are directly linked to demonstrating physical sequestration of the FFT are described here. In situ geotechnical testing performed in BML shows the FFT peak undrained shear strength (S_u) approximately ranges from 0.5 to 1 kPa in most testing locations within the lake (Figure 3-7). Figure 3-7 shows the sharp transition of measureable S_u, right at the mudline, implying the distinctiveness of the mudline. This distinctive mudline is corroborated by the sharp contrast of the fluid samples collected above and below the mudline as shown by Figure 3-8. A statistical analysis of Oil Water Solids (OWS) data demonstrated that overall, the solids contents (SC) of the FFT is higher in 2017 than in previous years (Figure 3-9). This pattern of S_u and SC is consistent with both the prediction and measurement of the FFT settling with time as previously discussed.

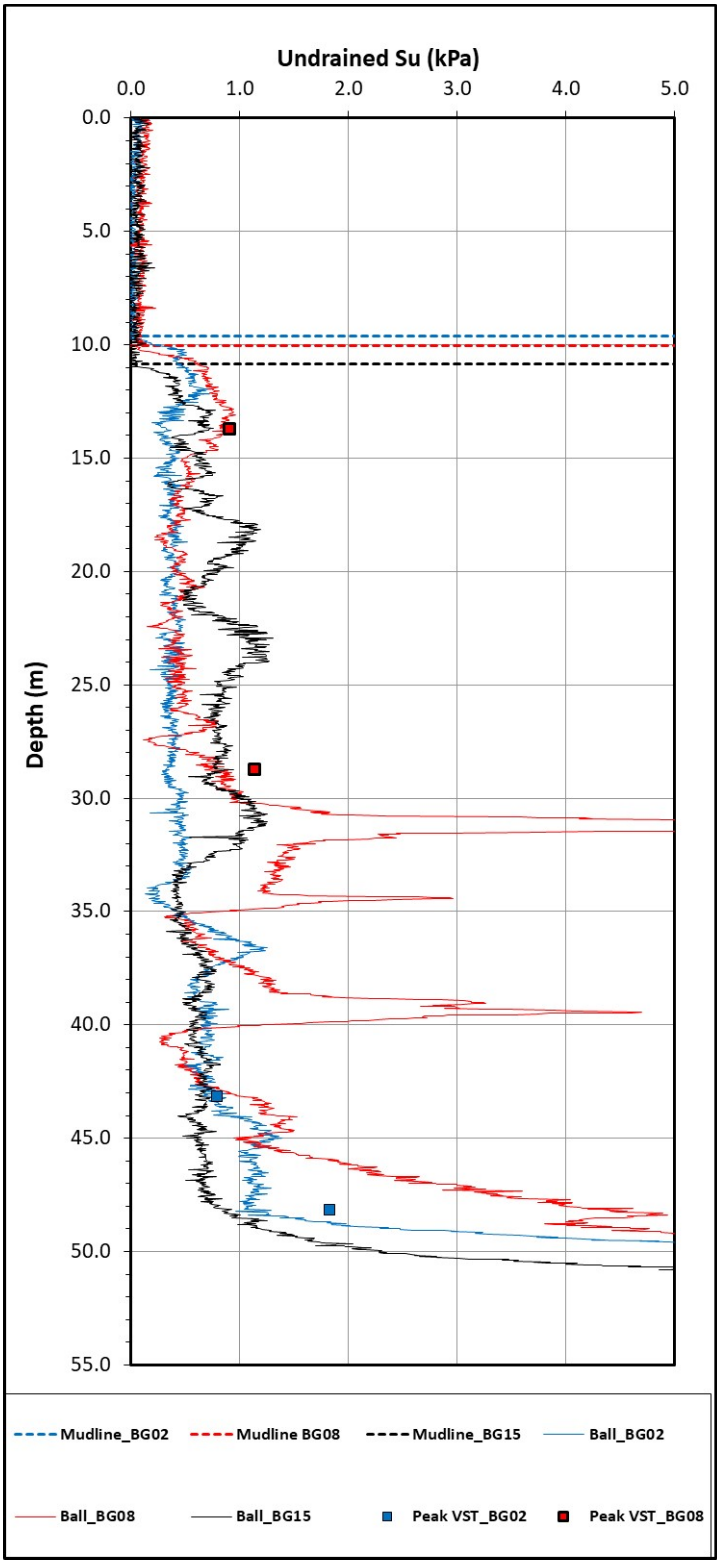


Figure 3-7: Profiles of undrained shear strength in three sampling locations in BML completed in 2017, with Ball CPT (BGCPT) and peak electronic vane shear tests (Peak VST) shown. Also shown is the respective mudlines at the testing location.

Figure 3-8: Samples extracted via Fixed Interval Sampling method. Note the distinct difference in appearance between samples from the water cap (on the left) vs. samples from beneath the mudline (on the right).

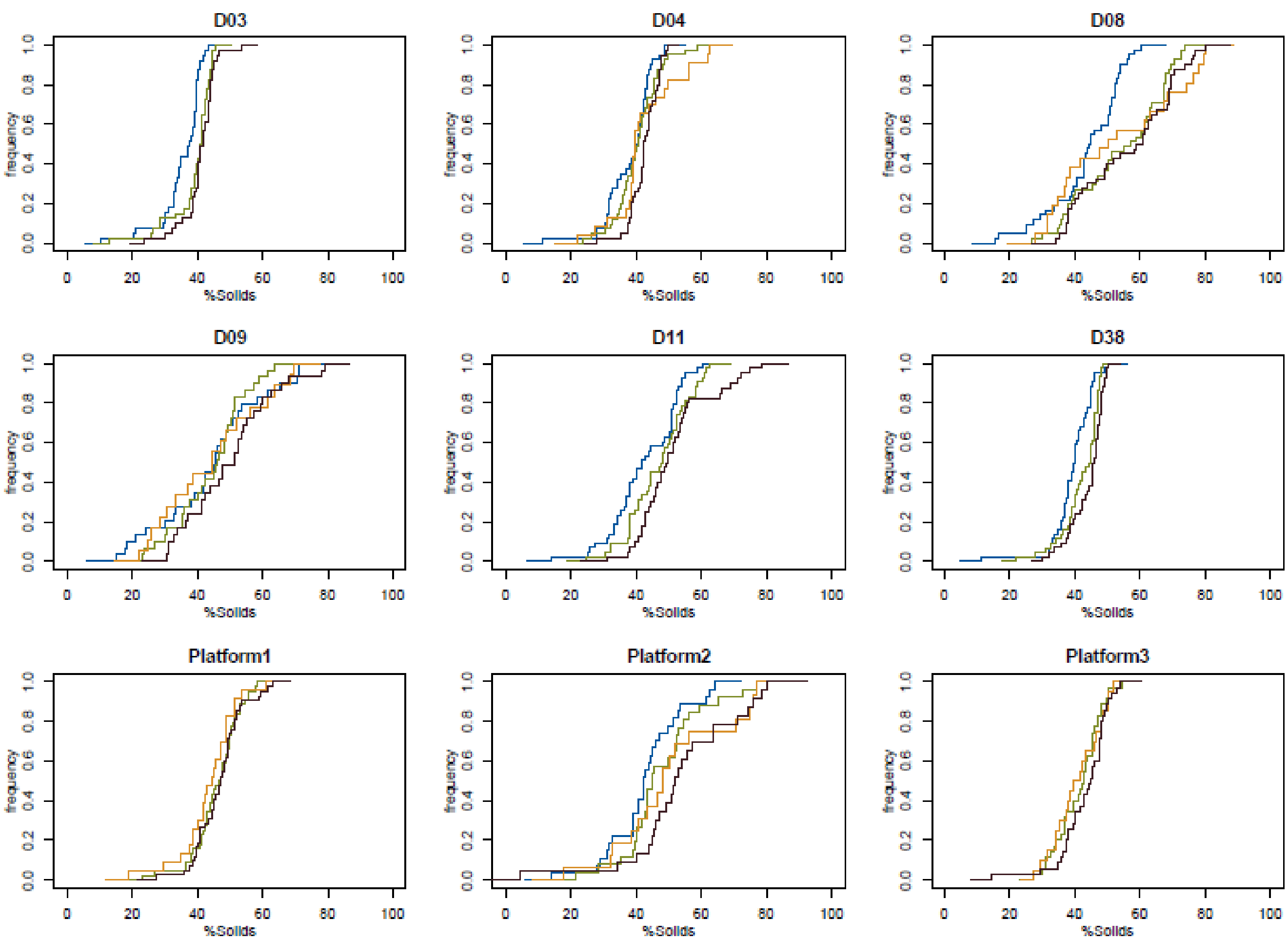


Figure 3-9: Empirical cumulative distribution functions of the percent mineral solids in year 2012, 2013, 2014 and 2017, plotted in blue, green, orange and black colour, respectively.

3.1.3. FFT settlement and change in water cap depth over time

The surface of the FFT continues to settle annually, and the overall water depth in BML increases at a corresponding rate, taking into account lake surface elevation changes. Overall settlement of the FFT surface is continuing as expected. The magnitude of cumulative settlement in BML since 2012 has been up to 6 m. The volume of FFT in BML decreased from 174.86 Mm^3 in October 2017 to 172.91 Mm^3 in October 2018 due to settlement. The change in FFT surface elevation from October 2012 to October 2018 is shown in Figure 3-10.

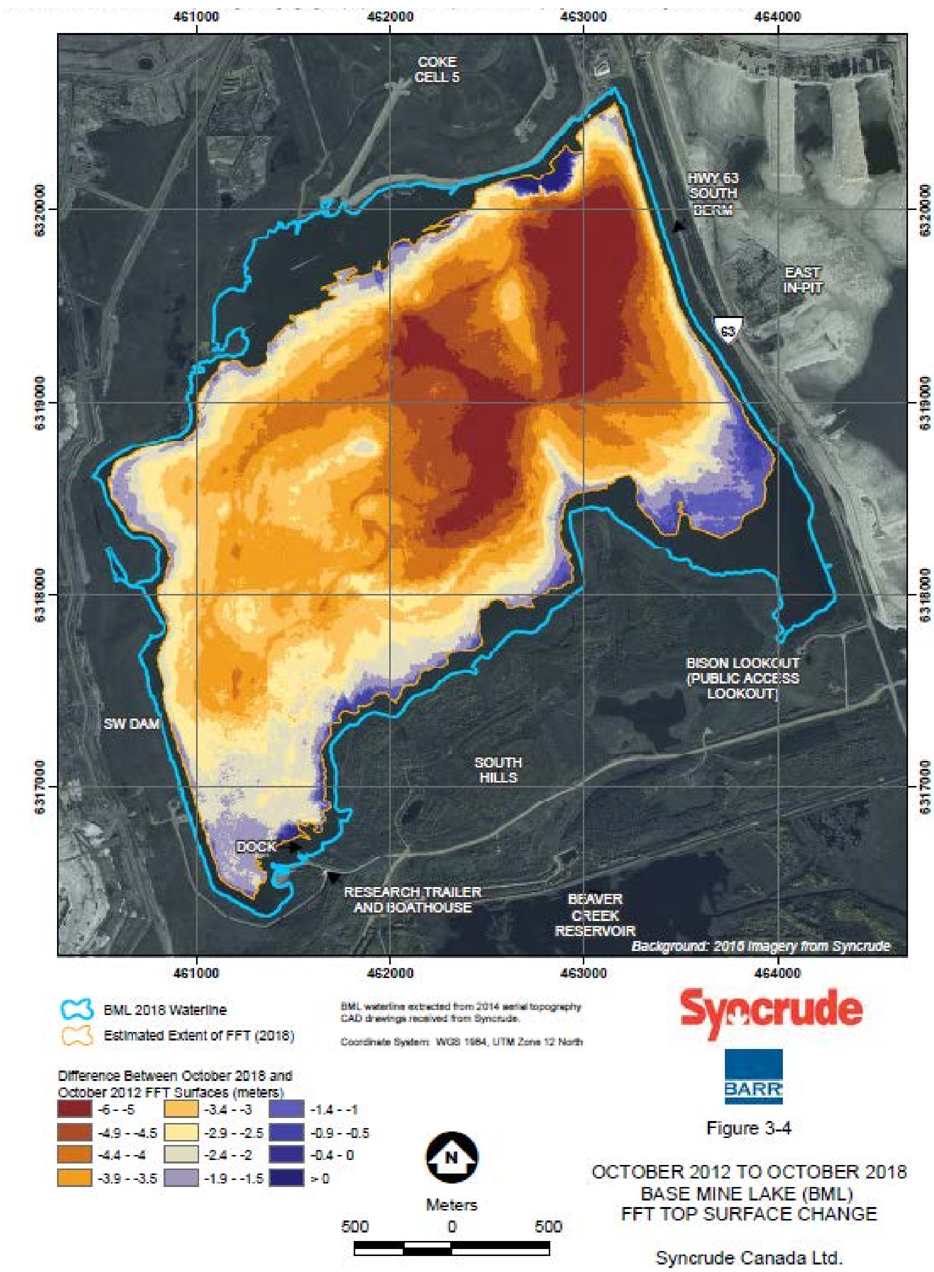
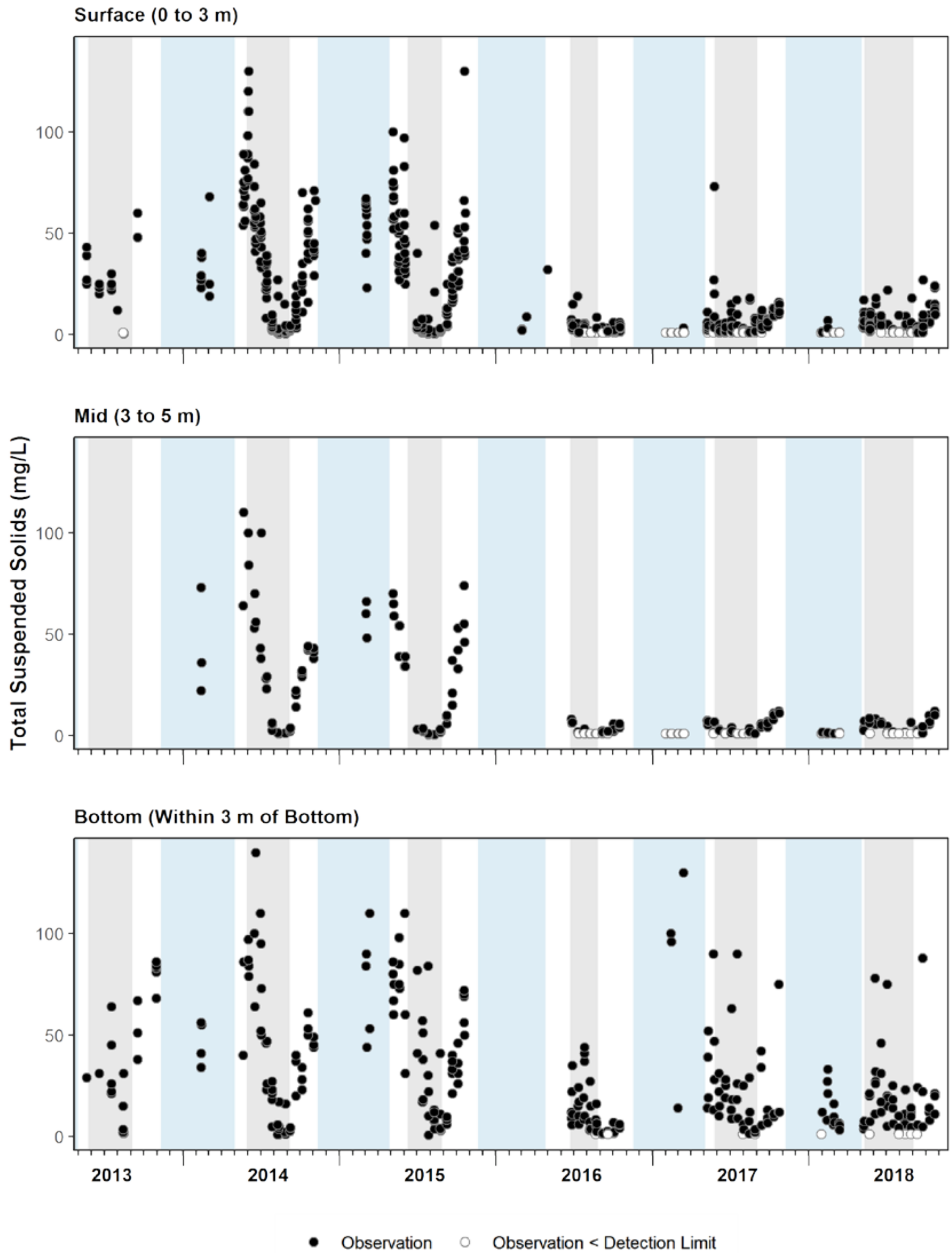


Figure 3-10: Change in surface of FFT in Base Mine Lake between October 2012 to October 2018

3.1.4. Temporal trends in Total Suspended Solids in the BML water cap

Total Suspended Solids (TSS) concentrations in BML remained relatively high from 2013 through 2015, before decreasing and becoming more stable from 2016 through 2018 (Figure 3-11). Seasonal variations in TSS concentrations were apparent in BML in 2018, with median concentrations measuring 1.1 mg/L in winter, 5 mg/L in spring, 4 mg/L in summer, and 6.9 mg/L in fall. This seasonal trend was consistent with previous years, with the exception of 2016 when the alum treatment caused TSS concentrations to decrease between the summer and fall sampling events.

TSS has also shown vertical variations over the monitoring years, with less stable and higher concentrations near the bottom of the lake (Figure 3-11). It is important to note that there is no evidence of an increase in TSS since commissioning, which indicates that the fines are physically isolated beneath the water cap. In contrast to previous years, there were no unusually high near-bottom TSS concentrations recorded in 2018 (an individual max of 190 mg/L TSS in 2018 vs 5,600 mg/L TSS in 2017). The more consistent TSS measurements in recent years may be due to a more distinct FFT-water interface, allowing for better delineation of the water-FFT interface in advance of near-bottom water sampling. This aligns with the empirical evidence that the FFT is settling and strengthening as expected over time.



Ice-covered (blue) and stratified (grey) periods shown as filled areas on each panel.
Guideline for TSS is based on background condition, and therefore not presented.
Scale adjusted to focus on overall trends; full-scale plot presented in Appendix A5.2.

Figure 3-11: Annual Trends in Total Suspended Solids (TSS) in mg/L with depth in Base Mine Lake.

3.2. Surface Water Quality improvements

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. Except for F2 hydrocarbons (where the guideline value is interim and derived from soil guidelines) all parameters measured are below Alberta Surface Water Quality short term guidelines for the Protection of Aquatic Life. Some key performance outcomes are summarized below.

3.2.1. Water column toxicity evaluation

Water toxicity testing assesses lethal or inhibitory effects that BML water may have on representative aquatic organisms. These tests are laboratory assays that use standardized methods to assess the relative toxicity of a water sample on cultured bacteria, algae, aquatic vascular plants (i.e. macrophytes), benthic invertebrates, zooplankton, and fish. Survival endpoints report the proportion of test organisms that survive over a fixed duration. The measurement endpoints (e.g. LC50) are estimates of the concentration of exposure medium (i.e. BML water) that results in a lethal or sub-lethal effect on test organisms, with increasing concentrations representative of decreasing effects on test organisms. Water toxicity results for 2018 and a description of trends since commissioning are summarized in Table 3-1.

Since monitoring was initiated in 2013, chronic toxicity effects have been observed for some test organisms, while acute toxicity has not been observed in BML since the summer of 2014. The lake is not acutely toxic. No clear seasonal trends in chronic toxicity have been evident since the onset of monitoring in 2013, with standard deviations between years and months overlapping across most test organisms. In 2018, toxicity effects of BML water were within the range of results from previous years.

3.2.2. Improvement in Chloride concentration since commissioning

Chloride has remained the dominant anion in BML since monitoring was initiated in 2013, and is useful as a conservative tracer for tracking water quality improvements. Median chloride concentrations from 2016 to 2018 measured 400 mg/L, representing a modest decline from the first three years of monitoring (440 mg/L median). Chloride concentrations are below the Government of Alberta (GoA) short-term surface water quality guideline (640 mg/L), but have remained greater than the GoA long-term surface water quality guideline for the protection of aquatic life (120 mg/L) since the lake was commissioned. Consistent with previous years, there were no vertical concentration gradients of chloride in BML in 2018 (Figure 3-12). Modelling is underway to understand the long term trend in chloride concentration in the water cap. This is possible because due to having a good water balance, a good prediction of FFT dewatering rates through time, FFT pore-water geochemistry, and a chemical mass balance of the water cap. This modelling will help inform water management inflow and outflow decisions.

3.2.3. Comparison of BML Surface Water Quality to Alberta Surface Water Protection of Aquatic Life Guidelines (AEP 2018)

An extensive suite of water quality variables (ranging from 111 to 185 analytes, depending on sampling frequency) were measured from six variable groups including conventional physico-chemical variables, ions, nutrients, metals, organics, and polycyclic aromatic hydrocarbons (PAHs). All parameters are generally below short-term PAL guidelines except for F2 Petroleum Hydrocarbons. The F2 hydrocarbon fraction has an interim short-term guideline derived from soil guidelines and may not be especially relevant to BML surface water quality. All parameters will continue to be monitored. It is expected that the F2 fraction may change in response to hydrocarbon mitigation activities.

The 2018 analytical results for the discrete water quality samples from BML were screened against surface water quality guidelines for the protection of aquatic life. The most conservative value was used for variables with multiple guidelines (e.g. for variables with GoA and CCME guidelines, or acute and chronic guidelines). Site-specific guidelines (e.g. hardness-dependent) were calculated for each sample, as applicable.

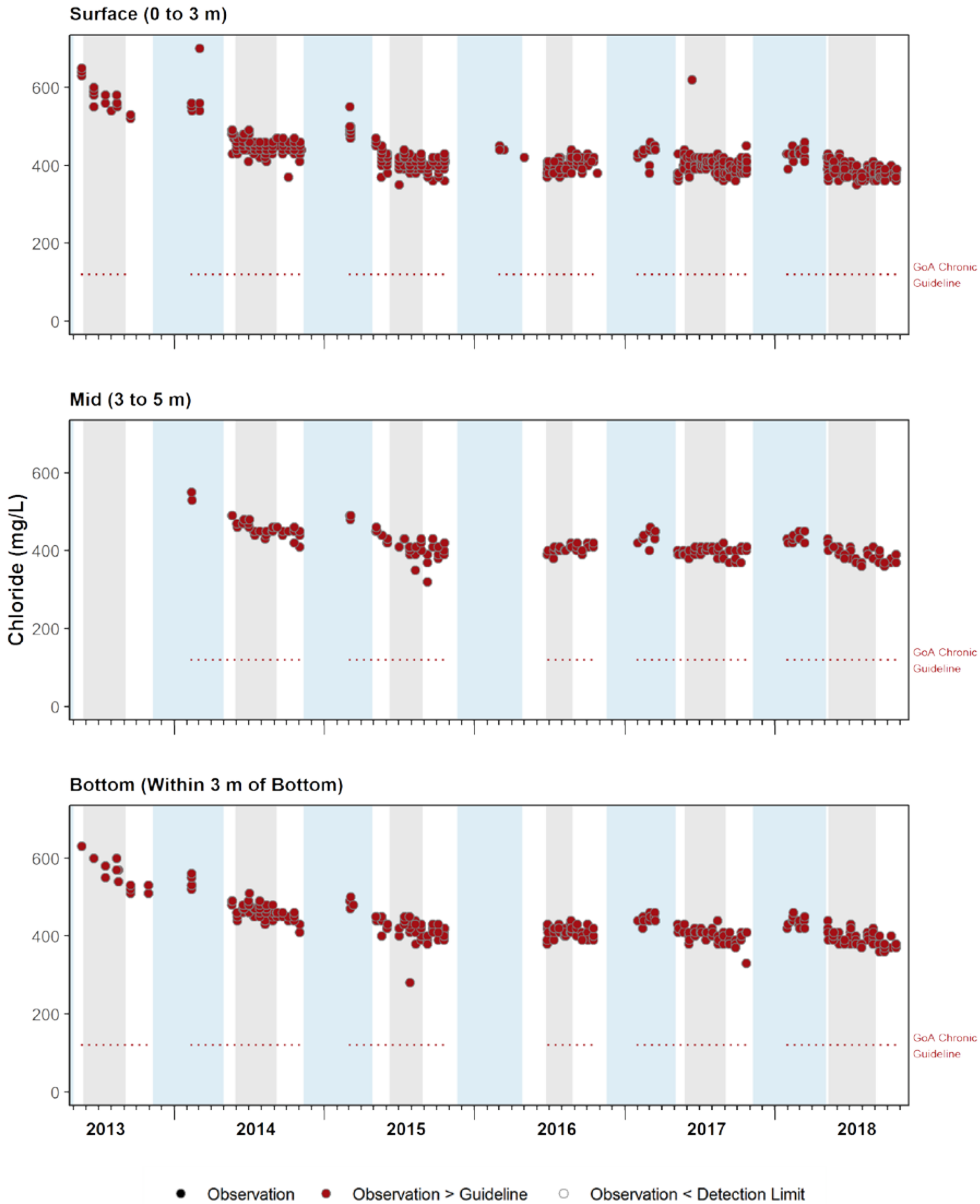
The following water quality variables had concentrations frequently (i.e. more than 50% of observations) greater than GoA chronic guidelines in BML in 2018: ammonia (55%), chloride (100%), sulphide (69%)[1], total phenolics (79%), total boron (100%), and F2 (C10 to C16) hydrocarbons (96%). Observations greater than chronic guidelines were less frequently observed for 20 other variables, which included both metals and organic compounds. The frequency of observations greater than guidelines has decreased since 2013, particularly for the following variables: ammonia, nitrite, sulphate, dissolved aluminum, total mercury, anthracene, and pyrene.

Metals that most frequently exceeded guidelines each year were total boron (from 86% of samples in 2016 to 100% of samples in 2013, 2014, and 2018), followed by total chromium (15% of samples in 2017 to 100% of samples in 2015) and dissolved aluminum (3% of samples in 2018 to 39% of samples in 2017). Boron is a chemical that is generally elevated in the region naturally. Dissolved aluminum spiked in the lake after alum was added to manage mineral turbidity. After the alum dosage, aluminum concentrations have declined. This will continue to be monitored to understand the effect of the alum dosage on many aspects of lake performance.

The parameters that are currently exceeding long-term guidelines are expected to improve with time. As the lake continues to develop, freshwater import dilutes the water cap, and the contribution of chemistry from FFT pore-water advection as a result of settlement declines. As the tailings continue to consolidate and dewater, there is less advective contribution of FFT pore-

[1] Sulphide guideline was equal to or less than the analytical DL from 2013 to 2018; however, the calculated proportion of exceedances includes measurable results only (i.e. values greater than DL).

water to the water cap. The FFT pore-water is the source of elevated chemical concentrations in the water cap and as consolidation begins to slow over time, so too does the influence of pore-water on the water cap. Syncrude will continue to monitor water quality and FFT settlement, and will use this information in combination with the water balance to determine mass balance in the water cap and assess how this will change over time. This will in turn inform adaptive management of the lake, specifically decisions about water import and export.



Ice-covered (blue) and stratified (grey) periods shown as filled areas on each panel.
Mean weekly guideline values shown as dotted red line.
Scale adjusted to focus on overall trends; full scale plot presented in Appendix A5.8.

Figure 3-12: Chloride concentrations (mg/L) with depth in the BML water cap since commissioning.

Table 3-1: Summary of toxicity bioassays on Base Mine Lake water.

Type and Duration of Tests	Endpoint	Short-term trends (2018)	Long-term trends (2013-2018)
Acute Toxicity			
Rainbow Trout 96 hour Static Acute	LC50	No trend; no acute toxicity effects observed	No trend; no acute toxicity effects observed since July 2014
Daphnia 48 hour Static Acute	LC50	No trend; no acute toxicity effects observed	No trend; no acute toxicity effects observed
Daphnia 48 hour Static Acute	EC50	No trend; no acute toxicity effects observed	No trend; no acute toxicity effects observed
Chronic Toxicity			
Fathead Minnow 7-day Survival	LC50	No trend; no chronic toxicity effects observed	No trend; no chronic toxicity effects observed since July 2013
Fathead Minnow 7-day Growth	IC25	No trend; moderate monthly variation, moderate spatial variation	No trend; infrequent chronic toxicity effect since July 2013
Algal Growth 72-hour Inhibition	IC25	No trend; moderate monthly variation, moderate spatial variation	No trend; high monthly and inter-annual variation
Lemna minor 7-day Growth (Dry Weight)	IC25	No trend; moderate monthly variation, high spatial variation	No trend; high monthly and inter-annual variation
Lemna minor 7-day Growth (Frond Number)	IC25	No trend; high monthly variation, high spatial variation	No trend; high monthly and inter-annual variation
Ceriodaphnia 7-day Survival Test	LC50	No trend; low monthly variation, moderate spatial variation	No trend; moderate monthly and inter-annual variation
Ceriodaphnia 7-day Reproduction	IC25	No trend; moderate monthly variation, moderate spatial variation	No trend; high monthly and inter-annual variation
Bacterial Luminescence (15 min)	IC20	No trend; low monthly variation, high spatial variation	No trend; high monthly and inter-annual variation
Bacterial Luminescence (15 min)	IC50	No trend; low monthly variation, low spatial variation	No trend; moderate monthly and inter-annual variation

4. SUMMARY OF KEY PERFORMANCE OUTCOMES: TECHNOLOGY VALIDATION

The two key desired outcomes for BML that are important for the validation of WCTT are the physical sequestration of the fines below the water cap and water quality improvements over time.

Results from research and monitoring indicate that the fines are physically isolated beneath the water cap. The FFT is settling as predicted by the numerical model, the mudline is declining in elevation year over year, and the water cap is increasing in depth. Profiles of shear strength indicate about 0.5 to 1 kPa over almost the entire depth of the FFT in most locations within the lake. The profiles of solids content of the FFT is also increasing over time. 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. Alum addition was an effective method to mitigate mineral turbidity in the lake.

Surface water quality has been improving with time in Base Mine Lake, as expected. This is a crucial component for the successful demonstration of Water Capped Tailings Technology. The lake water is not acutely toxic. Except for the F2 hydrocarbon fraction in the water, all parameters measured are below Alberta Surface Water Quality short term guidelines for the Protection of Aquatic Life. The F2 guideline value is interim and derived from soil guidelines, which makes it challenging to interpret for surface water quality performance. Monitoring of the lake water quality as hydrocarbon mitigation actions are taken will help Syncrude understand the long term changes that can be expected for this parameter. A large proportion of the lake chemical parameters are already below long-term Surface Water Protection of Aquatic Life guidelines, which are important for closure outcomes. Many of these parameters are naturally elevated in the region, or are expected to improve as the lake continues to develop.

5. RESULTS FROM BML MONITORING PROGRAM

The following is a summary of key findings from a variety of components of the BML Monitoring Program including FFT settlement and geochemistry, ground and surface water quality, water and chemical mass balance, physical limnological processes and aquatic biology and toxicity.

5.1. FFT Settlement Assessment

A full-lake surface sonar survey of BML is conducted annually in October. These annual assessments of the FFT surface are used to track FFT dewatering, and are also used to determine water cap depth and volume to estimate water balance.

Since the inauguration of BML, FFT settlement has been monitored. From 2012 through 2015, the top of FFT was determined by single-beam sonar, with mudline elevation determined via the reflection of a series of single acoustic pulses off the FFT surface as the sonar boat moved across the BML surface. From 2012 to 2015, the procedures and transect spacing of the sonar boat were improved and refined, thereby improving the quality of the single-beam sonar data. Regardless, the single-beam data collection required interpolation of data between the individual boat tracks. The biggest change in sonar technology occurred in 2016 when the single-beam sonar was replaced with multi-beam (or swath bathymetry) sonar equipment. The multi-beam sonar provides a spatially continuous 3D bathymetric measurement of the BML top-of-FFT surface. This results in a continuous point cloud of bathymetric data, higher spatial resolution of the FFT surface, and minimizes errors associated with interpolation between transects.

Table 5-1: FFT Settlement Assessment Key Findings

FFT Settlement Assessment Key Findings
• *Converting from single beam sonar to multi beam swath bathymetry has resulted in a more accurate assessment and representation of the top of FFT surface.*
• *The top of FFT surface elevation is not flat. There is considerable variability in the surface across the lake that generally corresponds to the original pit topography.*
• *FFT is settling as expected, up to 6 m between October 2012 and October 2018.*
• *The volume of FFT in BML decreased from 174.86 Mm^3 in October 2017 to 172.91 Mm^3 in October 2018 due to settlement.*
• *The FFT surface changes observed in the 2018 FFT program are consistent with trends observed in the historic BML programs since 2012.*
• *The top-of-FFT surface continues to settle annually and the overall water depth in BML increases at a corresponding rate, taking into account lake surface elevation changes.*

5.2. FFT Geochemistry Assessment

The geochemical assessment of the FFT is undertaken to determine the geochemical composition of the FFT pore-water. This information is important to understand the effects of FFT pore-water release on the overlying water cap, and helps in the predictions of water quality changes with time.

Sampling for the geochemical assessment of the FFT was conducted in August 2016. Depth profiles of pore-water chemistry obtained from five locations were interpreted with the assistance of statistical analyses and geochemical modelling. Previous sampling programs revealed distinct geochemical gradients across the FFT-water interface, however, variations in pore-water chemistry have also been observed deeper in the FFT profile (Dompierre *et al*., 2016). Therefore, the 2016 sampling program included samples collected at high spatial resolution across the FFT-water interface plus samples collected at greater vertical spacing deeper into the FFT deposit. These data contributed important new insight into the geochemical development of FFT during the early years of BML operation.

The increased vertical sample resolution was made possible by implementation of a Fixed Interval Sampler (FIS). This device integrates 20 pistons positioned at 0.1 m intervals to support high vertical resolution sampling of FFT across the tailings-water interface. Samples were obtained with the FIS at 0.1 m intervals from approximately 0.5 m above to 3.5 m below the FFT-water interface (i.e. mudline) at three locations, and from approximately 0.5 m above to 1.5 m below the mudline at two other locations. Two replicate 250 mL samples were obtained for each depth and combined to ensure sufficient sample volume for comprehensive analysis. Discrete FFT samples were collected using a fluid sampler at 1.0 to 2.0 m depth intervals from approximately 4 m to 10 m below the interface. Overall, FFT samples were obtained at 175 discrete depths distributed among locations P1 (n = 45), P2 (n = 45), P3 (n = 45), D04 (n = 20), and D09 (n = 20). Detailed descriptions of the FIS sampler and fluid sampler can be found in Dompierre *et al*. (2016) and Dompierre *et al*. (2017), respectively.

Table 5-2: FFT Geochemistry Assessment Key Findings

FFT Geochemistry Assessment Key Findings
• *Anaerobic respiration processes, including sulfate reduction and methanogenesis, are principal influences on FFT pore-water chemistry.*
• *These processes directly influence pH and pore-water alkalinity, hydrogen sulfide, and methane concentrations, which indirectly influence mineral precipitation-dissolution and ion exchange reactions.*
• *Spatial variations in Cl depth profiles among locations suggested that relative rates of advection, diffusion and physical mixing were not consistent around BML.*
• *Anaerobic respiration processes control, to varying degrees, dissolved concentrations of major ions (e.g. sodium, sulfate, bicarbonate, calcium and magnesium) and trace elements (e.g. vanadium, nickel, molybdenum).*
• *V, Ni and Mo concentrations are very low. This is likely due to anaerobic processes or conditions (e.g. V reduction may occur indirectly due to anaerobic respiration).*
• *These data provide valuable new insight into spatial variability of biogeochemical processes that influence pore-water chemistry and, therefore, chemical mass fluxes between FFT and the water cover.*

5.3. BML Groundwater Assessment

For 2018, the groundwater component of the BML program included semi-annual monitoring and sampling activities in June and October at groundwater wells located within 11 well nests around BML. There are 27 monitoring wells in the network which are classified as shallow, intermediate or deep based on the elevation and hydrostratigraphic formation intercepted by the screened intervals. Seven of the wells typically cannot be sampled due gas concerns, obstructions, bitumen presence, or damage. Continuous groundwater elevations are being recorded at seven deep well locations with dataloggers.

The June groundwater monitoring event consisted of verifying the status of 27 BML monitoring wells that have been historically included as part of the BML Program, as well as conducting groundwater level measurements and collecting groundwater samples when sufficient groundwater was present. Groundwater wells are classified as Active for a monitoring event if sufficient water is available to sample and the headspace testing results are within the safe range. In June, 19 wells were classified as Active and sampled, while 18 wells were classified as Active and sampled in October.

Monitoring and sampling activities at the Active wells included:

- Observation of well condition and status;
- Measurement of groundwater levels;
- Measurement of field variables (pH, temperature, specific conductivity and dissolved oxygen);
- Downloading of datalogger data, if transducer present; and
- Collection and submission of groundwater samples for analysis of conventional physicochemical variables, nutrients, dissolved metals, organics and hydrocarbons, and stable isotopes.

Table 5-3: BML Groundwater Assessment Key Findings

BML Groundwater Assessment Key Findings
• *Overall, groundwater level and quality results for 2018 appear to be following consistent trends with, or fall within previously measured ranges of the historical data collected between 2013 and 2017.*
• *Groundwater levels, and inferred flow directions, exhibit similar trends to prior years and indicate the presence of both groundwater inflow and discharge zones around BML's perimeter.*
• *The monitoring program results suggest that the infilling of the lake has altered subsurface pressures and groundwater flows.*
• *The key indicator variables evaluated do not suggest any significant adverse changes since BML was filled. Groundwater flow in and out of the lake is negligible.*
• *The majority of identified trends are likely related to chemical evolution processes (e.g. ion exchange) which may be associated with groundwater movement.*

BML Groundwater Assessment Key Findings
• *Among the monitoring wells, there were 58 statistically significant trends detected among 16 water quality variables (particularly for major ions), 47 of which observed decreasing trends.* o *Positively charged calcium and magnesium ions, and calculated hardness (which is dependent on calcium and magnesium concentration) encompass 27 of the 58 identified trends.* o *Increasing trends in concentrations were limited, they have been noted for ammonia, alkalinity, PHC F2, bicarbonate, and naphthenic acids. This indicates that some geochemical evolution is occurring, potentially as a result of filling BML, but the results do not suggest negative impacts are occurring.*

5.4. BML Surface Water Quality Assessment

The surface water quality component of the 2018 program consisted of both winter and open-water sampling events.

The 2018 winter field program was the most extensive program executed since the lake was commissioned. The program focused efforts at the three BML platforms and two deep stations. Winter sampling was conducted every two weeks between January 29 and March 14. Sampling stations were accessed depending on safety of ice access, therefore not all locations were accessible throughout the entire winter program. The snow sampling program was conducted twice: once in February and again in March. The ice program was conducted once during the week of February 27, in conjunction with the water quality program. Snow samples were collected at the three platform and two deep stations, while ice samples were only collected at the three platform stations; snow and ice samples were analyzed for select chemical variables. In situ lake profile data were collected using a YSI multi-meter probe, and light penetration depth was measured using a Li-Cor light sensor logger.

The 2018 open-water sampling events extended from May 7 to October 23, and consisted of multiple site visits (weekly, bi-weekly, and monthly, depending on the types of variables measured) to the three platform, two deep, and five littoral stations, as well as the BML Pump-Out station and the BCR Pump-In station; however, not all stations were accessible during the entire open-water sampling program. Two littoral stations could not be sampled in late summer and fall due to the placement of oil booms that were deployed to mitigate the presence and potential deposition of surface bitumen in the north-west littoral zone.

Table 5-4: BML Surface Water Quality Assessment Key Findings

BML Surface Water Quality Assessment Key Findings	
In-situ and Conventional Physico-Chemical Variables	
Summary of 2018 Observations	• *Dimictic lake with typical patterns of mixing in spring and fall and stratification in winter and summer.* • *Elevated concentrations of monovalent anions (chloride) and cations (sodium) compared to freshwater.* • *Near-neutral or slightly alkaline pH.* • *Reduced light penetration during periods of mixing.*
Temporal Trends	• *Climate-driven seasonal patterns are evident—formation of ice-cover in winter, turnover in spring and fall, and summer stratification.* • *Decreased concentrations of major anions, cations, and TDS since 2013.* • *Decreased concentrations of suspended solids, and evidence for further decrease and increased stability since 2016 alum treatment.*
Spatial Trends	• *Seasonal suboxic conditions in deep waters, during periods of stratification.* • *Higher concentrations of TSS and turbidity in the bottom stratum of BML.*
Guideline Exceedances (long-term)	• *Dissolved oxygen concentrations less than minimum guideline requirements in the hypolimnion during winter and summer stratification.* • *Chloride and sulphide concentrations remained greater than long-term guideline for protection of aquatic life. [NOTE: Sulphide guideline was equal to or less than the analytical DL from 2013 to 2018; however, the calculated proportion of exceedances includes measurable results only (i.e. values greater than DL).]*
Nutrients	
Summary of 2018 Observations	• *Primary nutrients (i.e. nitrogen- and phosphorus-containing compounds) are available in BML in sufficient concentrations to support primary production.* • *Variation in nutrient concentrations observed among seasons and depth strata within BML, related to expected biogeochemical processes.*

BML Surface Water Quality Assessment Key Findings	
Temporal Trends	• *Seasonal variations of ammonia, nitrate, and phosphorus observed; likely the result of balance between remineralization of organic matter and consumption of nutrients:* o *Highest concentrations during winter and fall; and* o *Lowest concentrations during summer.* • *Lower nutrient concentrations in 2018 relative to the previous monitoring years.*
Spatial Trends	• *Depth-related variation in nutrient concentrations:* • *BML bottom layer potential source of ammonia and potential sink for nitrate.*
Guideline Exceedances (long-term)	• *Ammonia and nitrite concentrations greater than guidelines, however, the frequency of exceedances has decreased since 2013.*
Metals	
Summary of 2018 Observations	• *100% measurable concentrations of 17 metals in BML in 2018.* • *Concentrations of 11 metals, including bismuth, cadmium, chromium, iron, lead, silver, thallium, titanium, tin, and zinc, often near or below analytical detection limits.* • *Variation among depth strata, and modest variation among seasons.*
Temporal Trends	• *Concentrations of many metals have decreased in BML since 2013: arsenic, cadmium, chromium, copper, iron, lead, mercury, molybdenum, selenium, silver, thallium, uranium, and zinc.* • *Boron, cobalt, and nickel concentrations have remained similar year-to-year.* • *Dissolved aluminum concentrations increased in response to the fall 2016 alum treatment, then returned to pre-treatment levels by summer 2017 and remained stable through the end of 2018.*
Spatial Trends	• *Sporadic observations of higher metal concentrations occurring in deep samples; more often occurring during winter.*
Guideline Exceedances (long-term)	• *Boron and chromium concentrations consistently greater than long-term guidelines.* • *Sporadic observations of concentrations greater than long-term guidelines for a range of metals, including: arsenic, cadmium, cobalt, copper, lead, methyl mercury, and zinc.*

BML Surface Water Quality Assessment Key Findings	
Organics	
Summary of 2018 Observations	• *Some petroleum-associated compounds continued to be measurable in BML:* o *Naphthenic acids, alkylated PAHs, total phenolics, F2 hydrocarbons, and F3 hydrocarbons.* • *Most volatile organics (e.g. benzene, xylene, toluene) near or below analytical detection limits.*
Temporal Trends	• *Seasonal variation: increased concentrations of naphthenic acids and PAHs in winter; and total phenolics, F2, and F3 hydrocarbons in spring and summer.* • *Improvements to the extraction method for naphthenic acids in 2015 has resulted in higher concentrations being reported in recent years.* • *Negligible variation in naphthenic acid concentrations over the last three years (2016 to 2018).*
Spatial Trends	• *Limited depth-related variation, with PAH concentrations marginally higher in bottom water samples.*
Guideline Exceedances (long-term)	• *Total phenolics and F2 hydrocarbons consistently greater than guidelines. [NOTE: F2 hydrocarbons have only a short-term guideline.]* • *Pyrene and anthracene concentrations occasionally greater than guidelines.*

5.5. BML Water Balance

Estimating the water balance of BML has important implications for the chemical, energy and constituent mass balance of the lake, and provides information about the sustainability of EPLs in the closure landscape. The water balance has been completed for BML from November 2013 through December 2018, with a daily time step in terms of both total volumes and millimetres of water in/out. For analysis purposes, only 'water years' (Nov-Oct) have been presented as yearly totals in mm of water in Table 5-5.

Table 5-5: Yearly water balance totals (in mm of water) for five water years

Year	Evaporation	Pump OUT	Pump IN	Rain	Snow	Runoff
2014 Total	350.6	954.5	852.0	308.9	55.0	29.2
2015 Total	350.9	952.6	780.2	254.4	50.0	21.0
2016 Total	515.8	375.9	402.1	368.6	50.0	0.2
2017 Total	469.8	181.2	368.4	286.1	40.0	2.0
2018 Total	525.4	155.6	366.1	398.1	100.0	0.1

This volume data is displayed in Figure 5-1. There are several important items to note: 1) the volume of water expressed from FFT is declining with time. This will have longer-term influences on BML mass loading. Due to the timing of the water balance determination, 2018 values were taken as the same as 2017, but these will be updated for the future. 2) The pumps have contributed less water into and out of BML with time. 3) Runoff contributions are negligible and groundwater contributions are assumed zero. 4) Evaporation has increased with time and is now in line with what is expected from a Boreal lake. 5) Precipitation (rain and snow) have been below the long-term average for this period, yet 2018 was relatively wet.

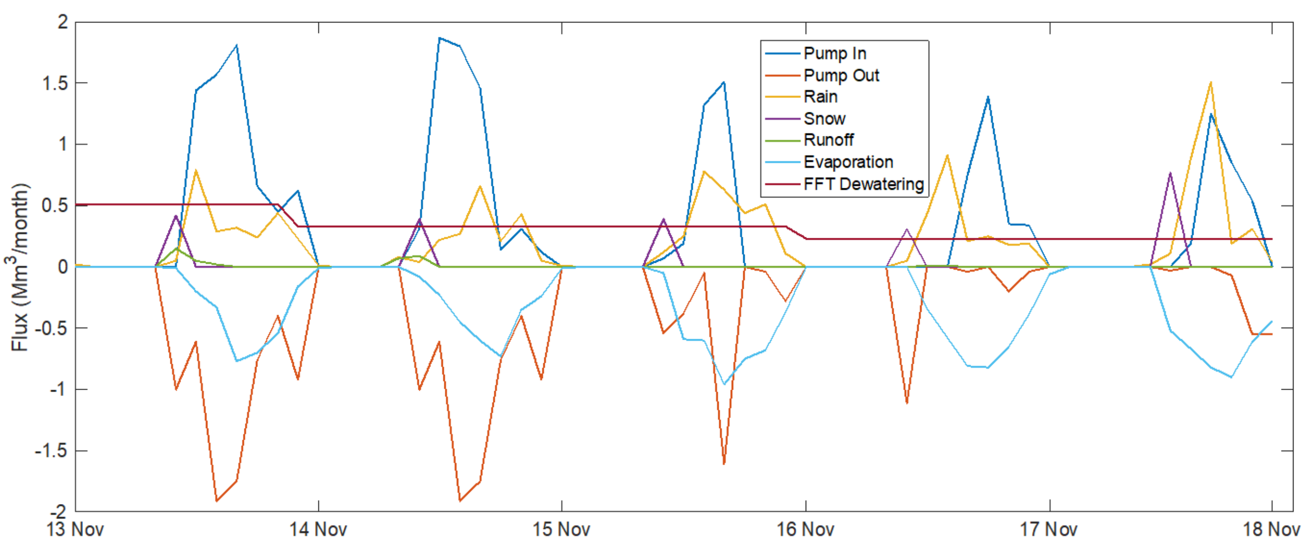


Figure 5-1: Monthly water balance values in mm of water for Mm3 of water for four water years.

5.6. BML Water Cap Chemical Mass Balance

As a result of completing the water balance, Syncrude is able to use the water balance along with the surface water quality and FFT pore-water chemistry data to determine the chemical mass balance of the BML water cap.

The conceptual model for the water and mass balance is illustrated in Figure 5-2. The control volume for the water balance is the entire pit volume (including FFT), thus the inputs and outputs into the pit volume are only those that impact the water cover surface elevation (i.e. pump-out, pump-in, precipitation, runoff, and evaporation). The control volume for the mass balance is the water cover (i.e. free water) volume, therefore its volume changes with both the water cover surface elevation and FFT elevation due to settlement. The annual water and mass balance analyses were conducted for four hydrologic water years defined as the period from November 1 of one year, to October 31 of the following year.

The mass balance was undertaken in two steps. In the first step, a mass balance for a conservative chemical species (chloride, Cl) was used to evaluate whether the observed changes in mass within the water cover could be explained by the observed FFT settlement and FFT pore-fluid chemistry, assuming all other mass inputs and outputs except for FFT were accurately quantified. Once it was established that FFT settlement and pore-fluid chemistry provided a reasonable estimate of the FFT mass contribution to the water cover, the second step relied on this estimate of loading from FFT to look at the mass balance for non-conservative species.

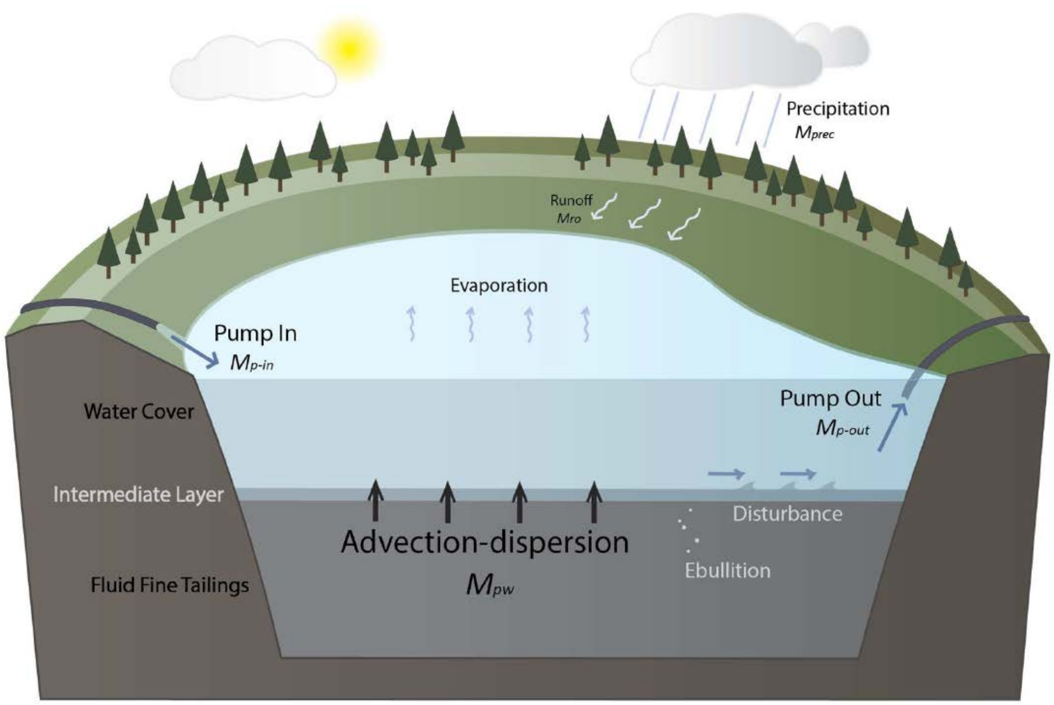


Figure 5-2: EPL in early years: water balance and mass balance components (from Dompierre, 2016)

Table 5-6: BML Water Cap Chemical Mass Balance Assessment Key Findings

BML Water Cap Chemical Mass Balance Assessment Key Findings
• *Annual chemical mass balances have been completed for BML from 2013-2017.*
• *The chemical mass inputs to BML are from water pumped from the fresh water reservoir (Beaver Creek Reservoir), precipitation, and surface runoff, as well as the pore-water expressed during settlement of the underlying FFT.*
• *The primary chemical mass output from the lake is from water pumped from BML to the recycle water circuit.*
• *The contribution of FFT settlement to mass loading of BML was calculated for a conservative tracer (i.e. chloride) for each water year and compared to estimates made directly from measurements of FFT settlement and FFT pore-water concentration.*
• *The results indicated that at present, FFT pore-water release is the primary source of mass loading to the BML water cap. The average settlement over the four-year period was 2.15 m based on the Cl mass balance and 2.44 m using the sonar survey measurements.*
• *The major components of the conservative (Cl) mass balance were: pump-out (8153 tonnes, 50%) and FFT pore-water release (7955 tonnes, 49%).*
• *The apparent loss(-)/gain(+) in brackets for the conservative and non-conservative species are: Cl (-704 tonnes), Na (-1979 tonnes), Ca (-113 tonnes), Mg (-43 tonnes), K (-132 tonnes), SO4 (1489 tonnes), NH3-N (-209 tonnes), B (-7 tonnes), and Li (-1 tonnes).*
• *The apparent 'loss' (i.e. unbalanced mass) in Cl (704 tonnes) over the 2013-2017 time period reflects the differences between the settlement calculated based on mass balance and the direct measurements of FFT settlement.*
• *The source of this discrepancy and the apparent Cl loss is mostly likely the result of a combination of factors, including but not limited to: accumulating errors in estimating the average FFT settlement from sonar (single-beam) surveys (2013-2015) and multi-beam surveys (2016-2018), the impact of alum addition (Sept 2016) in altering the 'sensed' mudline, and differences spatially in average settlement and FFT Cl concentrations.*

5.7. BML Physical Limnology Assessment

Physical limnology is the study of water circulation and mixing within lakes, examining specific physical processes such as temperature and salinity stratification, and the formation and breakdown of ice cover. These processes are driven largely by atmospheric forcing at the surface of a lake and play a critical role in biological and geochemical processes within the lake. The lake has consistently exhibited conventional lake physical processes since commissioning. During the winter, the lake forms ice annually. Once the ice melts in the spring, temperature driven density changes in the lake results in the lake mixing, or spring turnover. During the summer, the lake is thermally stratified. In the fall, thermal stratification diminishes as a result of cooling and wind. This results in the lake mixing again, or fall turnover. Key lake events since commissioning are indicated below in Table 5-7.

Table 5-7: Summary of ice-on, ice-off, stratification (whole lake) and turbidity extremes (2.5mP3)

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

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

[b] Estimate only

Table 5-8: Summary of the BML Physical Limnology Assessment Key Findings

Summary of the BML Physical Limnology Assessment Key Findings
Physical Limnological Processes there were similar in 2018 to all previous years.
• *Similar to previous years, in 2018 BML underwent many of the same physical processes that are generally observed in natural lakes including: summer thermal stratification, fall turnover, reverse thermal stratification in the winter, wind driven thermocline tilting and wind driven mixing.*
• *Turbidity had a strong seasonal cycle; increasing during the fall, decreasing under ice, increasing during the spring and decreasing again during the summer.*
• *Significant exclusion of salt from the ice resulting in about a 10% increase in water salinity under the ice.*
• *Low (70% to 0% saturation) and declining dissolved oxygen concentrations in the water both at 2 m and 6 m depths under the ice as the winter progressed.*
• *Increasing turbidity throughout the depth in late spring and early summer (May and June).*
• *Gradually declining turbidity at a depth of 2.5 m during the second half of the summer thermal stratification period.*
• *In the summer, weekly wind events (when wind speed exceeds approximately 5 m/s) in the summer that causes oscillations of the thermocline (internal seiches) and fluctuations in turbidity within and below the thermocline.*
• *Complete vertical mixing during fall turnover results in uniform temperature, salinity, turbidity throughout all but the very base of the water column (less than approximately 0.5 m above the sonar mudline).*
• *Similar to the winter of 2017, under-ice thermal stratification was absent throughout the upper half or third of the water column. Winters prior to alum dosing had thermal stratification throughout the water column under the ice. This homogeneity may be related to the dramatically reduced turbidity due to alum dosing.*
• *Many profiles indicate the presence of a region at the base of the water column up to approximately 0.5 m thick with very high turbidity that is intermediate in temperature between the temperature of the FFT and the water above (e.g. this layer is warmer than the water above in the fall and cooler than the water above in the spring). This intermediate region is not uniform horizontally, it is not always observed in profile data and is typically the thickest at the deepest station. During the fall of 2015 and 2016 this layer had a maximum thickness of approximately 1 m rather than 0.5 m observed in 2017 and 2018.*

Summary of the BML Physical Limnology Assessment Key Findings
Physical Limnological Processes that are different from previous years or newly observed
• *Spring turnover ended earlier (May 10) than any previous year. This may have been related to relatively calm winds in mid and late May as well as the lack of inflow from Beaver Creek Reservoir.*
• *The summer thermal stratification period lasted approximately 116 days from soon after ice-off (May 10, day 130) to September 3 (day 246). The early onset of stratification resulted in a longer summer stratified period than previous years (70 to 110 days in previous years).*
• *The turbidity in the fall of 2018 was intermediate, between the turbidity in the fall of 2016 (during alum dosing) and the fall of 2017. The long-term trend for turbidity post alum is therefore unknown; it may return to pre-alum conditions as the 2017 data suggested or it may continue to improve. Turbidity continues to be a focus of monitoring and research.*
• *Dissolved oxygen concentrations at depth at ice-off in 2018 were lower than at ice-off in 2017 (winter following alum) but higher than winters prior to alum dosing.*

5.7.1. Trends in turbidity

Turbidity has exhibited seasonal fluctuations tied to the physical limnological events in the lake (e.g. mixing and thermal stratification). In 2018, turbidity was approximately 50 NTU throughout most of the water column at the end of spring turnover (May 10). From in-lake moored sensor data, turbidity at 2.5 m below the air-water interface increased until approximately day 166 (June 15), except for brief increases associated with large wind events, and declined reaching a low value of approximately 5 NTU at the end of August (approximately day 240). At the moored sensor at 7.5 m depth below air-water interface, turbidity increased sporadically until day 189 (July 8). At the end of July, turbidity at 7.5 m converged with the turbidity at 2.5 m. This pattern in the turbidity during the spring and summer is similar to the patterns observed in 2015, 2016 and 2017. The lake increases in turbidity during fall turnover, but the magnitude of the increase varies, and has declined significantly since alum addition in 2016. Annual patterns in turbidity during fall turnover are shown in Figure 5-3.

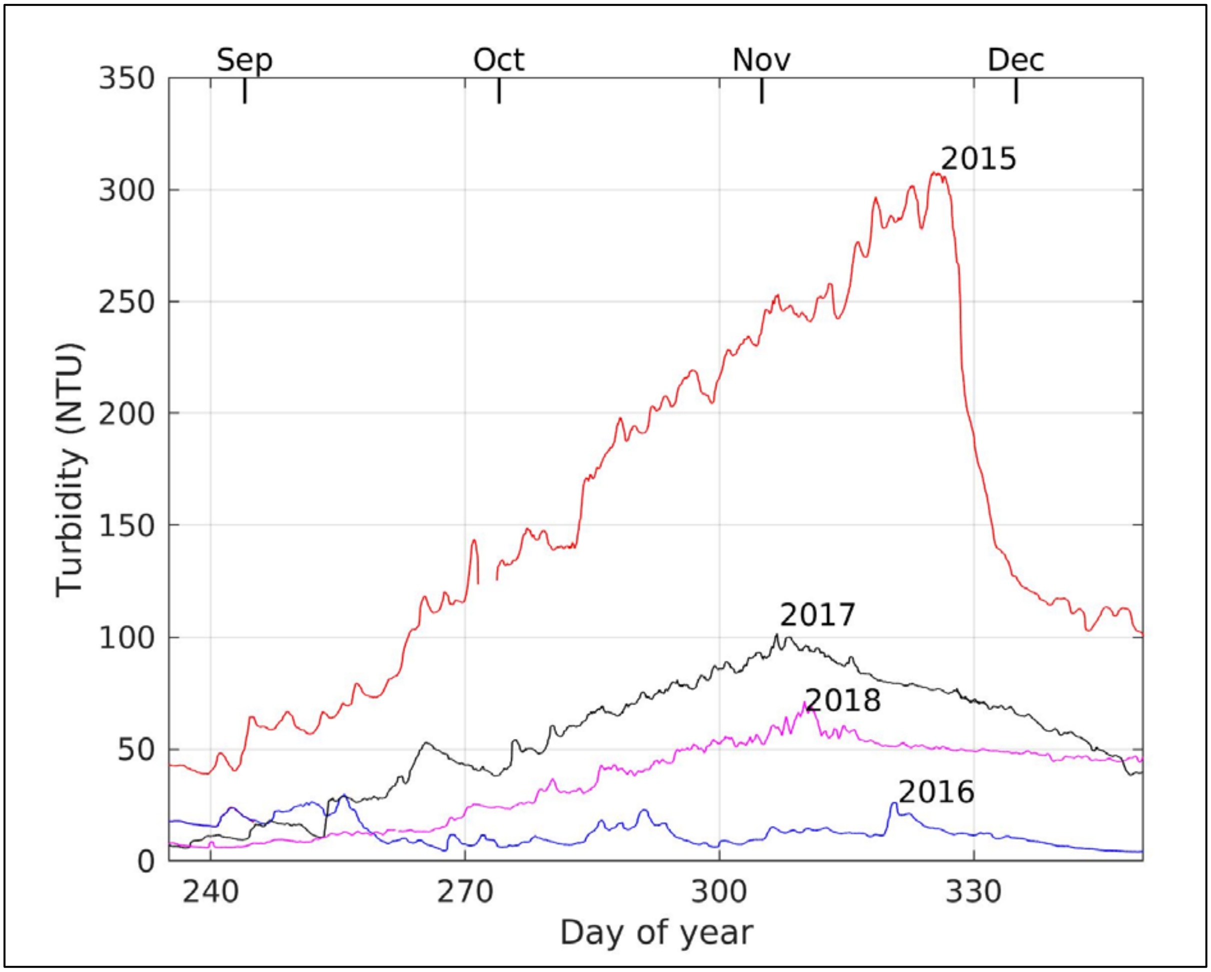


Figure 5-3: Fall turbidity at 2.5m during the last four years.

5.8. Aquatic Biology of BML

The 2018 aquatic biology program included six components: periphyton, phytoplankton, zooplankton, benthic invertebrates, sediment quality, and sediment and water toxicity.

The following monitoring was conducted for each component:

- Periphyton colonization and growth were monitored over 7, 14, 21, and 28-day test periods at the three platform stations from the end of July through August. Two replicates were collected at each platform;
- Phytoplankton samples were collected twice in winter (February and March), and monthly during open-water (May to October) from the three platforms and BCR pump-in station. Three replicates were collected at each station;
- Zooplankton samples were collected monthly from May to October at the three platforms and BCR pump-in station. Three replicates were collected at each station;

- Benthic invertebrate samples were collected in September from six littoral stations, equally distributed between the NW and SE quadrants of BML. Five replicates were collected at each station;
- Sediment quality samples were collected in September from the six benthic invertebrate littoral stations. Five replicates were collected at each station; and
- Acute and chronic toxicity tests were performed on water and sediments from BML, using a range of test organisms. Water toxicity samples were collected in May, July, and September at all three platform stations, while sediment toxicity samples were collected in September from the six benthic invertebrate littoral stations.

Table 5-9: Summary of the Base Mine Lake Aquatic Biology Monitoring Program Key Findings

Summary of the Base Mine Lake Aquatic Biology Monitoring Program Key Findings	
Periphyton	
Summary of 2018 Observations	• *Robust colonization of substrates by periphyton, indicating suitable conditions for growth.* • *Colonizing periphyton moderately diverse; diatoms and cyanobacteria dominant in abundance and diatoms and green algae dominant in biomass.*
Temporal Trends	• *Both abundance and biomass generally increased over monitoring years.* • *Same taxonomic groups dominated in abundance and biomass, but dominance of individual taxa has varied among years.* • *Diversity of colonizing periphyton communities has generally increased over monitoring years.*
Spatial Trends	• *No consistent spatial patterns in periphyton colonization.*
Phytoplankton	
Summary of 2018 Observations	• *Viable phytoplankton community in BML.* • *Phytoplankton abundance peaked in September.* • *Phytoplankton biomass peaked in August.* • *Moderately diverse community; cyanobacteria dominant in abundance and euglenoids and cryptomonads dominant in biomass.*
Temporal Trends	• *Abundance and biomass exhibited high monthly and annual variability with lower values in recent years.*

Summary of the Base Mine Lake Aquatic Biology Monitoring Program Key Findings	
	• *Dominance of taxonomic groups has varied over monitoring years, with euglenoids and cryptomonads the most dominant in recent years.* • *Diversity has increased over monitoring years.*
Spatial Trends	• *No consistent spatial patterns in phytoplankton abundance or diversity within BML.*
Zooplankton	
Summary of 2018 Observations	• *Zooplankton abundance peaked in July.* • *Zooplankton biomass peaked in June.* • *Moderately diverse community; more balanced community (cladocerans and copepods) in fall (September/October).*
Temporal Trends	• *Both abundance and biomass have exhibited high monthly and annual variability with 2018 recording the lowest total abundance since 2015.* • *Consistent monthly/seasonal community patterns among monitoring years.* • *Diversity has generally increased over monitoring years.*
Spatial Trends	• *Zooplankton communities varied among the three platforms without any distinct pattern.*
Benthic Invertebrates	
Summary of 2018 Observations	• *Similar abundance between the NW quadrant and SE quadrant but higher biomass in NW quadrant.* • *Midge larvae alone accounted for >92% of the abundance in both quadrants, while a more diverse community resulted in the higher biomass in the NW quadrant.*
Temporal Trends	• *Highly variable abundance and biomass among monitoring years; 2018 numbers lower than 2017.* • *Same taxonomic group dominant in all monitoring years (Diptera).* • *Similar diversity recorded in all monitoring years.*
Spatial Trends	• *Highly variable communities observed among sampling stations and between the NW and SE quadrants, with higher biomass in NW quadrant.*
Sediment Quality	
Summary of 2018 Observations	• *Physical and chemical compositions of sediments varied between NW quadrant and SE quadrant.*

Summary of the Base Mine Lake Aquatic Biology Monitoring Program Key Findings	
	• *Several sediment variables exceeded the Interim Sediment Quality Guidelines, with the NW quadrant exhibiting higher frequencies than the SE quadrant.*
Temporal Trends	• *Similar physical properties of sediments observed in all monitoring years.* • *Sediment chemistry has varied among monitoring years.*
Spatial Trends	• *Sediment composition and chemistry in NW quadrant better for development of benthic invertebrate communities than SE quadrant.*
Water Toxicity	
Summary of 2018 Observations	• *No acute toxicity effects observed on test organisms.* • *Chronic toxicity effects observed on bacteria, algae, macrophytes, zooplankton, and fish growth; no chronic effects observed on fish survival.*
Temporal Trends	• *Highly variable chronic toxicity effects among seasons.* • *No acute toxicity of BML water observed since 2014.*
Spatial Trends	• *Highly variable toxicity effects among stations/BML platforms.*
Sediment Toxicity	
Summary of 2018 Observations	• *Sediment toxicity tests conducted on freshwater midge larvae and amphipods showed effects on the survival and growth of both organisms.* • *Midge larvae growth tests for BML sediments observed higher biomass increase in comparison to control sediments.*
Temporal Trends	• *Highly variable toxicity effects among years.* • *Similar toxicity effects on test organisms in 2018 relative to previous years.*
Spatial Trends	• *Highly variable toxicity effects among stations as well as between the NW and SE quadrants.*

6. KEY RESULTS FROM THE RESEARCH PROGRAM

The BML 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.

As mentioned in Section 2.2.2.2, the current focus of the Research Program is to support the demonstration of the Water Capped Tailings Technology (WCTT). The program also provides supporting information about key processes fundamental to the progression of BML towards becoming a functional component of the closure landscape. The current research programs were focused on key parameters influencing early BML development.

Objectives of each program and key findings are outlined in the following sections. It is important to note that much of this work is underway, and the results described below should be considered preliminary. The program has a good record of publication already, and many scientific papers are in preparation. The next five years of research will continue to focus on similar activities that have been addressed, however the focus of the work will primarily be to understand the dynamics of methane ebullition, turbidity and hydrocarbon (bitumen) dynamics in the lake. Other research may be undertaken to assess potential mitigation strategies for turbidity and hydrocarbon in the lake when necessary.

6.1. Physical limnology of BML and the potential for meromixis (Lawrence, Tedford, Pieters: University of British Columbia)

The objective of this program is to understand the circulation of BML and its potential for meromixis. Some results are described below.

In 2018, BML continues to exhibit thermal stratification in the summer, similar to previous summers. A relatively calm spring resulted in the early onset of persistent summer stratification. Analysis of high resolution bathymetry and satellite images of ice prior to ice breakup (early April) revealed a tight correlation. These patterns in the bathymetry and ice are hypothesized to be controlled by processes within the FFT, in particular spatial variability in FFT heat content and FFT methane production.

Suspended solids concentration in the water cap, as indicated by turbidity, continues to follow a well-defined seasonal cycle: increasing during fall turnover, decreasing after ice-on, increasing after ice-off, and then decreasing during the summer stratified period. Unlike the winter of 2017, and similar to winters prior to alum dosing, the deepest oxygen sensor approached or reached 0% by the end of the ice covered period.

Profiles collected during the winters of 2017 and 2018 have evidence of FFT sourced salts. Although FFT sourced salt is expected due to dewatering of the FFT, these were the first profiles that have clear evidence of a bottom source. This new evidence may be the result of improved performance of the conductivity sensor due to lower suspended solids concentrations particularly near the FFT mudline.

Observations of the ice cover have revealed interesting patterns in ice appearance that appear to be related to lake bathymetry. The relationship between ice thickness, bitumen presence, methane bubbles and lake bathymetry is being further investigated. This is becoming an important focus of this research program, and is informing adjustments to the winter monitoring program.

6.2. Characterization of controls on mass loading to an oil sands end pit lake (Barbour, Lindsay: University of Saskatchewan)

The objective of this program is to define mass loading to Base Mine Lake by characterizing the mechanisms and distribution of heat and mass transfer from the tailings column to the overlying water column. This program examines processes controlling physical mass-transport and chemical mass-transfer across the FFT-water interface in BML. Recent findings offer insight on processes controlling mass-loading across this interface.

Key research topics include:

- identifying the dominant mechanisms of mass and heat transfer within the tailings and determining how the rates associated with these mechanisms change with time;
- determining if the rate of pore-water release defined by FFT settlement measurements adequately describe heat and mass fluxes from the fine tailings into the water cap;
- elucidating if mass transport is enhanced by other mechanisms occurring in the lake, for example, overturning of the water cap, ebullition of dissolved gases; and
- determining how pore-water release affects the chemical and thermal conditions across the FFT-water interface.

The principal research activities undertaken during 2018 were: (i) measurement of FFT temperatures and pressures; (ii) thermodynamic modelling of methane solubility; (iii) numerical modelling of conservative solute transport across the FFT-water interface; (iv) geochemical and mineralogical analysis of archived samples; and (v) integration of geochemical, mineralogical, and microbiological results.

6.2.1. Methane distribution and saturation

Work continued to refine methane solubility models and evaluate how different factors (e.g. pressure, temperature) may influence potential for methane exsolution and ebullition. Data from the 2017 FFT sampling program indicate that methane concentrations increase rapidly with depth over the upper 1 m to 3 m of FFT. These increases are sufficient for methane concentrations to reach the theoretical saturation limit, which facilitates exsolution (bubble formation) and ebullition (bubble escape). However, dissolved methane concentrations do not continue to increase at the same rate with depth as the methane solubility limit. This finding indicates that there is a discrete zone located approximately 1 m to 3 m below the FFT-water interface where methane production is sufficient for concentrations to reach the saturation limit and promote methane exsolution and ebullition. This finding also indicates that methane production rates at greater depths are likely insufficient to promote ebullition.

6.2.2. Conservative transport modelling

Work continues to refine initial conservative transport models developed by Dompierre (2016) that implemented periodic mixing of the upper FFT due to physical processes in the water cap (i.e. turnover, wave action) to effectively simulate observed chloride profiles from the August 2015 FFT sampling program. However, methane concentration data and associated solubility modelling suggest that ebullition may actually be the principal driver of mixing within the upper layer of FFT. Ebullition is more likely a continuous mixing process with the mixing intensity changing with ebullition intensity. Initial simulations implementing continuous mixing (represented in the model as enhanced diffusion) have generally provided better fits to 2015 and 2016 chloride profiles. Additional refinement of these models, which also use location specific rates of pore-water advection, should further constrain estimates of water fluxes across the FFT-water interface.

6.2.3. Geomicrobiology and geochemistry

This work examined relationships between FFT microbiology and pore-water chemistry to investigate how microbial processes influence the distribution and abundance of key pore-water constituents. Results identified microbes associated with a diverse range of metabolisms, notably hydrocarbon degradation, sulfate reduction and methanogenesis. The importance of microbial metabolisms shifted with depth and the greatest potential for biogeochemical cycling was observed near the FFT-water interface. Importantly, this work indicated that microbially-driven reactions within the upper 2 m of FFT have potential to decrease fluxes of dissolved methane, ammonium and hydrogen sulfide across the interface, which has implications for mass flux calculations and long-term mass loading estimates. The microbial community in deeper FFT was dominated by hydrocarbon degraders, syntrophs, and methanogens. Microbial methane production is likely controlled by hydrocarbon degradation and long-term methanogenic rates and pathways – organisms associated with both fermentative and hydrogenotrophic methanogenesis were detected – and will likely depend upon the availability of substrates produced by syntrophic microbes.

Research to date provides important estimates of water, mass, and thermal energy transfer from the FFT to the water cover in BML. Ongoing research in 2018 was focused on further constraining mass loading from the FFT to water cap through: (i) numerical modelling of conservative mass transport across the FFT-water interface; and (ii) mass balance calculations of chemical mass-loading across this interface. Although model development is ongoing, an important development has been the adoption by industry of area specific settlement rates, along with the concomitant area specific loading rates to assess the long-term evolution of lake chemistry. This approach, which accounts for different settlement rates around BML, was initially developed as part of the mass-loading calculations based on the BML water balance and chemistry. Both of these activities are helping to improve estimates of salt and water balance within BML.

Methane solubility modelling, coupled with 2017 methane concentration data, is helping to improve understanding of methane production, transport, and consumption within BML. This modelling is assisting in the identification of depths at which methane saturation is achieved, and to assess how changing temperatures and pressures may impact the potential for methane ebullition (i.e. bubble release) within BML. Understanding potential for methane ebullition in the FFT is important because it likely dominates the annual methane flux to the atmosphere. This interpretation is based on data from Dr. Lesley Warren (University of Toronto) which showed that dissolved methane is rapidly consumed through oxidation within the upper FFT and hypolimnion. Nevertheless, Dr. Sean Carey (McMaster University) has observed large methane fluxes from the water surface. Taken together, these findings suggest ebullition is the major driver of methane fluxes to the atmosphere. Modelling indicates that a relatively narrow zone of methane ebullition likely occurs 1 m to 2 m below the FFT-water interface. Additional simulations evaluating the impact of increased FFT depths – and consequently elevated rates of FFT settlement – coupled with FFT cooling over time, will increase methane solubility limits over time. Assuming methane production remains constant, it is feasible that ebullition may decline with time. Although this hypothesis needs to be tested, it does have important implications for methane emissions as dissolved methane appears to be readily oxidized with the water cover, whereas methane bubbles largely bypass the water cover.

6.3. Laboratory studies investigating chemical flux across tailings-cap water zones, simulating an end pit lake in the Athabasca oil sands region (Ulrich, Flynn, Siddique: University of Alberta)

This project uses an experimental approach to quantify physical and biogeochemical processes in a laboratory system simulating an EPL. The experiments are quantifying the flux of chemicals from underlying FFT to overlying cap water, mediated by advection, diffusion, ebullition, and biogeochemical reactions transforming clay minerals.

Complementary laboratory experiments are accelerating the flux of chemicals of concern to permit prediction and modeling of EPL development in situ. There are two main components to this work: (1) large-volume (~50 L) kinetic tests to determine advective and diffusive flux of inorganic and organic constituents of concern (including bitumen) from the FFT to the cap water; and (2) physical tests to quantify the relative importance of advection and convection on chemical flux from the FFT to cap water layer.

A series of physical, chemical and biological experiments were conducted to understand dynamics of mineral turbidity in BML. Physical experiments were conducted first to explain turbidity observed in the BML water cap. Laboratory experimental results concerning mixing in the vicinity of the BML mudline were carefully analyzed then synthesized. These reveal some unexpected results, i.e. that the role of ebullition in suspending solids material from FFT may be larger than previously recognized. The data also show fairly conclusively that buoyant convection in the immediate neighbourhood of the mudline is insufficient to result in significant mixing.

Chemical and biological experiments were performed subsequently to mitigate the elevated turbidity. Two chemical coagulants/flocculants ($CaCl_2$ and alum) were compared and different coagulation/flocculation mechanisms were revealed. Alum was more effective in coagulating/flocculating the suspended particles than $CaCl_2$, as expected. Biological coagulant (microalgae) addition could also effectively reduce turbidity in the BML water cap. Further integrated experiments are being planned to investigate whether chemical and biological treatments could mitigate solid suspension from FFT as identified by the physical experiments. Details of particular components of the work are described below

6.3.1. Temperature and Hydrocarbon amendments

To investigate the chemical flux from the underlying FFT to the overlying water cap in laboratory columns, two parameters were investigated: hydrocarbon amendment and temperature. Hydrocarbon amendment can enhance one particularly important biogeochemical process in FFT, methanogenesis, which may contribute to ongoing sources of turbidity, toxicity, bitumen, cations and anions, trace metals release, etc. in the water cap of an end pit lake. Some columns were amended with selected hydrocarbons to sustain the methanogenesis and to investigate presence or absence of the chemical flux in these columns. Temperature can speed up chemical and biochemical reactions and affect the overall biogeochemical process in FFT which may be critical in determining the chemical flux in an end pit lake. The temperature effect on the biogeochemical processes in FFT was investigated by incubating unamended columns at three difference temperatures: 10^oC, 20^oC and 30^oC. The enhanced biogeochemical processes and the resulting chemical flux can provide valuable information for the operators to predict the water chemistry in Base Mine Lake in the long term.

Hydrocarbon amendment has caused significant changes in the water chemistry. Acceleration of microbial activity with hydrocarbon amendments resulted in producing methane and carbon dioxide that dissolved in water forming bicarbonate and decreased pH; this process resulted in carbonate minerals dissolution and also increased HCO_3^- concentration. By the fourth sampling methanogenesis in 20^oC column declined, but bicarbonate concentration in cap water remained higher in the amended column. The general trend for HCO_3^- concentration in both amended and unamended columns was increasing in the water column after establishing anaerobic conditions (at the beginning of the experiment). In pore-water of amended columns, once methanogenesis started, concentration of HCO_3^- became significantly higher compared to unamended columns: it spiked once methanogenesis started and then stabilized or even slightly decreased (20^oC

amended column). Carbon dioxide dissolution led to pH decrease that resulted in carbonate and sulfate minerals dissolution, increase HCO_3^-, Ca^{2+} and Mg^{2+} concentration and release of Sr and Ba.

Positive flux of major cations was observed in all hydrocarbon-amended columns, this trend more pronounced for cap water of 20ºC amended columns. Additional experiments with 160 mL microcosms revealed that concentrations of aforementioned elements would continue to increase if methanogenesis was sustained. The sulfate-ion concentration decreased in hydrocarbon-amended columns due to sulfate reduction (negative flux was calculated). This process was accompanied by an increase in the population of *Desulfobacteraceae*, strictly anaerobic Proteobacteria that reduced sulfates to sulfides in amended columns compared to initial FFT. Then sulfides could precipitate forming iron sulfide minerals (e.g. pyrite). In amended columns, the amount of newly formed pyrite (FeS_2) increased compared to unamended columns. Immobilization of other metals is also possible due to sorption and co-precipitation of newly-formed minerals.

6.3.2. Nutrient dynamics

The supply of nitrogen to FFT increased the abundance of indigenous methanogenic microbial community and led to enhanced rate of hydrocarbon metabolism into biogases (CH_4 and CO_2) production. The addition of both N and P slowed the methanogenesis performance down and decreased the abundance of syntrophic bacteria and archaea. Stimulated methanogenesis with the addition of nutrients, particularly N, resulted in minerals (iron-bearing and carbonates) transformation.

6.3.3. Biological amendment/effect of algae and detritus on COC flux and O_2 dynamics

Two tested species (*Chlorella kessleri and Sporosarcina pasteurii*) could reduce cap water turbidity effectively. Turbidity in *S. pasteurii*-amended columns decreased faster than in *C. kessleri*-amended columns, whereas *C. kessleri* amended columns achieved the lowest turbidity amongst all treatments. Nutrient (nitrate and phosphate) amendment can also stimulate the growth of indigenous microbes, which is consistent with the published research. Turbidity removal was also observed after nutrient amendment.

Removal of model naphthenic acids by *B. braunii*, *C. kessleri,* BML indigenous microbes, and a coculture of *C. kessleri* and BML indigenous microbes was investigated. Columns containing two microalgae exhibited degradation of all model naphthenic acids, and the corresponding degradation pathways were also proposed. Cyclohexane acetic acid (CHAA) degradation by BML indigenous microbes didn't occur during the experiment period (60 days). When *C. kessleri* and BML indigenous microbes were inoculated together, enhanced degradation rates of Cyclohexane butyric acid (CHBA) and Cyclohexane carboxylic acid (CHCA) were observed. Research about the possible synergistic relationship between the algae and the indigenous microorganisms and the change of indigenous microbial community after the addition of the *C. kessleri* culture is currently ongoing.

The relationship between the algae and the indigenous microorganisms and the change of indigenous microbial community after the addition of the *C. kessleri* culture was investigated. It was found that addition of *C. kessleri* can increase the bacterial diversity in the BML indigenous microbial community.

6.3.4. Surface water dilution effect

The 15 L columns were monitored for 62 days under quiescent condition. The overall percent turbidity reduction were similar 83-85% for all three dilutions (80%, 40% and 0% BML OSPW). The initial turbidity for the 80%-OSPW column was 275.5 NTU, and reduced to 41.5 NTU at day 62. The initial turbidity for the 40%-OSPW column was 155 NTU, and reduced to 24 NTU at day 62. Finally, the initial turbidity for the 0%-OSPW (or 100% BCR water) was 163 NTU, and reduced to 28 NTU. Findings from the 15 L columns supports the preliminary findings that water dilution might not assist in significant turbidity reduction.

6.3.5. Turbidity reduction through chemical coagulant addition in the Base Mine Lake water cap

The coagulation test in this study suggests that aluminum is a more effective coagulant than calcium to mitigate the initial mineral turbidity in the BML water cap. Following coagulant addition and lake mixis in BML, it is postulated that previously settled coagulant-treated particles and untreated FFT particles may be resuspended into the overlying water cap which has elevated levels of residual coagulant. The subsequent re-settling of these particles should be a function of the remaining coagulant dosage in BML water cap, the size of the resuspended coagulant-treated particles, and possible interactions between coagulant-treated and untreated FFT particles. The remaining coagulant in BML water cap can still enhance the coagulation of the resuspended particles. However, this effect will disappear once the remaining effective cation species is consumed down to the background level. In the laboratory columns, particles treated by a maintained their size and demonstrated possible interactions with untreated particles after resuspension, resulting a faster re-settling rate than Ca-treated particles. This suggests that aluminum is a promising coagulant to reduce additional turbidity introduced during lake turnovers in the following years after initial turbidity removal.

The actual BML system is much more complex than the laboratory system in this study. A number of processes could affect the turbidity in BML, and the field data obtained to date are insufficient to make any conclusions about the mixing mechanisms of suspended solids in the water cap. This study specifically targeted the increase in turbidity caused by resuspension of fine particles at the FFT-water cap interface.

6.3.6. Physical Modelling

Analysis of the experimental data reveals two key results: (1) Buoyant convection owing to temperature differences between the FFT and cap water seem to play effectively no role in the suspension of solids material from FFT, and, (2) Suspension as a result of ebullition is, by contrast, much more significant. Estimates suggest that ebullition is already a more substantial mudline mixing mechanism than are shear currents owing to wind-driven free surface waves. This may help to explain the persistently high turbidity measured under ice cover (when the lake is isolated from the atmosphere). It also suggests that suspended solids may remain elevated until such time as the rate of gas production due to e.g. biogenic processes in the underlying FFT begins to decrease.

6.4. Field investigation of BML water cap oxygen concentrations, consumption rates and key BOD/COD constituents affecting oxic zone development (Warren, Slater: University of Toronto, McMaster)

This program focuses on field investigation of the BML water cap, characterizing spatial and temporal in-situ variations in depth dependent: (1) physico-chemistry, (2) oxygen concentrations, (3) real-time oxygen consumption rates (OCR), (4) potential oxygen consuming constituents (OCC), (5) redox reactive geochemical species and (6) microbial communities. This program will establish temporal and spatial variability in in-situ BML water cap oxygen concentrations, oxygen consumption rates and identify the biogeochemical processes linked to its consumption from the FFT-water interface to the BML water surface. The outcomes will identify the key OCC and processes affecting oxygen status throughout the BML water cap as well as any early developmental stage trends in water cap dissolved oxygen dynamics.

Results from 2018 BML water cap characterization (14 sampling campaigns, 6-12 depths of the BML water cap sampled per campaign including February, March under ice in 2018 and May-August) have identified a developing, rapid biogeochemical developmental trajectory within the BML water cap that is in turn impacting water cap oxygen concentrations. The alum amendment in 2016 added to improved clarity and facilitated greater primary productivity. More algal growth has created more dead algal biomass which in turn, supports more organic carbon degrading bacteria which has increased oxygen consumption in the water cap; especially in the lower waters closest to the FFT. Thus, while there was some increase in the oxygen concentration in the upper epilimnetic waters (up to concentrations of 9 mg/L or ~ 280 uM), evidence of anoxia in BML bottom waters observed for the first time in August 2017 was also observed again in late July 2018. This may indicate that physical entrainment mechanisms might no longer maintain an oxic FFT water interface. This will be the focus of the next phase of the research program.

Further, hydrogen sulphide was detected within the bottom waters of BML for the first time during the 2018 anoxic period consistent with transport out of the FFT to a higher depth and/or active sulfate reduction occurring within the anoxic bottom waters.

Microbial community and functionality results also indicate a shift pre and post alum addition, consistent with the emergence of different functional groups (i.e. aerobic heterotrophs, sulfate reducers). Late 2018 summer methane concentrations were also lower than in previous years (< 30 uM) consistent with greater methanotrophy occurring within the bottom waters as well as at the FFT water interface during the portion of the summer it was oxic. Results have also shown widespread and present throughout the 2015-2018 sampling campaigns capabilities for sulfur metabolism within the BML water cap, indicating that increased sulfur cycling is likely to occur rapidly within this system as the results from 2017-2018 post alum suggest. This will be a particular focus of the research program moving forward.

6.5. Microbial communities and methane oxidation processes in Base Mine Lake (Dunfield: University of Calgary)

This research project has three main objectives: (1) to study Biological Oxygen Demand (BOD) in the water cap of BML, especially the role of the role of methane oxidation and nitrification in contributing to it, (2) to examine a potential role of methanotrophs in the degradation of naphthenic acids (NAs), and, (3) to examine the microbial community in the water cap of BML, and its dynamics over time. So far, the main results are:

1) Methanotrophy was potentially a major contributor to biological oxygen demand (BOD) in BML from 2015-2017, but both BOD and methanotrophic activity have been declining over the three years. Methanotrophic bacteria are also seasonally variable. In winter methanotrophy is detected throughout the water column, and cold-adapted methanotroph species are highly predominant, accounting for up to 40% of all bacteria in the water. In summer methanotrophs are less predominant in the water column, but instead more abundant near the FFT interface. Methane oxidation in the water column is therefore most important in winter and during spring and fall turnover; while in the summer methanotrophs are located primarily at the FFT interface.
2) Methanotrophic co-degradation of a model naphthenic acid (NA) was demonstrated for the first time. The NA was degraded by BML water only in the presence of methane, indicating that methanotrophs were key to the process. More experiments are needed to elucidate the process and its importance in BML, but this could have broad impacts for bioremediation of the lake.
3) Communities of both prokaryotic and eukaryotic microbes have been monitored over three years. Communities were highly variable in time, but not space, indicating that there are large seasonal effects but good mixing of cells throughout the lake. The diversity of bacteria has been relatively stable over three years, but the diversity of eukaryotes has steadily and significantly increased. The number of eukaryotic microbial species has increased 2-3 fold since 2015. This may be a sensitive indicator of declining water toxicity, as eukaryotes are very intolerant to toxicity. The lake is gradually supporting a more natural diversity of microbial eukaryotes. The addition of alum to the lake in late 2016 immediately enabled algae to bloom. Multiples species of green, brown, and golden algae bloomed at various times in the 12 months after alum addition.

6.6. Understanding Air-Water Exchanges and the long-term hydrological viability of Base Mine Lake (Carey, Humphreys: McMaster, Carleton)

This research has three main focus areas: determining factors that control evaporation from BML, understanding long-term water balance for BML, and will measure and improve the understanding of the physical mechanisms controlling CH_4 and CO_2 fluxes across the air-water interface using the eddy covariance technique. Detailed results from the evaporation and water balance components of this work contribute to the water balance estimates (see section 5.5).

Carbon dioxide fluxes measured with eddy covariance have been negligible from BML since the onset of measurements. Methane fluxes from BML are considerable and variable over season and potentially over time. Due to the challenges with instruments, it is difficult to evaluate if there are changes over time, yet observations from July through October suggest that there may be some decline in methane fluxes since 2015. The greatest variability in methane flux occurs immediately after ice-off and persists through May. Following this, fluxes become less variable temporally and increase slightly (in variability) in October. The flux footprint analysis indicates that the methane measurement is not biased by wind direction. However, this does not suggest that the results are representative of BML as a whole.

There is considerable short-term variability in methane flux. Preliminary results suggest that lake dynamics (ice-off, turnover) influence CH_4 on a seasonal scale, whereas pressure changes influence CH_4 flux on shorter synoptic time scales, with pressure drops associated with increases in methane flux.

Compared with other reservoirs, BML has a CH_4 flux slightly greater than those reported using the eddy covariance technique (Figure 6-1). There are several important items to note: (1) the method of CH_4 flux estimation has a very large influence on the flux estimate, with eddy covariance typically reporting high values, and, (2) the inter-annual variability in fluxes is large for BML (right panel). The left panel synthesized a large set of measurements to present a single value per reservoir which varies in the length of temporal resolution. This is a very important finding as it suggests that CH_4 flux, while large, is highly variable. The variability in this flux is the subject of continued research.

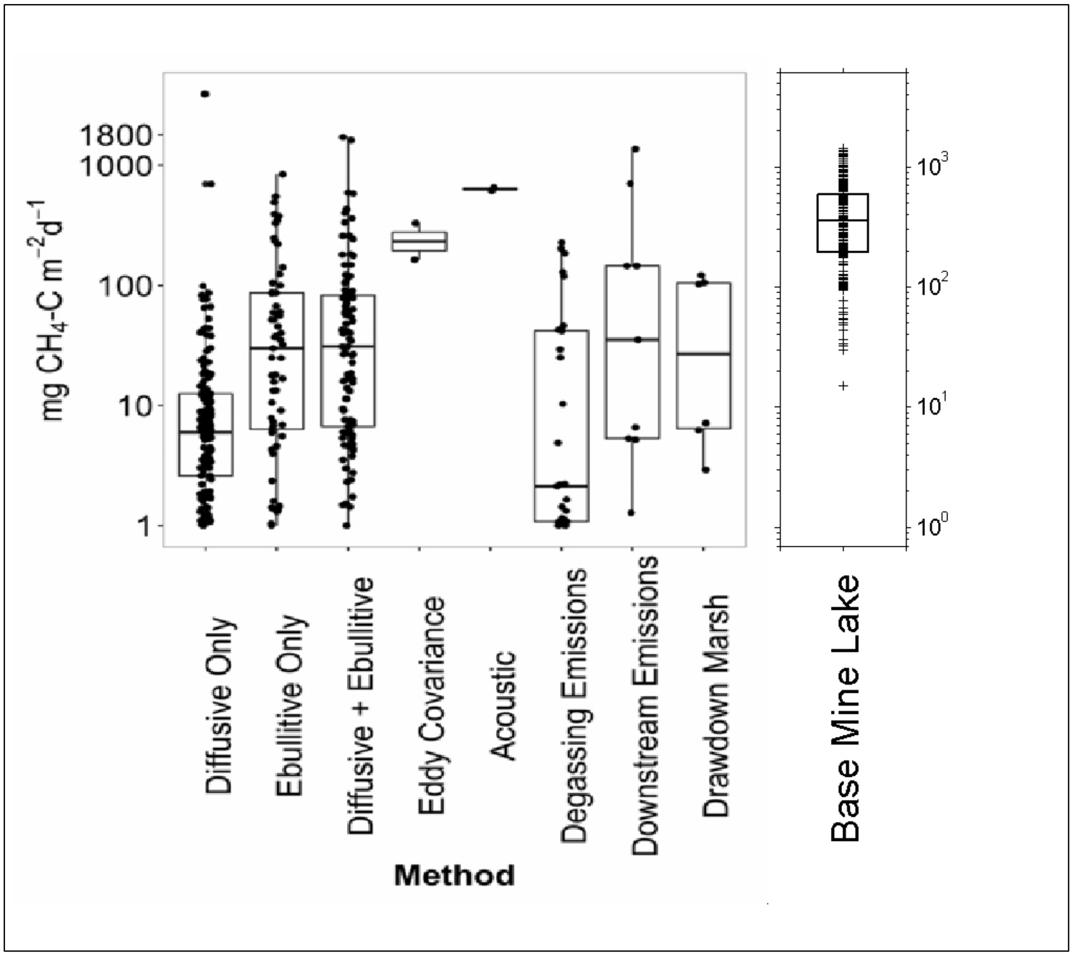


Figure 6-1: Areal Methane fluxes from BML compared to other reservoirs. Left panel is areal methane fluxes associated with reservoirs from Deemer *et al*. (2016). Values (dots) represent a single value per reservoir for a given method. Right panel is all daily methane flux data from BML.

6.7. List of Peer Reviewed Publications Produced by BML Research Programs

Research Project: University

Physical limnology of BML and the potential for meromixis: University of British Columbia

Publications:

Lawrence, G. A., Tedford E. W, and Pieters, R. 2016. Suspended solids in an end pit lake: potential mixing mechanisms. Can. J. Civ. Eng. 43:211-217

Tedford, E. W., Halferdahl, G., Pieters, R., and G. A. Lawrence. 2018. Temporal variations in turbidity in an oil sands pit lake. Environmental Fluid Mechanics. https://doi.org/10.1007/s10652-018-9632-6

Theses:

Hurley, David Lee. 2017. Wind waves and Internal Waves in Base Mine Lake. M.Sc. Thesis, University of British Columbia. 91 pp.

Characterization of controls on mass loading to an oil sands end pit lake: University of Saskatchewan

Publications:

Dompierre, K. A, and S. L. Barbour. 2016. Characterization of physical mass transport through oil sands fluid fine tailings in and end pit lake: a multi-tracer study. Journal of Contaminant Hydrology 189:12-26.

Dompierre, K. A., Lindsay, M. B. J., Cruz-Hernández, P., and Halferdahl, G. M. 2016. Initial geochemical characteristics of fluid fine tailings in an oil sands end pit lake. Sci Tot Env 556:196-206.

Dompierre, K., Barbour, S.L. (2017). “Thermal properties of oil sands fluid fine tailings: Laboratory and in-situ testing methods”, Canadian Geotechnical Journal, 2017, 54(3): 428-440.

Dompierre, K, Barbour, L, North, RL, Carey, SK, Lindsay, MB. (2017). “Chemical mass transport between fluid fine tailings and the overlying water cover of an oil sands end pit lake”, submitted to: Water Resources Res., Nov. 11.

Theses:

Dompierre, Kathryn, Ph.D. 2016. Controls on mass and thermal loading to an oil sands end pit lake from underlying fluid fine tailings. Ph.D. Thesis, University of Saskatchewan, Saskatoon, Canada, 157 pp.

Rudderham, S.B., 2019. Geomicrobiology and geochemistry of fluid fine tailings in an oil sands end pit lake. M.Sc. Thesis, University of Saskatchewan, Saskatoon, Canada, 98 pp.

Microbial communities and methane oxidation processes in Base Mine Lake: University of Calgary

Publications:

Aguilar M, Richardson E, Tan B, Walker G, Dunfield PF, Bass D, Nesbø C, Foght J, Dacks JB (2016) Next-generation sequencing assessment of eukaryotic diversity in oil sands tailings ponds sediments and surface water. J. Eukaryotic Microbiol. 63:732-743.

Rochman FF, Kim JJ, Rijpstra WIC, Sinninghe Damsté JS, Schumann P, Verbeke TJ, and Dunfield PF (2018) Oleiharenicola alkalitolerans gen. nov., sp. nov., a new member of the phylum Verrucomicrobia isolated from an oilsands tailings pond. International Journal of Systematic and Evolutionary Microbiology 68:1078-1084. doi: 10.1099/ijsem.0.002624

Rochman, F.F., Sheremet, A., Tamas, I., Saidi-Mehrabad, A., Kim, J.J., Dong, X, Sensen, C.W., Gieg, L.M., and Dunfield, P.F. (2017) Benzene and naphthalene degrading bacterial communities in an oil sands tailings pond. Frontiers in Microbiology 8: article 1845. doi: 10.3389/fmicb.2017.01845.

Rochman FF, Kim JJ, Rijpstra WIC, Sinninghe Damsté JS, Schumann P, Dunfield PF. Oleiharenicola alkalitolerans gen. nov., sp. nov., a new member of the Verrucomicrobia isolated from an oilsands tailings pond. International Journal of Systematic and Evolutionary Microbiology 68:1078-1084.

Saidi-Mehrabad A, Kits DK, Kim JJ, Tamas I, Schumann P, Khadka R, Rijpstra WIC, Sinninghe Damsté JS, Dunfield. PF. Methylomicrobium oleiharenae sp. nov., an aerobic methanotroph isolated from an oil sands tailings pond in Canada. submitted to International Journal of Systematic and Evolutionary Microbiology

Saidi-Mehrabad A, Kits DK, Kim JJ, Tamas I, Schumann P, Khadka R, Rijpstra WIC, Sinninghe Damsté JS, Dunfield. PF. (2018) Methylicorpusculum oleiharenae sp. nov., an aerobic methanotroph isolated from an oil sands tailings pond in Canada. International Journal of Systematic and Evolutionary Microbiology (in revision)

Theses:

Albakistani, Emad (2018) Methane Cycling and Methanotrophic Bacteria in Base Mine Lake, a Model End-Pit Lake in the Alberta Oilsands.

Haupt, Evan. (2016). Methanotrophic Bacteria and Biogeochemical Cycling in an Oil Sands End Pit Lake. MSc Thesis. University of Calgary. http://dx.doi.org/10.11575/PRISM/26893

Rawluk, Samuel (2017). The effect of chemical treatment on oil sand end-pit-lake microbial communities: an Investigation for a proxy of reclamation status. MSc in Sustainable Energy Development Capstone Project.

Rochman, Fauziah (2016) Aerobic hydrocarbon-degrading microbial communities in oilsands tailings ponds. PhD Thesis. University of Calgary. http://dx.doi.org/10.11575/PRISM/24733

Field investigation of BML water cap oxygen concentrations, consumption rates and key BOD/COD constituents affecting oxic zone development: University of Toronto, McMaster University

Publications:

Bowman, D.T., K.J. Jobst, X. Ortiz, E.J. Reiner, L.A. Warren, B.E. McCarry and G.F. Slater. 2018. Improved coverage of naphthenic acid fraction compounds by comprehensive two-dimensional gas chromatography coupled with high resolution mass spectrometry. J. Chromatography A. 1536:88-95. https://doi.org/10.1016/j.chroma.2017.07.017

Risacher, F., P.K. Morris, D. Arriaga, C. Goad, T Colenbrander Nelson, G.F. Slater and L.A. Warren 2018. The interplay of methane and ammonia as key oxygen consuming constituents in early stage development of Base Mine Lake, the first demonstration oil sands pit lake. Appl. Geochem. 93:49-59. https://www.sciencedirect.com/science/article/pii/S0883292718300738

Theses:

Arriaga, D. 2018. The Interplay of Physical and Biogeochemical Processes in Determining Water Cap Oxygen Concentrations within Base Mine Lake, the First Oil Sands Pit Lake, PhD Thesis, SGES, McMaster University.

Bowman, D. 2017. PhD. Chemical Fingerprinting of Naphthenic Acids by Comprehensive Two Dimensional Gas Chromatography Mass Spectrometry at Reclamation Sites in the Alberta Oil Sands PhD. McMaster University. 216 pp. http://hdl.handle.net/11375/21963

Goad, C. 2017. MSc. Methane biogeochemical cycling over seasonal and annual scales in an oil sands tailings end pit lake. McMaster University. 116 pp. http://hdl.handle.net/11375/21956

Morris, P.K. 2018. MSc. Depth Dependent Roles of Methane, Ammonia and Hydrogen Sulfide in the Oxygen Consumption of Base Mine Lake, the pilot Athabasca Oil Sands Pit Lake. McMaster University. 97 pp. http://hdl.handle.net/11375/23040

Risacher, F.F. 2017. MSc. Early stage water cap oxygen consumption trends within the first commercial scale oil sands pit lake, Base Mine Lake. McMaster University. 77 pp. http://hdl.handle.net/11375/22274

Laboratory studies investigating chemical flux across tailings-cap water zones, simulating an end pit lake in the Athabasca oil sands region (Ulrich, Flynn, Siddique: University of Alberta)

Publications:

Poon, H. Y., Brandon, J.T., Yu, X., and A. Ulrich. 2018. Turbidity mitigation in an oil sands pit lake through pH reduction and fresh water addition. Journal of Environmental Engineering. 144(12): 04018127-1 – 04018127-7.

Yu, X., Lee, K., Ma, B., Asiedu, E., Ulrich, A. 2018. Indigenous microorganisms residing in oil sands tailings biodegrade residual bitumen. Chemosphere, 209: 551-559.

Yu, X., K. Lee, and Ulrich, A. 2018. Model naphthenic acids removal by microalgae and Base Mine Lake cap water microbial inoculum. Submitted to Chemosphere on December 20, 2018.

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Brandon, J. T. 2016. Turbidity mitigation in an oil sands end pit lake through pH reduction and fresh water addition. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Alberta. 135 pp.

Poon, H.Y. 2019. An Examination on the Effect of Diluent on Microbial Dynamics in Oil Sands Tailings and the Mechanistic Insight on Carbon Dioxide-mediated Turbidity Reduction in Oil Sands Surface Water. Ph.D. Thesis, Department of Civil and Environmental Engineering, University of Alberta. 207 pp.

Samadi, Najmeh. 2019. Partitioning of contaminants between fluid fine tailings and cap water under end-pit lake scenario: Biological, chemical and mineralogical processes. M.Sc. Thesis, University of Alberta. 152pp.

Yu, X. 2019. Improving Cap Water Quality in An Oil Sands End Pit Lake with Microbial Applications. Ph.D. Thesis, Department of Civil and Environmental Engineering, University of Alberta.

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