2022 Pit Lake Monitoring and Research Report
(Base Mine Lake Demonstration Summary: 2012-2021)

Environmental Protection and Enhancement Act
Approval No. 26-03, as amended

Submitted to:

Alberta Energy Regulator

Submitted by:

Suncor Energy (Syncrude) Operating Inc. (SESOI)

June 30, 2022

LIMITATIONS

This report is provided to the Alberta Energy Regulator (AER) by Suncor Energy (Syncrude) Operating Inc. (SESOI) in its capacity as the operator of the Syncrude Project[1].

Findings and interpretations found in this report are superseded by any future Base Mine Lake report.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 Base Mine Lake 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] Referred to as Syncrude throughout the remainder of this submission.

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1 Executive Summary

Syncrude is committed to responsible oil sands development, which includes continuous improvement of our environmental performance and progressively reclaiming the land disturbed by our operations to meet mine decommissioning and closure objectives. Pit lakes are common closure landforms found in essentially all open pit mines throughout the world, including Alberta, regardless of the commodity extracted. The inherent nature of open pit mining lends itself to the creation of pit lakes once the mine pit has reached its end of life; therefore, they become critical components of all closure plans in the oil sands mining industry. Syncrude's 2016 Life of Mine Closure Plan (LMCP) includes three planned pit lakes at the Mildred Lake site (including Base Mine Lake) and one at the Aurora North site. These pit lakes are integral components of the Mildred Lake and Aurora North closure plans, regardless of whether they contain tailings, since it is imperative that both industrial wastewater[2] and surface water run-off can be effectively managed in the future post-closure landscape in order to support the planned end land use objectives.

The materials remaining after bitumen is extracted from oil sands are called tailings. Tailings are a mixture of sand, water, silt, clay and some residual hydrocarbons and salts, which are found naturally in oil sands deposits. The tailings are distributed hydraulically via a network of pipelines and deposited into in-pit or out-of-pit tailings storage facilities. A primary fluid tailings management challenge is considered to be the long period of time it can take for some of the smallest solid components (fines) to settle within the fluid tailings[3]. As a result, application of fluid tailings management or treatment technologies is typically necessary in order to meet reclamation and mine closure objectives. To address this challenge, Syncrude has developed and successfully implemented several tailings technologies to manage its fluid tailings, including the Water-Capped Tailings Technology (WCTT).

Syncrude first began investigating the WCTT in the early 1980's through the establishment of a research program founded on progressive scaled-up testing of water-capped fluid tailings. The technology involves the placement of fluid tailings in-pit, followed by capping with a sufficient layer of water; as a means of physically sequestering tailings solids within the pit lakes in the closure landscape and to enable low-energy water treatment processes within the engineered pit lake facility. The water layer becomes deeper as the tailings solids settle and pore water is expressed. As adequate water in-flows and out-flows are established to the lake, the water quality improves over time.

In 1994, Syncrude received endorsement from the Energy Resources Conservation Board (ERCB) for the proposed WCTT concept, as well as specific approval to develop Base Mine Lake as a full-scale demonstration of water-capped tailings in a pit lake. In 1995, Syncrude received *Environmental Protection and Enhancement Act* (EPEA) Approval No. 26-01-00 from the former Alberta Environmental Protection (AEP), which provided formal approval for the full-scale Base Mine Lake demonstration.

[2] The terms industrial wastewater, oil sands process-affected water (OSPW) and recycle water are used interchangeably throughout this report.

[3] The terms fluid tailings and Fluid Fine Tailings (FFT) are used interchangeably throughout this report.

For tailings ponds that transition into pit lakes, the lake is typically commissioned once tailings solids infilling is complete and the facility is no longer utilized for active tailings management. For the Base Mine Lake demonstration, placement of fluid tailings into the mined-out pit began in 1995 and was completed in late 2012. The facility was removed from Syncrude's active tailings network when it became commissioned as Base Mine Lake on December 31, 2012. During 2013, additional fresh water and process-affected water were added to the existing upper water layer to attain the final elevation. Infrastructure has been installed to pump fresh water into Base Mine Lake from Beaver Creek Reservoir and as required, water is pumped out of Base Mine Lake to the closed-loop Industrial Wastewater Control System where it is utilized as recycle water in the bitumen extraction process. This flow-through process dilutes the water cap and will be in place until a more substantial upstream surface watershed is reclaimed and connected to Base Mine Lake, and outflow is established to the receiving environment.

Syncrude submitted its first Base Mine Lake Research and Monitoring Plan to AEP in 1996. An updated Base Mine Lake Monitoring Plan and an updated Base Mine Lake Research Plan were further submitted to the former Alberta Environment and Sustainable Resource Development (AESRD) in 2012 and 2013, respectively. Syncrude submitted its latest Base Mine Lake Monitoring and Research Plan to the AER on November 13, 2020, which was authorized on April 22, 2021. As indicated in EPEA Approval No. 26-03 (as amended), the objective of the Base Mine Lake Monitoring and Research Plan 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."

Execution of the Base Mine Lake monitoring and research program began upon commissioning and is ongoing. The various components comprising the monitoring and research program are closely linked. A key purpose of the program is to continue to support the adaptive management of Base Mine Lake towards both the short- and long-term objectives. The monitoring and research program is designed to assess lake performance against key performance indicators and evaluate the need for management interventions. The initial focus of the monitoring and research program is to support the demonstration of the WCTT and to provide a body of scientific evidence which demonstrates that Base Mine Lake is on a trajectory to become integrated into the reclaimed landscape. The two key desired outcomes for Base Mine Lake that are important for the validation of WCTT are the physical sequestration of the tailings fines below the water cap and water quality improvements over time.

Demonstrating the physical isolation of tailings fines beneath the water cap of Base Mine Lake is considered a key performance outcome related to the validation of WCTT. To date, the results from the monitoring and research program indicate that the fine tailings is settling as forecasted by model predictions, the mudline is declining over time, 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 water layers. Surface water quality is also improving with time in Base Mine Lake, as expected to demonstrate the viability of the WCTT.

2 Introduction

2.1 Syncrude Project

The Syncrude Project is a Joint Venture undertaking among Suncor Energy Inc., Imperial Oil Resources Limited; Sinopec Oil Sands Partnership; and CNOOC Oil Sands Canada. The Syncrude Joint Venture currently holds eight oil sands leases (OSLs) and two major production facilities, located north of Fort McMurray, Alberta in the Regional Municipality of Wood Buffalo (RMWB). Current Syncrude production facilities include the Mildred Lake and Aurora North mines and bitumen production facilities, and the Mildred Lake Upgrader and supporting infrastructure, known collectively as the Syncrude Project. Suncor Energy (Syncrude) Operating Inc. became the project operator in 2021. Overviews of the Mildred Lake and Aurora North sites are provided in Figures 2-1 and 2-2, respectively.

Oil sands mining is currently achieved through truck and shovel surface mining technology. The oil sands ore is mixed with warm water and delivered to a primary extraction facility using hydro-transport technology. The extraction facility's role is to separate the bitumen from the oil sands. The produced bitumen froth is further processed at the Mildred Lake site through secondary extraction and upgrading, and produced into value-added light, sweet crude, called Syncrude Sweet Premium (SSP).

The materials remaining after bitumen is extracted from oil sands are called tailings. Tailings are a mixture of sand and a fluid component which consists of water, silt, clay and some residual hydrocarbons and salts, which are found naturally in oil sands deposits. The tailings are distributed hydraulically via a network of pipelines and deposited into in-pit or out-of-pit tailings storage facilities. The tailings storage facilities serve two important purposes; firstly, they serve as the primary source of recycle water for use in bitumen processing, and secondly, they serve as temporary or permanent containment areas for tailings materials. As surface mining advances, new in-pit containment dykes are often constructed to establish additional in-pit tailings storage facilities, as required.

Syncrude is committed to responsible oil sands development, which includes continuous improvement of our environmental performance and progressively reclaiming the land disturbed by our operations to meet mine decommissioning and closure objectives. Due to the longevity of oil sands mining projects, reclamation and closure planning and execution needs to be undertaken throughout the life of the project, and in consideration of the various milestones along the way. Syncrude's overarching objective is to develop a self-sustaining closure landscape, which attains the following fundamental goals:

- is integrated with the surrounding area;
- yields water suitable for return to the natural environment;
- has capability equivalent to that existing prior to development;
- establishes boreal forest uplands, wetlands and lake communities; and
- is planned in consultation with local, directly affected stakeholders.

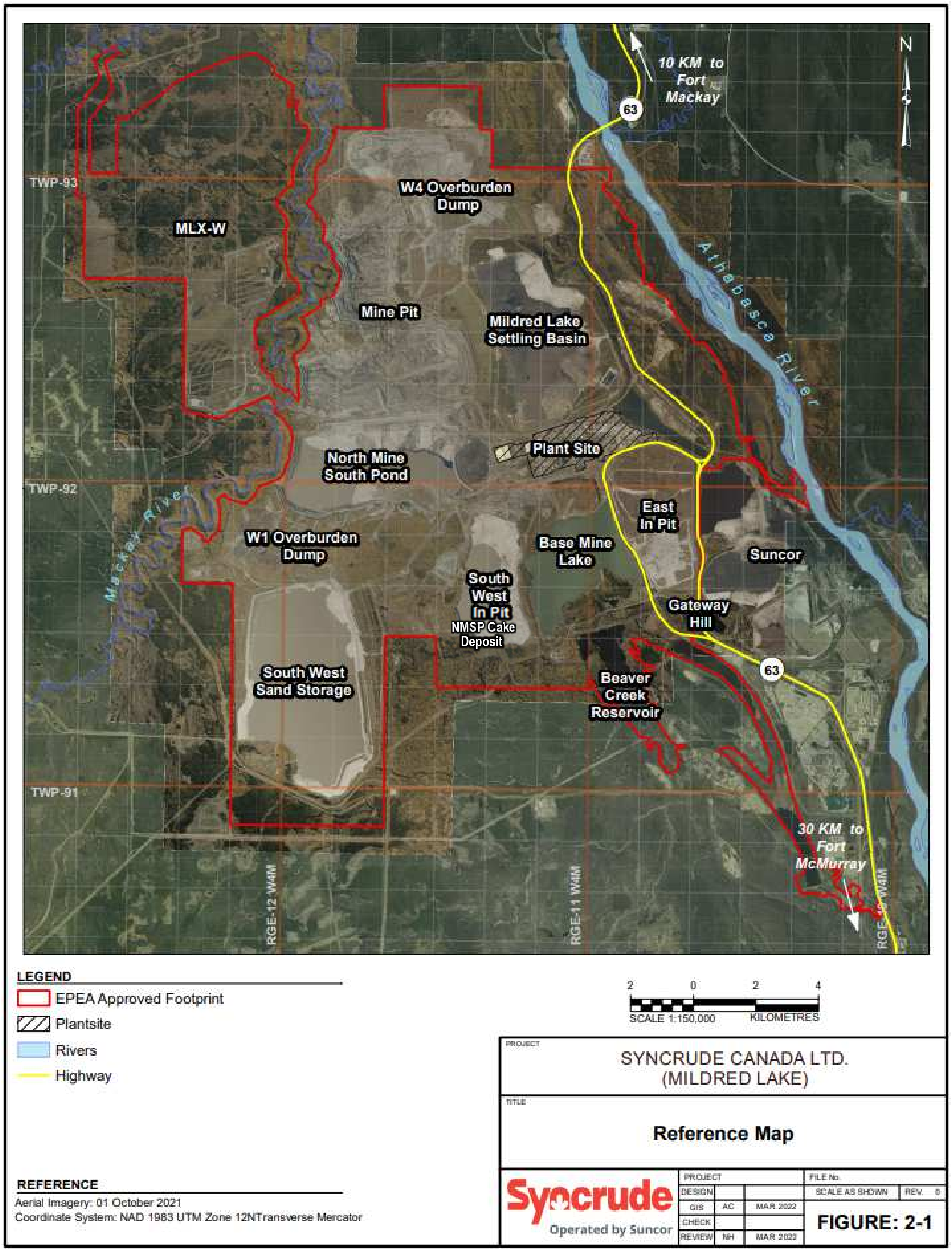

Figure 2-1: Mildred Lake Site Overview

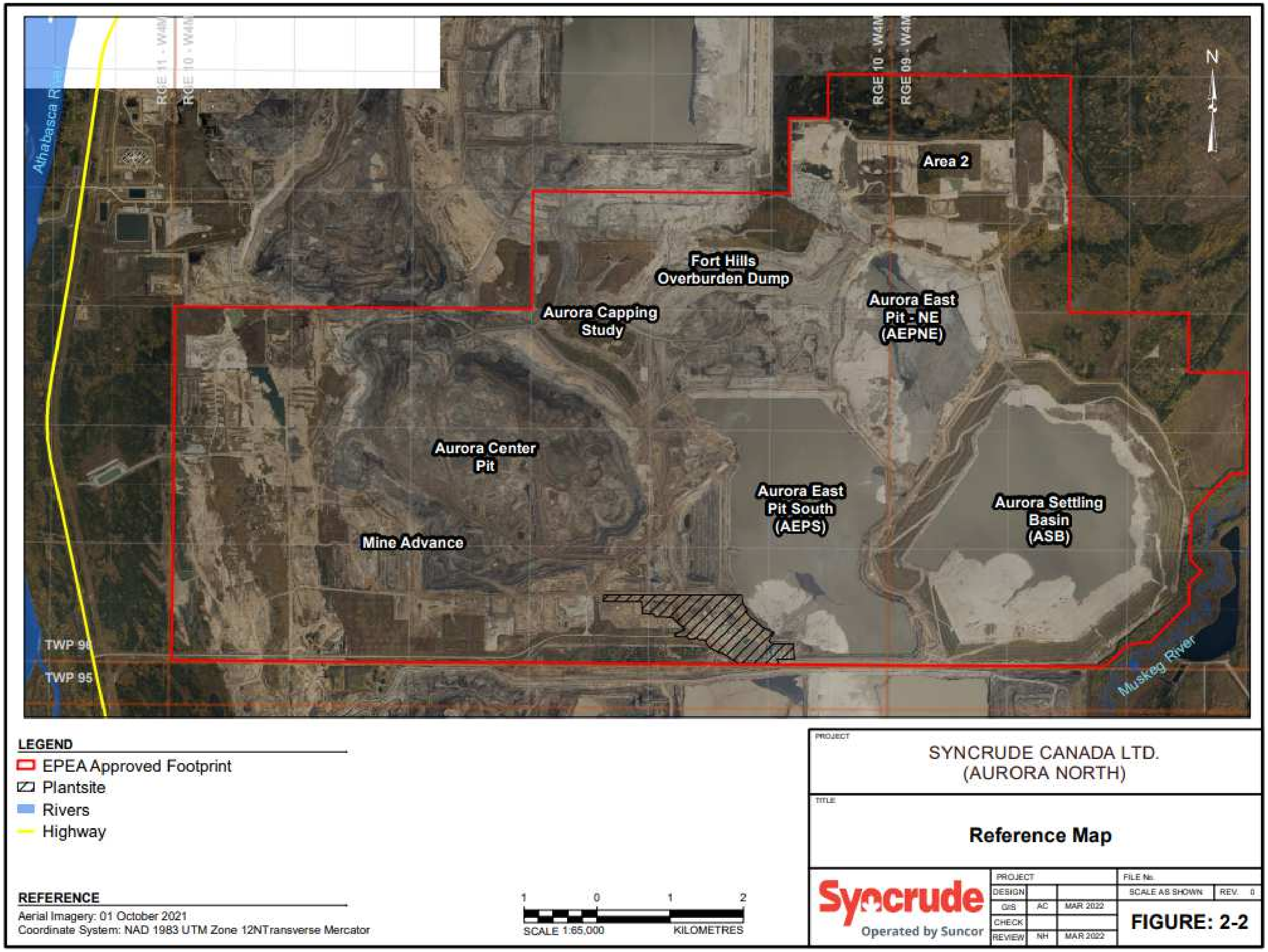

Figure 2-2: Aurora North Site Overview

2.2 Regulatory Context

Syncrude received *Environmental Protection and Enhancement Act* (EPEA) Approval 26-03-00 ("the EPEA Approval") from the Alberta Energy Regulator (AER) on June 18, 2020. The following Pit Lake Monitoring and Research Report is submitted to the AER in accordance with the EPEA Approval, which requires Syncrude to submit an annual "End Pit Lake Research and Development Report" and an annual "Base Mine Lake Monitoring and Research Summary Report", as follows:

5.2.3 The approval holder shall submit an End Pit Lake Research and Development Report to the Director on or before February 28, 2021, and every year thereafter, unless otherwise authorized in writing by the Director.[4]

7.5.16 The approval holder shall submit a Base Mine Lake Monitoring and Research Summary Report to the Director annually on June 30, starting in 2021, unless otherwise authorized in writing by the Director.

Base Mine Lake is Syncrude's first commercial scale demonstration of the WCTT within a pit lake; therefore, many of the research related reporting requirements under condition 5.2.3 are being addressed through the Base Mine Lake demonstration. In accordance with EPEA Approval conditions 7.5.5 and 7.5.7, Syncrude submitted an updated Base Mine Lake Monitoring and Research Plan to the AER on November 13, 2020, which was authorized on April 22, 2021. As per EPEA Approval condition 7.5.9:

> *"The objective of the Base Mine Lake Monitoring Plan and Base Mine Lake Research Plan referred to in subsections 7.5.5 and 7.5.7 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."*

In addition to internal research projects, Syncrude also participates in activities that support regional pit lake research initiatives through Canada's Oil Sands Innovation Alliance (COSIA). COSIA is an alliance of oil sands producers focused on accelerating the pace of improvement in environmental performance in Canada's oil sands through collaborative action and innovation. Along with Syncrude's Base Mine Lake demonstration, there are two other key research programs that directly support building knowledge about pit lakes in the oil sands region supported through partnerships at COSIA: Suncor's Lake Miwasin demonstration and the COSIA Demonstration Pit Lake Mesocosm study. A summary of these programs is provided in Section 3.7.

It is Syncrude's interpretation that the annual report requirements listed under EPEA Approval condition 5.2.4 are primarily focused on pit lake designs and plans, rather than pit lake research. Many of these plans have been provided to the AER in previous EPEA and/or *Oil Sands Conservation Act* (OSCA) approval submissions or are subject to future submissions as required under Syncrude's most

[4] As per AER File No. 4101-00000026-0202, on February 8, 2022, Syncrude received authorization to extend the submission date of the End Pit Lake Research and Development Report from February 28, 2022 to June 30, 2022.

recent EPEA and OSCA approvals. In alignment with ongoing efforts to reduce regulatory red tape and improve regulatory efficiency, Table 2-1 lists the reporting requirements under EPEA Approval condition 5.2.4 and the relevant Syncrude submissions where the information has been or will be provided to the AER. Table 2-2 outlines the Base Mine Lake monitoring and research reporting requirements, as per EPEA Approval condition 7.5.17, and the sections in this report which satisfy the requirements.

Table 2-1: Pit Lake Research and Development Report Concordance

Condition 5.2.4 Requirement	Submission
The End Pit Lake Research and Development Report referred to in subsection 5.2.3 shall address, at a minimum, all of the following with specific reference to the tailings technology used by approval holder:	
(a) a proposed schedule for all research and development undertaken, including a mechanism to track progress towards meeting the schedule over time;	Base Mine Lake Monitoring and Research Plan
(b) water budgets and solute mass balances for end pit lakes including quantities, sources and quality of water to be used to fill the lake, and including groundwater recharge and seepage rates and quality;	Life of Mine Closure Plan Mine Reclamation Plan Base Mine Lake Monitoring and Research Plan
(c) identification of key uncertainties in the water budget and solute mass balances and proposed research to address these uncertainties with particular attention to the hydrology of the effective catchment area and connectivity with groundwater;	Life of Mine Closure Plan Base Mine Lake Monitoring and Research Plan
(d) research assumptions, predictions, and validations to support fisheries, aquatic resources, and aquatic habitat: (i) as proposed in the closure landscape at various timeframes of end pit lake development for each the following: (A) chemical and physical behavior of untreated or treated tailings placed in an end pit lake; (B) water quality and toxicity; (C) geotechnical stability; and, (D) effects of long-term shoreline retrogression. (E) landform design; and	Base Mine Lake Monitoring and Research Plan Pit Lake Monitoring and Research Annual Report

Condition 5.2.4 Requirement	Submission
(F) sustainable water levels and hydrological connectivity under a range of late 21st century regional climate change scenarios developed by the Intergovernmental Panel on Climate Change; (ii) for water release scenarios;	
(e) estimates of water quality concentrations at closure for end pit lakes for parameters identified as substances of concern by the Director, including assumptions on decay rates and partitioning;	Life of Mine Closure Plan
(f) confirmation of the assumptions and expectations for water quality release outlined in the application, including refinement, update, and validation of the predictive models;	Life of Mine Closure Plan Base Mine Lake Monitoring and Research Plan Pit Lake Monitoring and Research Annual Report
(g) an indication of treatment efficiency required for end pit lakes to maintain suitable water quality given the quality of the source waters and the research;	Base Mine Lake Monitoring and Research Plan Pit Lake Monitoring and Research Annual Report
(h) the role of wetlands, riparian habitat and littoral zone in creating continuity between the reclaimed landscape and end pit lakes;	Life of Mine Closure Plan
(i) identification of wetland/macrophyte research that will be required to ensure proposed end pit lakes provide sustainable habitat and achieve other functions such as enhanced water treatment, shoreline protection and flood buffering;	COSIA Annual Reports
(j) watershed hydrologic connections and associated closure goals and targets for fish and fish habitat;	Life of Mine Closure Plan
(k) consideration of potential elevated contaminant influences on fish ecology, health, palatability and consumption safety;	Base Mine Lake Monitoring and Research Plan
(l) consideration of long-term shoreline retrogression and related effects on littoral zone, adjacent wetlands, landforms, and water budget and solute mass balances (especially in relation to evaporation);	Base Mine Lake Monitoring and Research Plan

Condition 5.2.4 Requirement	Submission
(m) identification of research that will be required to ensure end pit lakes adequately: (i) treats site drainage; (ii) provides a sustainable aquatic ecosystem and aquatic habitat; (iii) is geotechnically stable; and (iv) achieves other functions such as shoreline protection and flood buffering;	Base Mine Lake Monitoring and Research Plan
(n) lake design features which: (i) promote natural biodegradation and detoxification rates for toxic parameters; (ii) minimize erosion and protect shorelines; (iii) promote recreational, domestic and commercial fisheries potential; and (iv) optimise water residence time with particular consideration of salinity;	Life of Mine Closure Plan Base Mine Lake Monitoring and Research Plan
(o) biodegradation, detoxification and dilution of parameters identified as substances of concern by the Director;	N/A
(p) research related to subsections 5.1.2(d) and 5.1.2(e) for end pit lakes;	Base Mine Lake Monitoring and Research Plan
(q) a review and assessment of other mitigative options for end pit lakes if water quality is a concern;	COSIA Annual Reports
(r) adaptive incorporation of any guidelines prepared or provided by the Director related to end pit lakes;	N/A
(s) identification of research or modelling limitations and uncertainties in achieving the targeted locally common boreal forest closure outcomes;	Life of Mine Closure Plan Base Mine Lake Monitoring and Research Plan
(t) plans and schedules to address research or modelling limitations and uncertainties in achieving the targeted locally common boreal forest closure outcomes;	Life of Mine Closure Plan Base Mine Lake Monitoring and Research Plan

Condition 5.2.4 Requirement	Submission
(u) the applicability of Syncrude Canada Limited Base Mine Lake (BML) research to the other proposed water capped end pit lakes;	Life of Mine Closure Plan Base Mine Lake Monitoring and Research Plan
(v) how Syncrude will address uncertainties and risks where BML research is not applicable;	Life of Mine Closure Plan Base Mine Lake Monitoring and Research Plan
(w) the rationale for the siting of the proposed end pit lakes adjacent to the Athabasca River and McKay River escarpments, including: (i) the benefits and disadvantages of relocating the proposed pit lakes farther away from the Athabasca River and McKay River escarpments;	Life of Mine Closure Plan
(x) data submission and reporting schedule; and	Base Mine Lake Monitoring and Research Plan
(y) any other information as required in writing by the Director.	N/A

Table 2-2: Base Mine Lake Monitoring and Research Summary Report Concordance

Condition 7.5.17 Requirement	Report Section
The Base Mine Lake Monitoring and Research Summary Report referred to in subsection 7.5.16 shall include the following, unless otherwise authorized in writing by the Director:	
(a) a summary of the results of monitoring for the previous year;	7
(b) a summary of the results of research for the previous year;	8
(c) a description and presentation of trends across all timeframes;	7
(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	N/A
(f) any other information as required in writing by the Director.	N/A

The following Pit Lake Monitoring and Research Report summarizes the key findings from the Base Mine Lake monitoring and research program for 2021. Background information is provided for additional context, in order to support the reader's understanding and interpretation of the information.

3 Background

3.1 Tailings Management and Closure Regulatory Overview

Reclamation and closure of industrial sites is a requirement under Alberta legislation; primarily under EPEA for the mineable oil sands. In order to meet the Province's reclamation and closure objectives for oil sands mining projects, in 2015 the Government of Alberta (GoA) released the *Tailings Management Framework for the Mineable Athabasca Oil Sands* (TMF), which seeks to balance environmental protection and the associated risk of increasing fluid tailings volumes. The primary objective of the TMF is to reduce fluid tailings accumulation on the landscape by ensuring that fluid tailings are managed such that they can achieve a Ready-to-Reclaim state in a timely manner, which may reduce the potential for negative environmental effects. Requirements under the TMF are administered primarily through OSCA and EPEA:

- Under OSCA, *Directive 085: Fluid Tailings Management for Oil Sands Mining Projects* (Directive 085) sets out the requirements for managing and reporting fluid tailings volumes for oil sands mining projects to meet the intended outcomes set forth under the TMF.

- Under EPEA, *Specified Enactment Direction 003: Direction for Conservation and Reclamation Submissions Under an Environmental Protection and Enhancement Act Approval for Mineable Oil Sands Sites* (SED-003) outlines the requirements for the collection and reporting of conservation and reclamation information to the AER to fulfill the terms and conditions of the EPEA approval.

In addition, fluid tailings dam or impoundment requirements are managed through the *Water Act* and the *Alberta Dam and Canal Safety Directive* (Dam Safety Directive). The Dam Safety Directive contains requirements for dam owners that are applicable to the entire life cycle of a dam. *Manual 019: Decommissioning, Closure, and Abandonment of Dams at Energy Projects* (Manual 019) is a guide focused on section 9 of the Dam Safety Directive and provides additional guidance regarding decommissioning, closure, and abandonment plans and completion reports for tailings facilities with dams regulated by the AER.

In accordance with the legislation and requirements outlined above and in compliance with Syncrude's approvals and authorizations issued under EPEA, OSCA and the *Water Act*, Syncrude submits several plans and reports to the AER related to tailings management, dam abandonment, reclamation and closure. Key submissions associated with tailings reclamation and closure are summarized below.

- Life of Mine Closure Plan

  A Life of Mine Closure Plan (LMCP) is a project-level plan required under EPEA (SED-003) for mineable oil sands projects. Syncrude submitted an updated LMCP to the AER in 2016 for the Mildred Lake and Aurora North sites. The LMCP functions as Syncrude's conceptual plan for the orderly and sustainable progression of reclamation activities to achieve a state of final closure and to accommodate all constituent requirements including fluid tailings management, as well as dam closure and abandonment. The LMCP is aligned with the goal of equivalent land capability and is designed to support commercial, recreational and traditional end-land uses. As required under condition 7.3.8 of the EPEA Approval, Syncrude will be submitting an updated LMCP to the AER in 2023. Performance reporting is completed through the submission of Annual Reclamation Progress Tracking Reports, in accordance with SED-003 and Syncrude's EPEA Approval.

- Tailings Management Plan

  A Tailings Management Plan (TMP) is a project-level plan required under OSCA (Directive 085) for mineable oil sands projects. Syncrude submitted updated TMPs to the AER in 2016 for the Mildred Lake and Aurora North sites. The TMPs are aligned with the principles and objectives in the TMF and provide an overview of Syncrude's plans for managing and treating new and legacy fluid tailings throughout the life of the Mildred Lake and Aurora North projects. As required under condition 17 of Mildred Lake OSCA Approval No. 8573Q and condition 13 of Aurora North OSCA Approval No. 10781N, Syncrude will be submitting updated TMPs to the AER in 2023. Performance reporting is completed through the submission of Annual Fluid Tailings Management Reports, in accordance with Directive 085 and Syncrude's OSCA Approvals.

- Dam Decommissioning, Closure, and Abandonment Plan

  A Dam Decommissioning, Closure and Abandonment Plan (DCAP) is a facility-level plan required under the *Water Act* (Dam Safety Directive) for tailings facilities with dams regulated by the AER, which have an accepted consequence classification of significant, high, very high or extreme. As required under the Dam Safety Directive, a DCAP must address all stages of decommissioning, closure and abandonment of the dam. The scope of the DCAP is determined by qualified professionals and is based on the consequence classification or risk posed by the structures. Performance reporting is completed through the submission of Annual Performance Reviews, in accordance with the Dam Safety Directive and Syncrude's *Water Act* Approvals.

Figure 3-1 provides an overview of Syncrude's understanding of the tailings management and closure regulatory framework in Alberta.

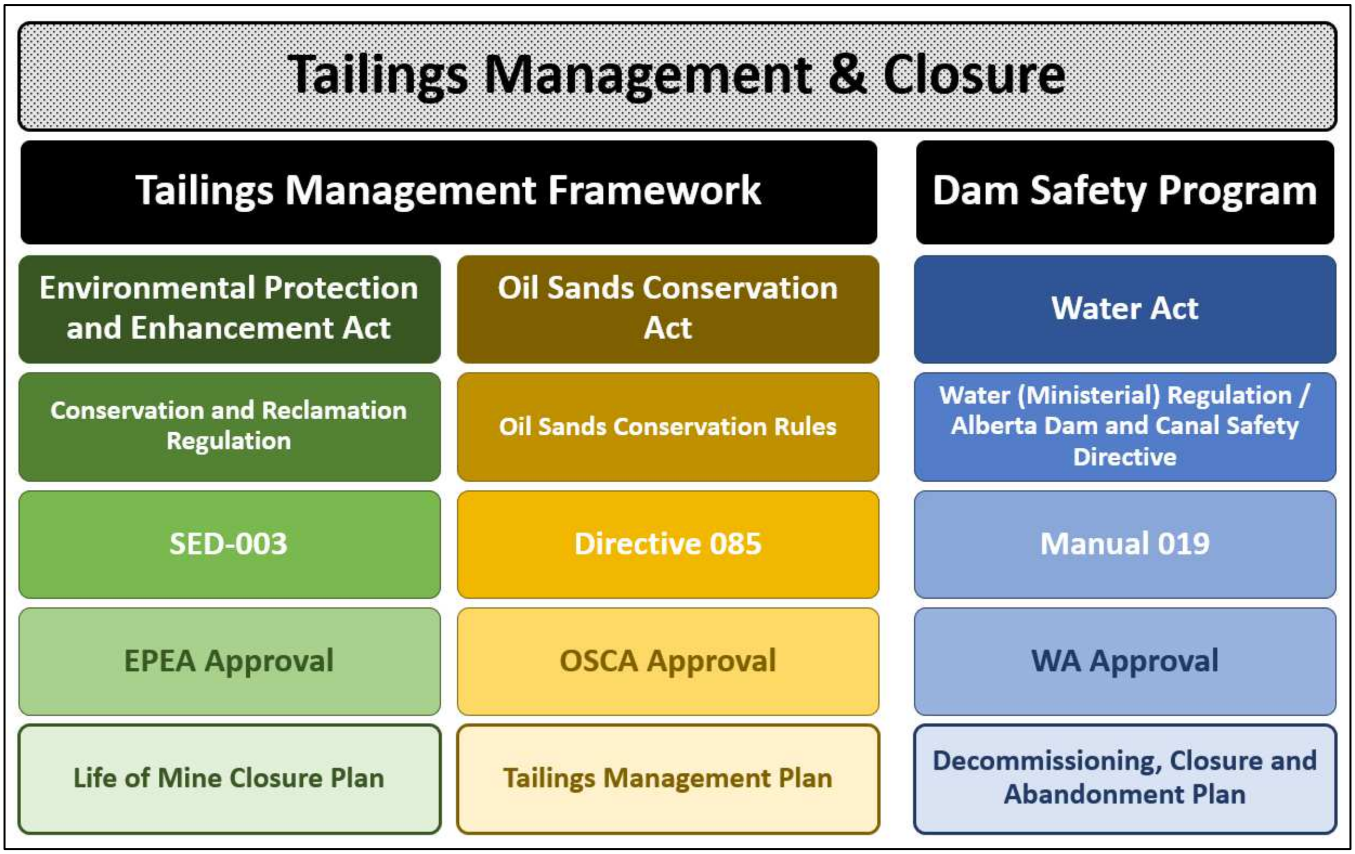

Figure 3-1: Tailings Management and Closure Regulatory Overview

3.2 Syncrude Fluid Tailings Management Technologies

A primary fluid tailings management challenge is considered to be the long period of time it can take for some of the smallest solid components (fines) to settle within the fluid tailings. As a result, application of fluid tailings management or treatment technologies is typically necessary in order to meet reclamation and mine closure objectives. Tailings technology development at Syncrude typically utilizes a progressive scale-up process beginning with bench scale laboratory testing, followed by field pilots (often multiple tests with increasing scale) and, if validated and selected, commercial implementation. This process has been successfully implemented for the tailings technologies currently approved for use or under commercial development at Syncrude, including:

- Water-Capped Tailings Technology (Base Mine Lake demonstration);
- Composite Tailings;
- Centrifuge Cake;
- Fluid Tailings/Overburden Co-mixing; and
- Flocculated Tailings.

In addition, Syncrude is also assessing further opportunities for co-deposition of different tailings materials. Tailings co-deposition is a depositional strategy which involves the intentional placement of more than one tailings product into a single containment structure, without separation by divider dykes. This approach to tailings deposition improves tailings storage efficiency by not requiring additional dykes or berms to separate each tailings product. While co-deposition in itself is not a technology, the depositional environment of the tailings product(s) has the potential to improve deposit performance through enhanced dewatering and consolidation by combining tailings materials with complementary properties.

Figure 3-2 provides an overview of Syncrude's current and proposed fluid tailings management technologies, including WCTT.

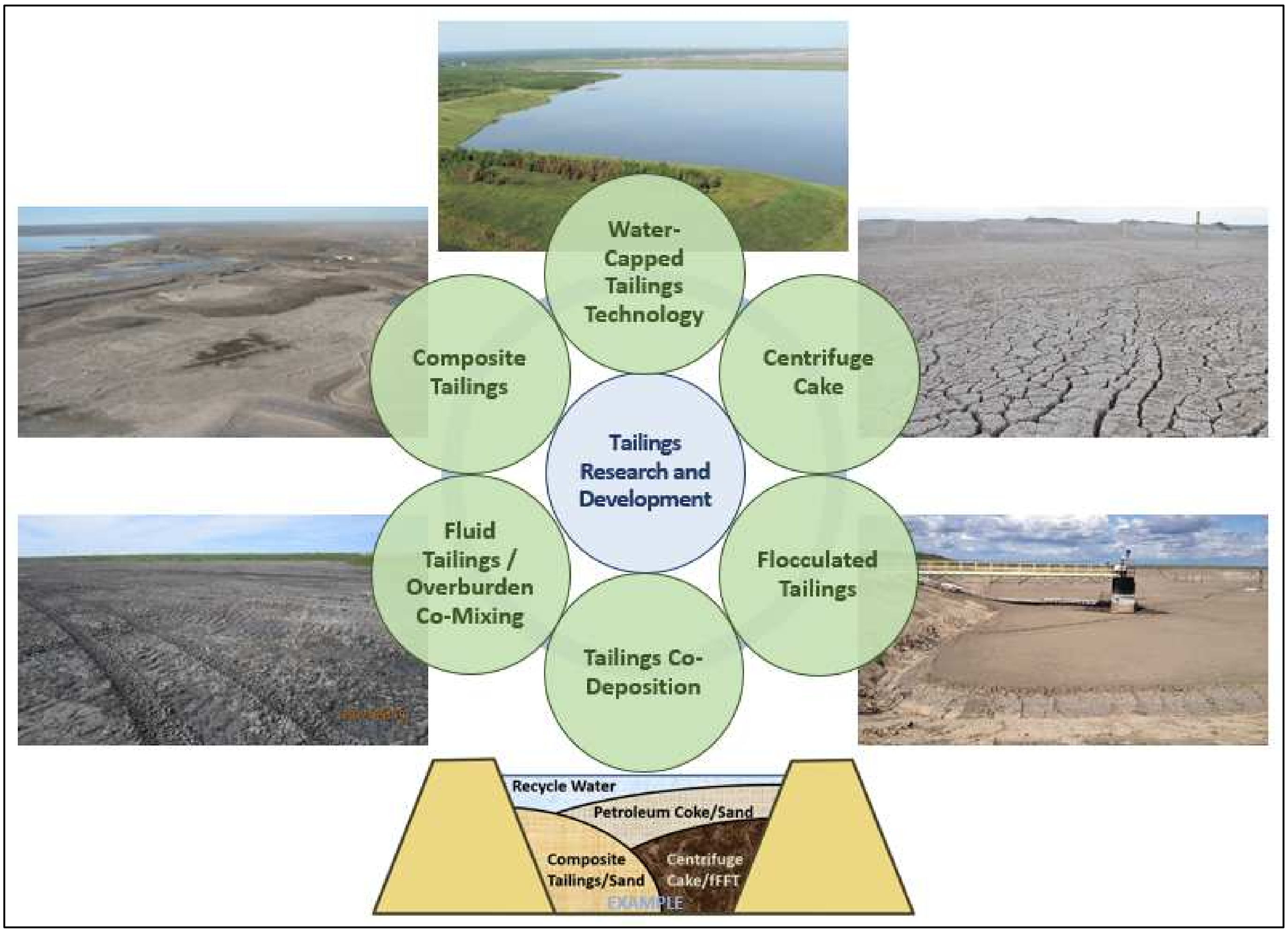

Figure 3-2: Overview of Syncrude Fluid Tailings Management Technologies

3.3 Water-Capped Tailings Technology Development

Pit lakes are common closure landforms found in essentially all open pit mines throughout the world, including Alberta, regardless of the commodity extracted. The inherent nature of open pit mining lends itself to the creation of pit lakes once the mine pit has reached its end of life; therefore, they become critical components of all closure plans in the oil sands mining industry. An oil sands pit lake is an area where overburden and oil sand has been removed through surface mining and is then filled with fluids prior to mine closure. Pit lakes contain water (from the process of oil sands extraction or from the environment, or both) and may or may not contain fluid tailings and/or other solids (e.g., coarse tailings sand, mine overburden).

Water-Capped Tailings Technology (WCTT) involves the placement of a water layer of sufficient depth over fluid tailings as a means of physically sequestering the tailings solids within the pit lakes in the closure landscape and to enable low-energy water treatment processes within the engineered pit lake facility. Based on extensive research, modelling, and experience, the expectation for WCTT is that the tailings solids remain sequestered below the water cap and the pit lake water quality improves with time. In simple terms, the water in the spaces between the finer (clay) particles moves to the surface as the particles settle. The water cap becomes deeper as the solids consolidate and release pore water. As adequate water in-flows and out-flows are established, the lake water quality improves over time.

A simplified overview of the fluid tailings settlement and increasing water cap depth over time is provided in Figure 3-3. Figure 3-4 provides a schematic of the WCTT concept.

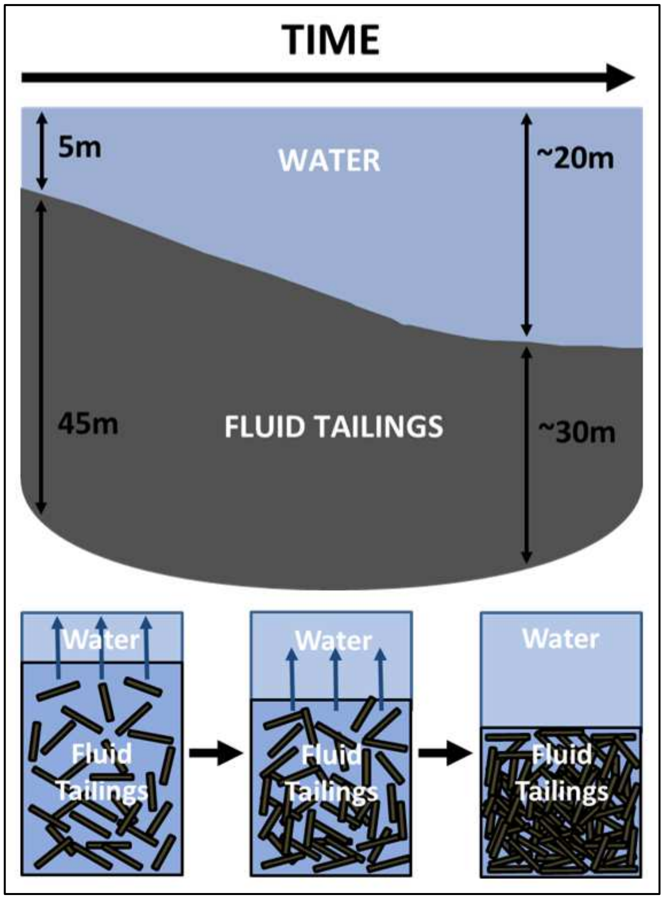

Figure 3-3: Simplified Depiction of Water-Capped Tailings Settlement over Time (not to scale)

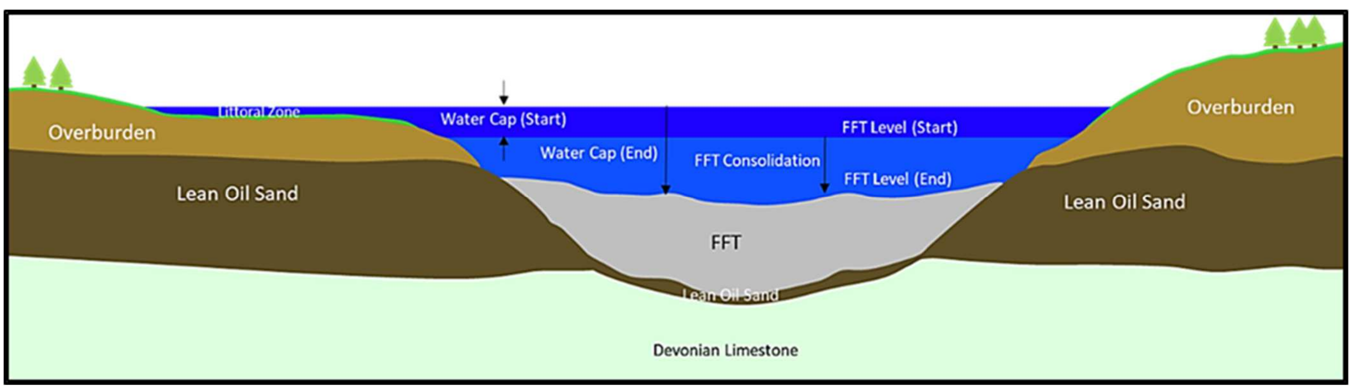

Figure 3-4: Water-Capped Tailings Technology Schematic (not to scale)

Syncrude first began investigating the WCTT over four decades ago through the establishment of a research program founded on progressive scaled-up testing of water-capped fluid tailings. Research began in the early 1980's with bench scale laboratory studies and from 1989 to 2012 the studies were scaled up to a series of 'surrogate lake' basins, consisting of 12 pilot test ponds ranging in size from roughly 0.5 to 4.0 hectares and from 2,000 m^3 to 140,000 m^3 total volume. Some ponds were filled with roughly three metres of fluid tailings and capped with water from a range of sources. Monitoring of the test ponds continued until 2012. Some key findings from the Syncrude Test Ponds and modelling activities include:

- Naturally occurring bacteria were able to break down many compounds, such as ammonia, sulfate and dissolved organics;
- The relatively small-scale test ponds demonstrated that acute water toxicity dissipated quickly and chronic toxicity declined over time. These small ponds did not reflect normal boreal lake mixing dynamics that are important drivers of lake performance at full-scale; and
- For the Base Mine Lake configuration, including the lake size and orientation, the water cap must be at least five metres deep to prevent fines from the lake bottom from being re-suspended by wind-generated waves (Lawrence, 1991).

The learnings from the decades of laboratory and field pilot research, monitoring and modelling were used to develop the Base Mine Lake demonstration at Syncrude's Mildred Lake plant site, which was commissioned on December 31, 2012.

Figure 3-5 provides an overview of the WCTT research and development progression at Syncrude.

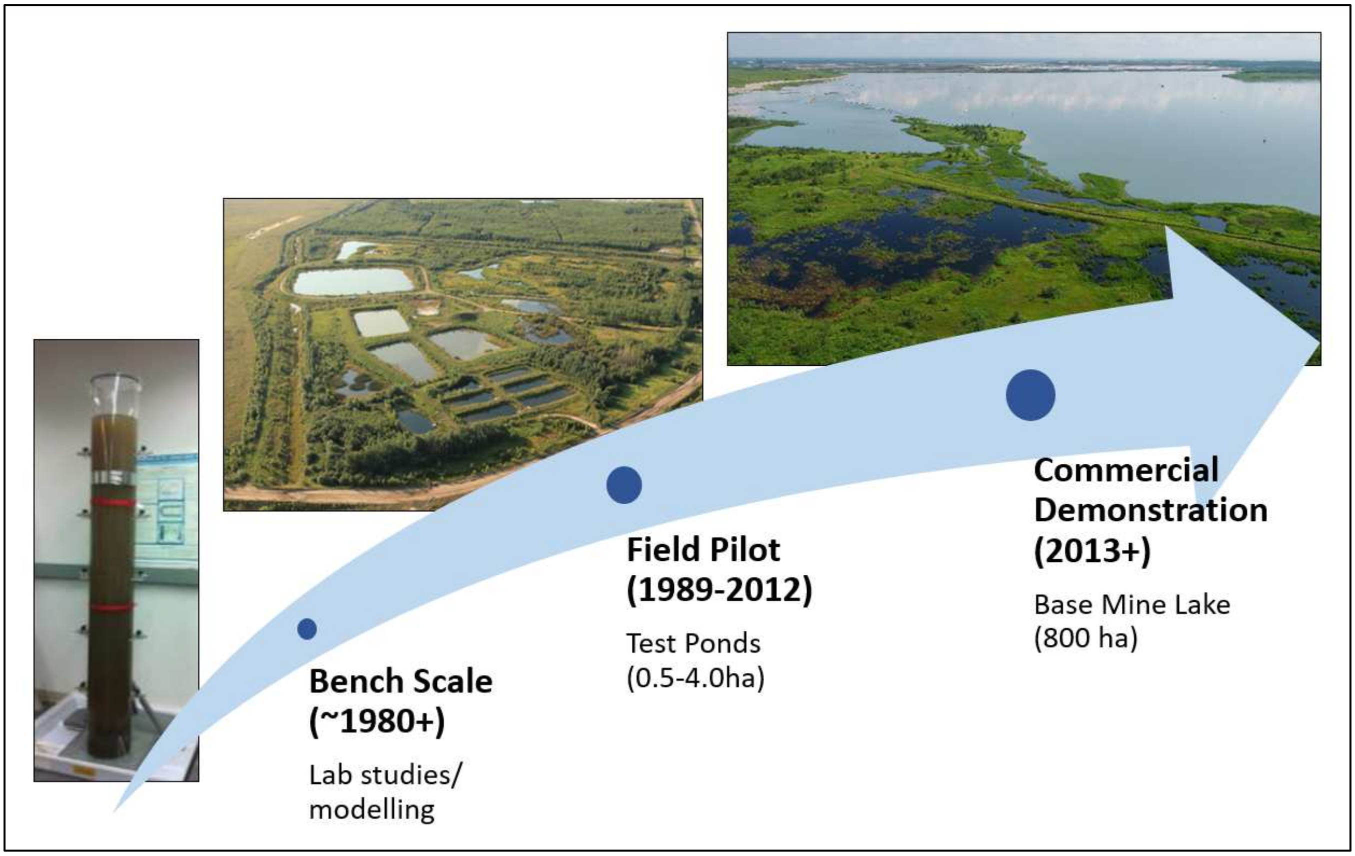

Figure 3-5: Progression of Water-Capped Tailings Research and Development

3.4 Water-Capped Tailings Approval History

Pursuant to the *Oil Sands Conservation Act* (OSCA), in September 1992 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. 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 tailings (FFT) 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 WCTT 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 FFT with a 5 m water cap. This test became known as the Base Mine Lake (BML) demonstration.

In July 1994, Syncrude received endorsement from the ERCB for the proposed WCTT concept, as well as specific approval to develop BML as a full-scale demonstration of WCTT in a pit lake; as indicated in the decision report for Application No. 921321 (Decision 94-5), as follows:

> 5. The conceptual mining, lease development and reclamation plans, including the proposed water-capped lakes technique for fine tails reclamation, are endorsed subject to:
>   - Syncrude developing the 'base mine lake' with a suitable monitoring program and successfully demonstrating the associated reclamation technique, and
>   - Syncrude continuing research and development efforts into alternative reclamation and tailings management technologies.
>
> 7. The development of the base mine demonstration lake is specifically approved subject to Syncrude developing associated comprehensive monitoring and scientific investigation programs in consultation with its stakeholders.

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 Base Mine Lake 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.

As required under clause 12.3.13 of EPEA Approval No. 26-01-00, Syncrude submitted its first Base Mine Lake Research and Monitoring Plan to AEP on June 26, 1996. An updated Base Mine Lake Monitoring Plan and an updated Base Mine Lake Research Plan were further submitted to Alberta Environment and Sustainable Resource Development in 2012 and 2013, respectively, in accordance with conditions 6.1.91 and 6.1.92 of EPEA Approval No. 26-02-05. Syncrude's most recent Base Mine Lake Monitoring and Research Plan was submitted to the AER on November 13, 2020, in accordance with conditions 7.5.5 and 7.5.7 of EPEA Approval No. 26-03-00; Syncrude received AER authorization for the plan on April 22, 2021.

3.5 Tailings Pond Progression into a Pit Lake

Disturbed land resulting from Syncrude's oil sands mining projects progresses through a number of defined stages towards ultimate reclamation certification, and transition from one stage to the next is typically separated by a defined progressive reclamation milestone. Reclamation stages are periods characterized by time and/or activities, and reclamation milestones are checkpoints that are characterized by the attainment of defined performance expectations.

For landforms containing fluid tailings, the first milestone is typically meeting Ready-to-Reclaim (RTR) criteria. Directive 085 defines RTR as the "state achieved when fluid tailings have been processed through an accepted technology, have been placed in their final landscape position, and have achieved necessary performance criteria." As described in the TMF, becoming RTR is just one stage in the process of progressive reclamation for fluid tailings deposits. Once a fluid tailings deposit meets its defined RTR criteria, it is considered to be on the trajectory towards being "ready for reclamation". SED-003 defines "ready for reclamation" as "areas that are no longer required for mine or project purposes and are available for reclamation but where reclamation has not yet started." As explained in Directive 085:

- "Ready to Reclaim" is used to track the performance of treated fluid tailings in active, operational tailings deposits; and
- "Ready for Reclamation" is used to identify project areas (inclusive of tailings deposits) that are no longer operational and are available for reclamation to begin.

For tailings ponds that transition into pit lakes, the pit lake is typically commissioned once tailings solids infilling is complete and the facility is no longer utilized for active tailings management. It is at this stage that the facility is considered "ready for reclamation", although reclamation of the surrounding slopes, littoral zone and water-capping activities have likely already commenced.

Figure 3-6 illustrates the relationship between reclamation stages, as well as progressive reclamation and certification milestones for pit lakes and aquatic reclamation, as provided by Syncrude in the 2016 LMCP.

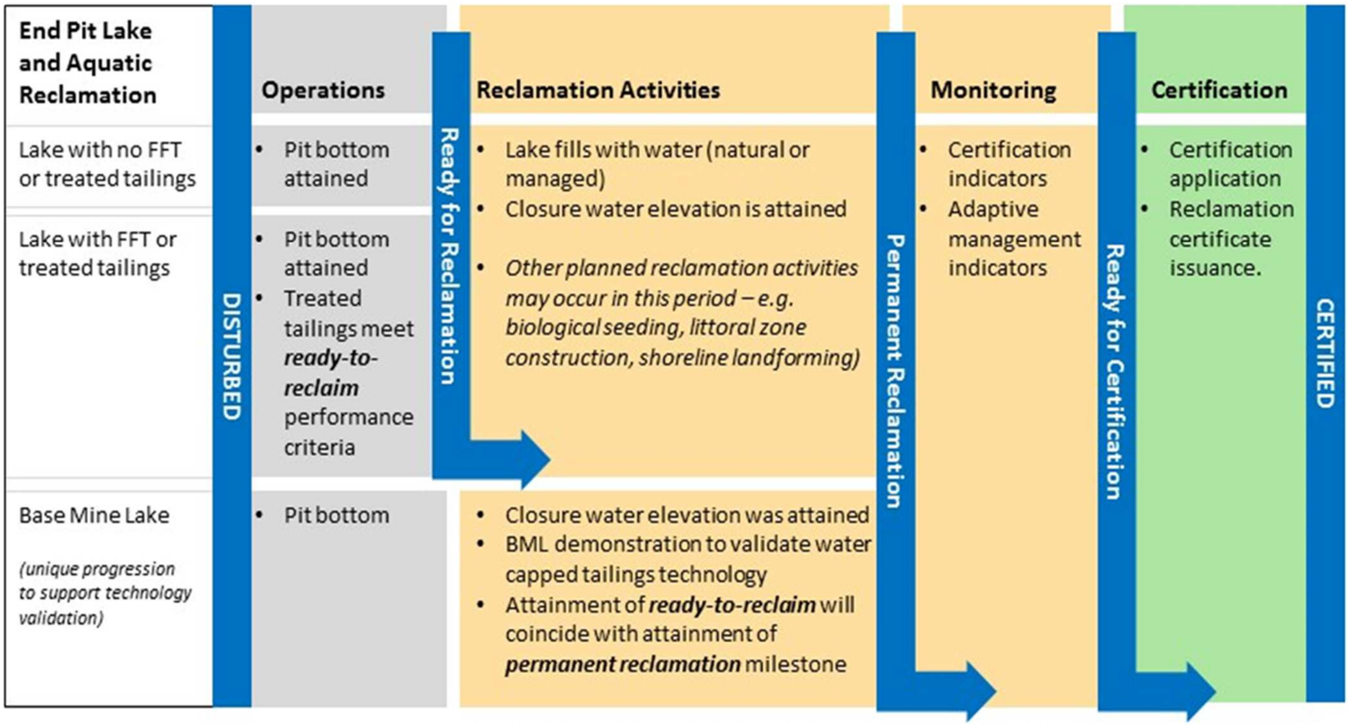

Figure 3-6: Conceptual Diagram of Progressive Certification Stages and Milestones for Pit Lake and Aquatic Reclamation (Syncrude 2016)

3.6 Syncrude's Planned Pit Lakes

Syncrude's 2016 LMCP includes three pit lakes at the Mildred Lake site and one at the Aurora North site:

- Base Mine Lake,
- North Mine Lake,
- MLX-West Pit Lake, and
- Aurora North Pit Lake.

These pit lakes are integral components of the Mildred Lake and Aurora North closure plans, regardless of whether they contain water-capped tailings, since it is imperative that both industrial wastewater and surface water run-off can be effectively managed in the future post-closure landscape in order to support the planned end land use objectives. Water will not be released from any of Syncrude's proposed pit lakes until it is proven to meet applicable water quality standards, which will be the subject of future regulatory submissions. The data that is being collected through the Base Mine Lake integrated monitoring and research program will be helpful in ensuring that these future standards can be met. Table 3-1 outlines the proposed end land use goals for each of Syncrude's planned pit lakes, as per the 2016 LMCP.

Table 3-1: Proposed End Land Use Goals for Syncrude's Pit Lakes (Syncrude 2016)

End Land Use Goal		Description	Planned Pit Lakes
1	Pit lake supports ecological functions	Pit lake performs as a conventional boreal lake and water quality supports typical lake algae, plants and macroinvertebrates.	
2	Pit lake supports ecological functions, including sustainable small-bodied fish populations	Small-bodied fish are able to survive in the lake. Food is present, oxygen is at appropriate levels, and no winter fish kills.	• Base Mine Lake • North Mine Lake • Aurora North Pit Lake
3	Pit lake supports ecological functions, including sustainable large-bodied fish populations	Same as above, but the lake is capable of supporting large-bodied fish populations.	• MLX-West Pit Lake

Landform design and water modelling are key components of Syncrude's mine closure planning process. Information on the current closure design and its considerations is available in the 2016 LMCP. Syncrude has initiated work on updating the LMCP for submission to the AER on January 31, 2023, which will include updates to the surrounding landscape. To ensure the sustainability of its future pit lakes, Syncrude is developing an updated hydrologic model that will incorporate the changes to the surrounding closure landscape that are being developed for the 2023 LMCP. HydroGeoSphere will be used to provide the necessary detail for the simulations and predictions for the performance of the closure landscape under a wide range of late-21st-century climate scenarios. HydroGeoSphere was chosen as it is a fully integrated surface and groundwater model that will provide the necessary detail for the simulations and predictions of the performance. The purpose of the hydrologic model is to provide Syncrude with a planning tool for analyzing closure watershed design scenarios; based on inputs and variables known today, together with information from the latest mine, tailings and reclamation plans. The model will be a dynamic tool that will be updated as new information is acquired and/or conceptual closure changes are made.

Figure 3-7 and Figure 3-8 show the locations of each of the pit lakes and the planned drainage paths at closure for the Mildred Lake and Aurora North sites, respectively, as provided in the 2016 LMCP.

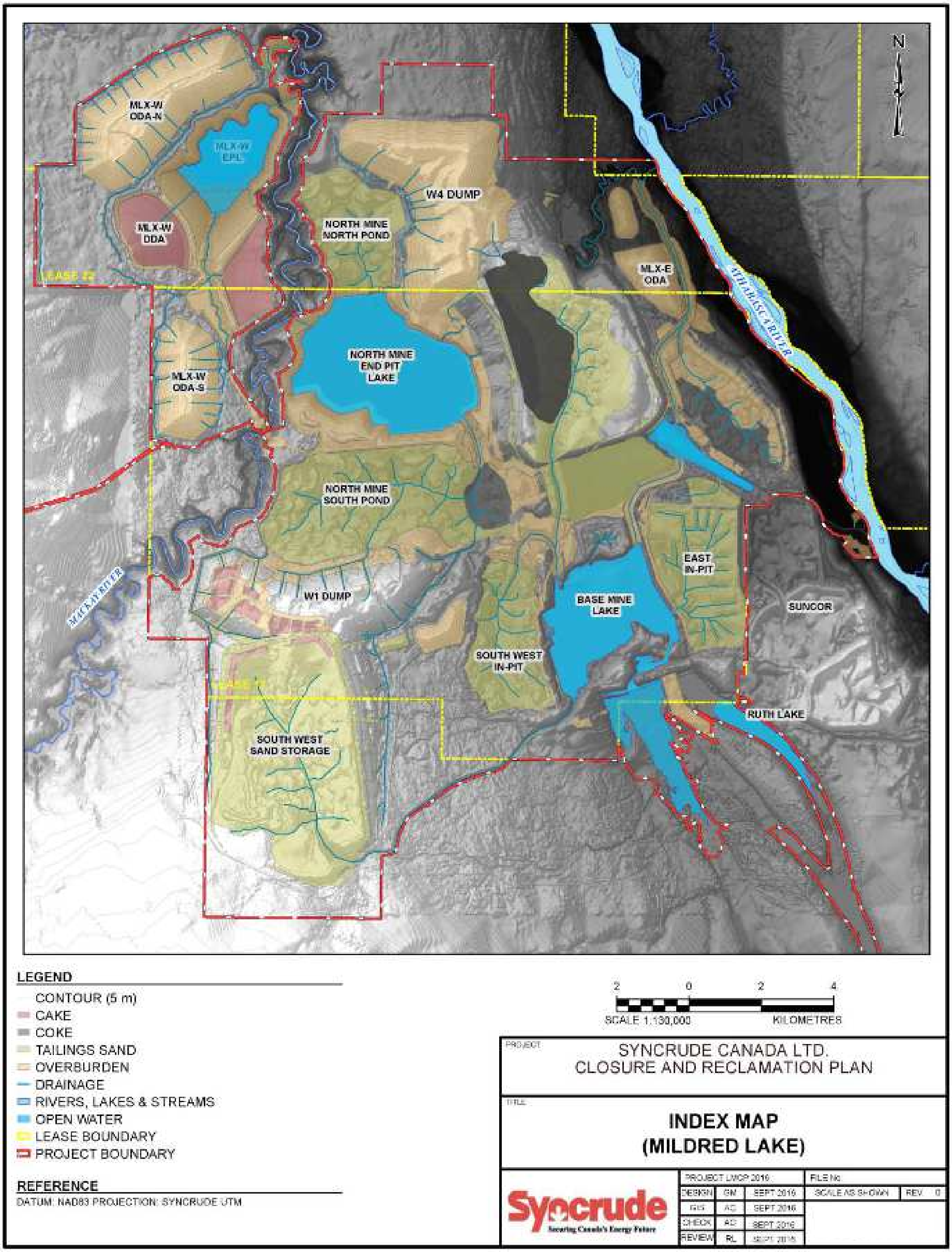

Figure 3-7: Mildred Lake Site Closure Overview (Syncrude 2016)

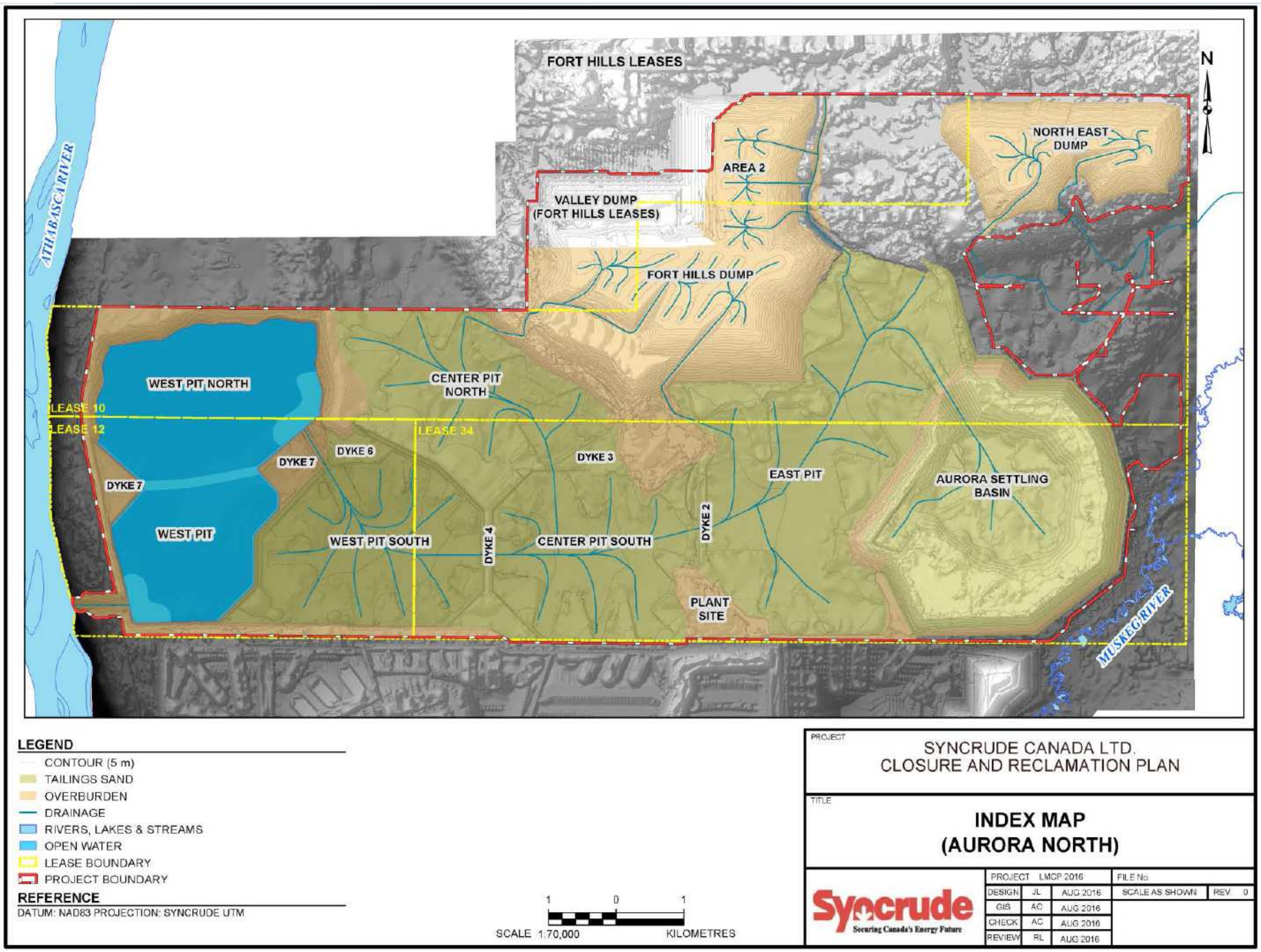

Figure 3-8: Aurora North Site Closure Overview (Syncrude 2016)

3.7 Regional Pit Lake Research Initiatives

Syncrude participates in regional pit lake research initiatives through its membership with COSIA. In addition to Base Mine Lake, two other key pit lake research programs with relevance to Syncrude are the Suncor Lake Miwasin Demonstration and the COSIA Demonstration Pit Lake Mesocosm Study. Summaries of these research programs are provided below. Additional details can be found in the COSIA annual reports posted online at www.cosia.ca.

3.7.1 Suncor Lake Miwasin Demonstration

Suncor Energy Inc. (Suncor)'s Lake Miwasin is a pilot-scale demonstration pit lake of the Permanent Aquatic Storage Structure (PASS) technology. This technology uses a coagulant and flocculant to dewater the fluid tailings, followed by water-capping to develop a pit lake. Lake Miwasin is a scaled representation of Suncor's aquatic closure plan for the East Bank Development Area. Lake Miwasin is located within an 18 hectare reclaimed demonstration area at Suncor's Base Plant site in Fort McMurray, Alberta, which includes the lake's surrounding watershed and a demonstration constructed wetland treatment system (CWTS). Construction and reclamation of Lake Miwasin and its watershed was completed in 2018 and an extensive research and monitoring program is underway to support the demonstration. Details can be found in the pit lake research and development reports submitted to the AER by Suncor, in accordance with EPEA Approval No. 94-03 (as amended).[5]

3.7.2 COSIA Demonstration Pit Lake Mesocosm Study

Since 2017, the COSIA Demonstration Pit Lake (DPL) project is using aquatic mesocosms to inform pit lake research. The COSIA DPL mesocosm study is located at the InnoTech facility in Vegreville, Alberta. The research facility consists of 30 small (1.5 m deep x 3.6 m diameter) in-ground mesocosms, which can be experimentally manipulated to test a variety of pit lake hypotheses. The first set of experiments tested the densified tailings performance to support development of Suncor's PASS technology. Details can be found in the research and development reports shared by COSIA.[6]

3.8 Base Mine Lake Demonstration Overview

Base Mine Lake is the first and currently the only full-scale commercial demonstration of water-capped tailings in a pit lake in the oil sands industry. The lake is located in the former West In-Pit (WIP) facility of the Base Mine at Syncrude's Mildred Lake site. It consists of a mined-out oil sands pit partially filled with fluid fine tailings (silt, clay, process-affected water and residual bitumen) that sits below a cap of

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[5] Suncor Energy Inc. [Suncor] 2021. Pit Lake Research and Development Report. Submitted to the AER on April 28, 2021. 38 pp.

[6] Innotech Alberta, 2021. Densified Fluid Fine Tails and Oil Sands Process Water - an extension of the 2017 Study, Final Report, Prepared for COSIA's Demonstration Pit Lakes Working Group. 169 pp. Available at: https://cosia.ca/sites/default/files/attachments/2018%20Mesocosm%20Research%20Report.pdf

oil sands process-affected water and fresh/environmental water. The two key desired outcomes for Base Mine Lake that are important for the validation of WCTT are the physical sequestration of the tailings fines below the water cap and water quality improvements over time. The short-term objective is to successfully demonstrate the viability of the WCTT and the long-term objective is to integrate Base Mine Lake into the closure landscape and obtain reclamation certification.

Placement of fluid tailings into WIP began in 1995 and was completed in late 2012. The facility was removed from Syncrude's active tailings network when it became commissioned as Base Mine Lake on December 31, 2012. During 2013, additional fresh water and process-affected water were added to the existing upper water layer to attain the final elevation of 308.7 meters above sea level (masl). Base Mine Lake has a fluid surface area of roughly 800 hectares and a total volume of roughly 240 Mm^3 (fluid tailings + water). An aerial overview of Base Mine Lake within the Mildred Lake site is shown in Figure 3-9.

Infrastructure has been installed to pump fresh water into Base Mine Lake from Beaver Creek Reservoir and as required, water is pumped out of Base Mine Lake to the closed-loop Industrial Wastewater Control System, where it is utilized as recycle water in the bitumen extraction process. This flow-through process dilutes the water cap and will be in place until a more substantial upstream surface watershed is reclaimed and connected to Base Mine Lake, and outflow is established to the receiving environment (i.e., Athabasca River). Design features incorporated into Base Mine Lake include:

- Isolation from operational tailings inputs (no additional tailings transfer);
- Sufficient depth of water to minimize potential for wind-driven fine tailings re-suspension;
- Fresh (environmental) water flow-through system to improve water quality; and
- Construction of breakwaters and controlled water level elevation for protection and development of littoral zones.

The Base Mine Lake monitoring and research program began upon commissioning and is ongoing. The initial focus of the monitoring and research program is to support the demonstration of the WCTT and to provide a body of scientific evidence which demonstrates that Base Mine Lake is on a trajectory to become integrated into the reclaimed landscape.

Results from the Base Mine Lake monitoring and research program have been shared with the AER through biennial/annual summary report submissions and annual update meetings. The last summary report (2021 Pit Lake Monitoring and Research Report) was submitted to the AER on June 30, 2021, in accordance with Syncrude's EPEA Approval.

Figure 3-9: Aerial Overview of Base Mine Lake (Fall 2021)

4 Adaptive Management Approach

4.1 Mitigating Uncertainties

Syncrude recognizes that the amount, distribution and quality of water in the closure landscape is critical to supporting the attainment of the closure goals defined in the LMCP and is committed to the successful implementation of WCTT in pit lakes as part of its overall mine, tailings, reclamation and closure strategy. Syncrude utilizes an adaptive management approach to mitigate uncertainties and steward tailings management and reclamation activities towards meeting the desired closure outcomes. Adaptive management is an iterative process, including research and development, designing, planning, modelling, monitoring, analyzing, and making adjustments in response to new information.

Monitoring of pit lakes throughout their progression from active deposition to final end land use is a key component to compare actual performance to expectations. Plans are reconciled annually based on the previous year’s results to ensure that future plans are optimized appropriately. Based upon the analysis of monitoring results, adaptive management strategies may be identified to improve performance. These type of activities not only address current issues, but can also advance research and inform future plans.

Critical information on the viability of WCTT is being provided through the Base Mine Lake demonstration. The Base Mine Lake monitoring and research program is providing data that improves our understanding of the design and operation of pit lakes, and the time required for each stage of development. The learnings from the Base Mine Lake demonstration, combined with learnings from regional pit lake research initiatives, are being used to inform Syncrude’s future pit lake designs and plans.

4.2 A Decision Making Framework

Under SED-003, the AER defines adaptive management as “a management approach that involves the monitoring and evaluation of performance followed by any necessary actions to achieve the intended performance objectives. Adaptive management also allows information to be fed back into the planning and design process so that future performance will meet the intended outcomes.” Furthermore, Directive 085 states that “the AER will include conditions in approvals that are outcomes based, manage risk and uncertainties, support flexibility and adaptive management, and are enforceable.”

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, as shown in Figure 4-1.

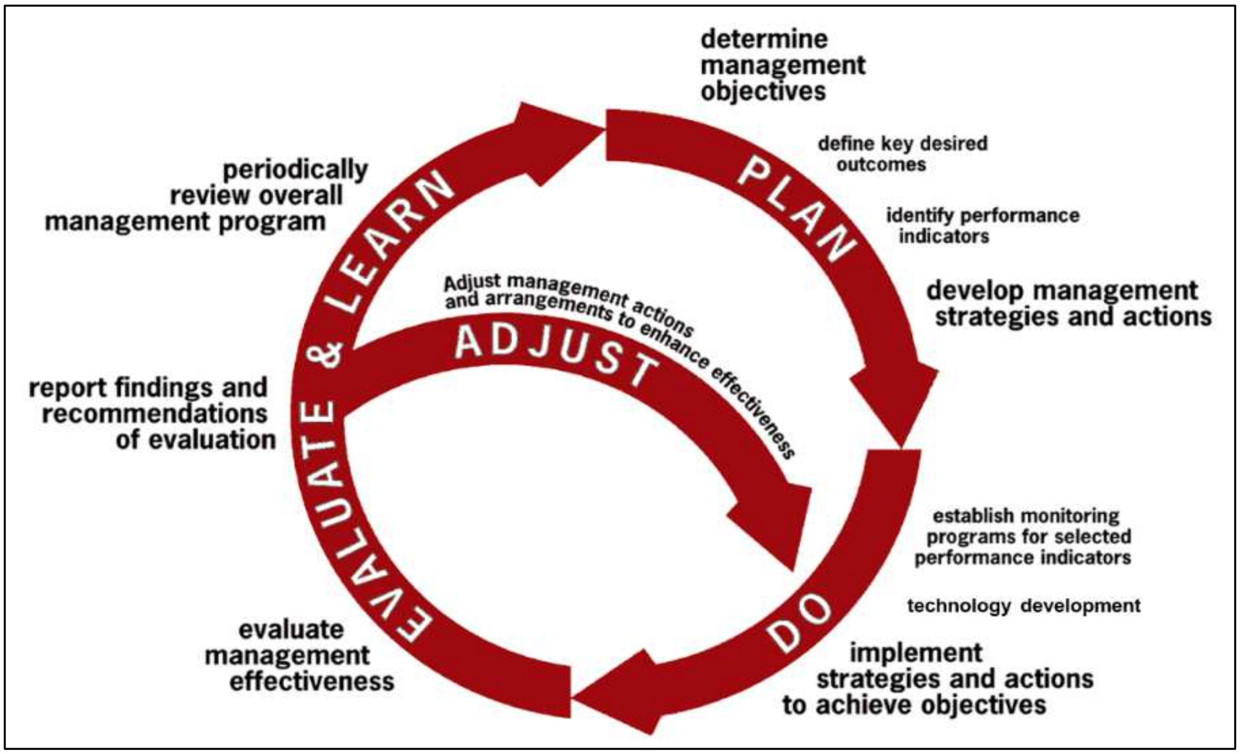


Figure 4-1: The Adaptive Management Cycle (after Jones 2005)

Adaptive management is a “learn by doing” approach; not a “trial and error” approach. There are four key components to the cycle:

- Plan;
- Do;
- Evaluate and Learn; and
- Adjust, as required.

Each of these components are described more specifically for Base Mine Lake in the following sections.

4.3 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 towards its short and long-term objectives. Some key components of the adaptive management framework as applied specifically to Base Mine Lake are described herein.

4.3.1 Adaptive Management: Plan

The planning component of the adaptive management cycle is key to success. As such, Syncrude has defined two primary management objectives, which are to:

- Validate the viability of the Water-Capped Tailings Technology; and
- Ensure the lake becomes a functioning component of the closure landscape.

The key desired outcomes and performance indicators are described in more detail in the following sections.

4.3.1.1 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).

4.3.1.2 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 shorter-term, Syncrude has identified performance indicators that are associated with validation of the WCTT. In the longer-term, Syncrude has determined that performance indicators for reclamation certification are appropriate. It is important to identify longer-term performance indicators in the early planning stages so that management decisions are made with these progressive milestones in mind. Base Mine Lake is expected to change over time and performance expectations for each milestone are necessarily different.

4.3.1.2.1 Shorter-Term: Performance Indicators to Validate Water-Capped Tailings Technology

Validation of Water-Capped Tailings Technology requires demonstration that the fines are physically sequestered beneath the water cap and that the lake water quality is improving with time. As such, Syncrude has identified the following Base Mine Lake performance indicators for validation of the WCTT[7]:

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

4.3.1.2.2 Longer-Term: Performance Indicators to Support Reclamation Certification

Certification of Base Mine Lake 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 may be appropriate as performance indicators to support certification of Base Mine Lake include:

- Environmental Quality (chronic) Guidelines for Alberta Surface Waters (AEP 2018);
- Canadian Water Quality (chronic) Guidelines for the Protection of Aquatic Life (CCME 2014c);
- Canadian Sediment Quality Guidelines for the Protection of Aquatic Life (CCME, 2014a); and
- Canadian Tissue Residue Guidelines for the Protection of Wildlife that Consume Aquatic Biota (CCME, 2014b).

[7] The performance indicators identified for the Base Mine Lake demonstration will be considered in the assessment of applicable Ready to Reclaim (RTR) criteria for Water-Capped Tailings Technology, required to be submitted to the AER by January 31, 2023, in accordance with condition 23 of Mildred Lake *Oil Sands Conservation Act* Approval No. 8573R.

The dissolved oxygen guideline for the protection of aquatic life will be particularly important for ensuring the lake can support small-bodied fish populations. Science-based site-specific standards for select parameters may need to be developed, as provided for by the Environmental Quality Guidelines for Alberta Surface Waters (AEP 2018) and the Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME 2014c).

4.3.2 Adaptive Management: Do, Evaluate and Learn

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

The monitoring program is designed to track trends in the lake both seasonally and annually, and measure these trends against key performance metrics, as previously outlined. The research program focuses on key scientific questions designed to elucidate the mechanisms and processes that govern the current state of Base Mine Lake, 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. The Base Mine Lake monitoring and research programs 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 monitoring program further guides the priorities for the research program. This integrated Base Mine Lake monitoring and research program supports the adaptive management of the lake's performance towards attainment of the key desired outcomes.

At the time of writing, the Base Mine Lake demonstration is supported as a Joint Industry Project (JIP) under COSIA. As such, the Base Mine Lake monitoring and research program also provides knowledge and guidance valuable to the integration of other pit lakes in the Athabasca mineable oil sands region. Syncrude will continue to share findings from the research and monitoring programs with its industry partners to advance understanding of a range of pit lake topics; including design, operation, modelling and adaptive management.

4.3.2.1 Base Mine Lake Monitoring Program

The specific objective of the Base Mine Lake 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 Base Mine Lake monitoring program is demonstrating that the fine tailings are sequestered and that the water quality in the lake is improving. The monitoring program is designed to do this by tracking the physical, chemical and biological changes in Base Mine Lake. 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 the lake. The physical, chemical and biological components of the program are summarized in Table 4-1.

Table 4-1: Base Mine Lake Monitoring Program Components

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

4.3.2.2 Base Mine Lake Research Program

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

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

The research program has two overarching themes. The first theme is validating the WCTT. Several research programs will determine the potential fluxes from the fluid tailings to the water column, including chemical, geochemical, mineral, gases and heat. Physical, biological and chemical mechanisms are being investigated. The second key (and related) theme relates to the oxygen dynamics in the lake. These 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 4-2. A list of peer reviewed publications and theses from the research programs is provided in Section 5.3.

Table 4-2: Current Base Mine Lake Research Programs

Research Component	Primary Objective	University	Researchers (PIs)
Physical limnology of Base Mine Lake and the potential for meromixis	To understand the circulation of Base Mine Lake 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 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
Field investigation of Base Mine Lake water cap oxygen concentrations, consumption rates and key BOD/COD constituents affecting oxic zone development.	To establish temporal and spatial variability in in-situ Base Mine Lake water cap oxygen concentrations, oxygen consumption rates and identify the biogeochemical processes linked to its consumption from the tailings-water interface to the Base Mine Lake 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 Base Mine Lake, 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 Base Mine Lake and to understand the long-term water balance of Base Mine Lake	McMaster University / Carleton University	Sean Carey / Elyn Humphreys
Characterization of Organic Compounds and Naphthenic Acids in Base Mine Lake: Implications for methane production, transport, oxygen consumption, and NA persistence	To understand methane production and release, the sources of naphthenic acids and petroleum hydrocarbons to the Base Mine Lake water cap, and the role of ebullition in transporting fluid tailings constituents into the water cap	McMaster University	Greg Slater
Base Mine Lake Process Dynamics	To understand bitumen liberation to water surface, and develop monitoring and mitigation tools for bitumen	Syncrude	Barry Bara

4.3.3 Adaptive Management: Adjust

The adaptive management framework allows for adjustments 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 Base Mine Lake performance: application of alum to manage mineral turbidity, and hydrocarbon mitigation.

4.3.3.1 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 the water cap 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 Base Mine Lake monitoring and research program 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 4-1.

4.3.3.2 Hydrocarbon Mitigation

Residual bitumen makes up a relatively small component of the fluid tailings. When FFT was placed in the mined-out pit, some of this residual bitumen separated from the FFT, resulting in bitumen mats forming on the surface of the FFT; primarily focused in areas of the pit of tailings discharge (Figure 4-3 and 4-4). As detected by the Base Mine Lake monitoring program, some residual bitumen is also present as a hydrocarbon sheen on the water surface, some of which has accumulated along the shoreline. This sheen is a result of methanogenic bacterial consumption of residual hydrocarbon in the bitumen mat producing methane bubbles with bitumen attached being released to the air-water interface. Observations and empirical data from both the research and monitoring program has led to the development of a conceptual model (Figure 4-2) which is being tested empirically through a number of research and monitoring programs. Some results have validated that the bitumen mats were formed as a result of aeration of the tailings at deposition points (Figure 4-4).

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 visual 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 efforts 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 (i.e., 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 Base Mine Lake.

In 2018 and 2019, a horizontal auger dredge was deployed in Base Mine Lake to target removal of bitumen mats on the FFT surface. This preliminary dredging effort has provided valuable information to design and develop a more efficient dredging effort using a mechanical clam-shell environmental dredge piloted in 2021. Bitumen dredging activities were paused during the 2020 open water season due to COVID-19 restrictions; however, significant efforts were invested in the development of an ice core analysis program to detect gas and bitumen liberation, which will be used as a tool for monitoring changes after bitumen removal.

Ice cores are a record of bitumen and gas in the lake during the ice-on season. Because there are no internal mixing dynamics of the water column during the ice-on period, the gas and hydrocarbon trapped in the ice core represents gas and bitumen liberation from the FFT directly below the ice core location. Results from the ice core program in 2021 indicated that there are areas of the lake where there is gas and bitumen liberated, and these are located above areas where bitumen mats have been previously detected (Figure 4-5). There are also other areas of the lake where there is gas but no bitumen liberation (Figure 4-5). This supports the hypothesis that the dominant source of hydrocarbon to the water column is from the bitumen mats.

In 2021, the bitumen mat remediation campaign focused on the bitumen mats in the southwest corner of BML, identified in 2019 using ponar sampling (Figure 4-3). The clamshell dredge targeted bitumen mats on the FFT surface (Figure 4-4E), and each clamshell grab contains bitumen and some water and FFT. The clamshell is emptied into a hopper barge until full. The barge is then transferred to shore where an on-shore excavator moves the material into a truck for disposal (Figure 4-6). The mechanical process of lifting bitumen to the surface and loading barges resulted in an increase in bitumen sheen on the water surface in the area near the dredge. Booming the area and active skimming of the surface sheen was performed during the operation. Photos taken from the edge of dredged bitumen mats suggest the method is working effectively (Figure 4-7).

The Base Mine Lake monitoring and research program will help to determine the effects that bitumen mat removal have on the lake performance in both the short- and the long-term. Preliminary results quantifying gas and bitumen content in ice cores collected in 2022 (post-dredged areas) compared to 2021 (pre-dredged areas) indicate bitumen mat dredging using the environmental clamshell dredge reduces flux of hydrocarbon through the water column (e.g., Figure 4-8). Ice cores collected in 2022 are currently undergoing analytical processing and data compilation and interpretation of the ice core results to demonstrate effectiveness of bitumen mat removal will be presented in the 2023 annual report.

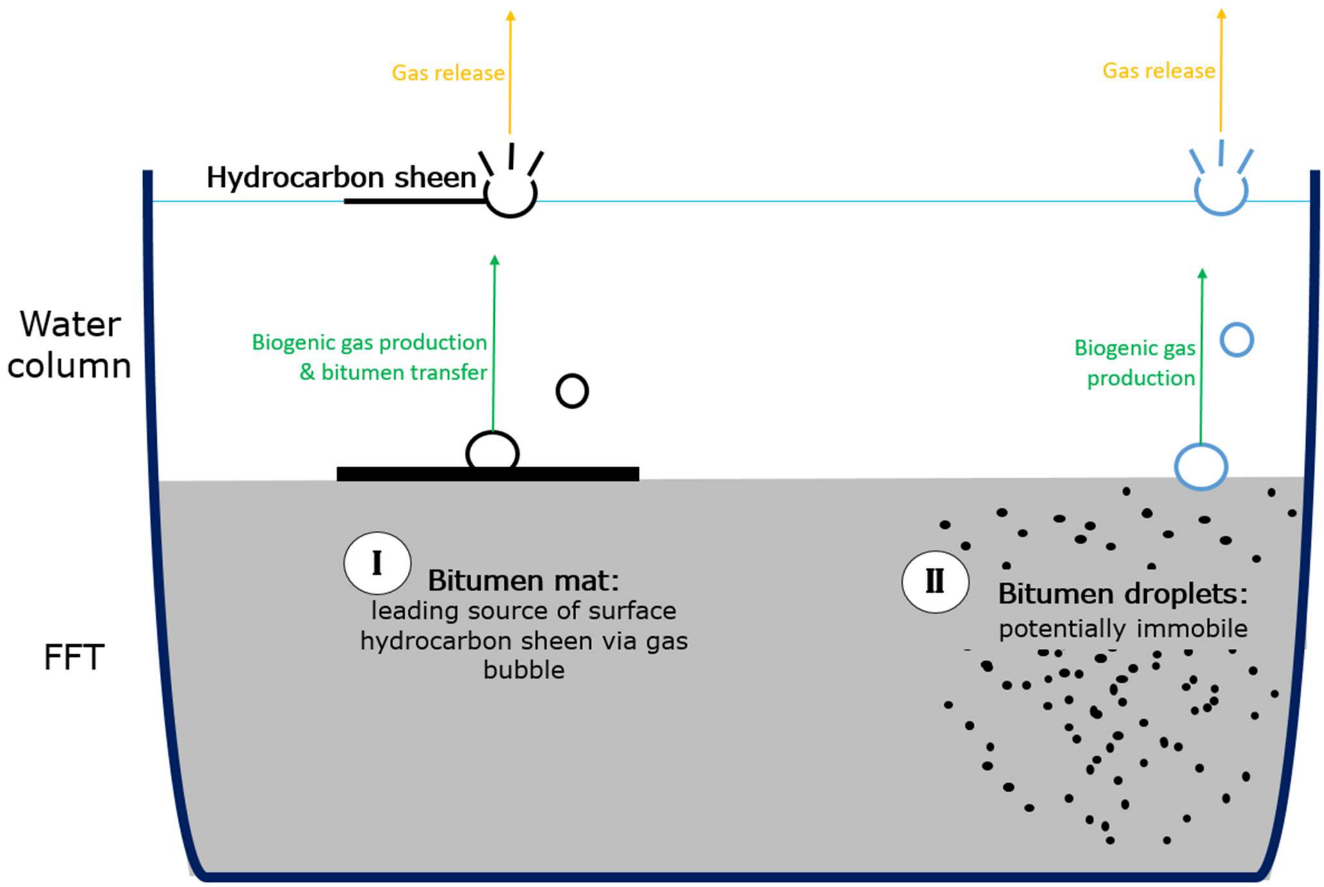


Figure 4-2: Conceptual model of bitumen dynamics in BML

Figure 4-3: Location of bitumen mats identified in 2019 using ponar sampling

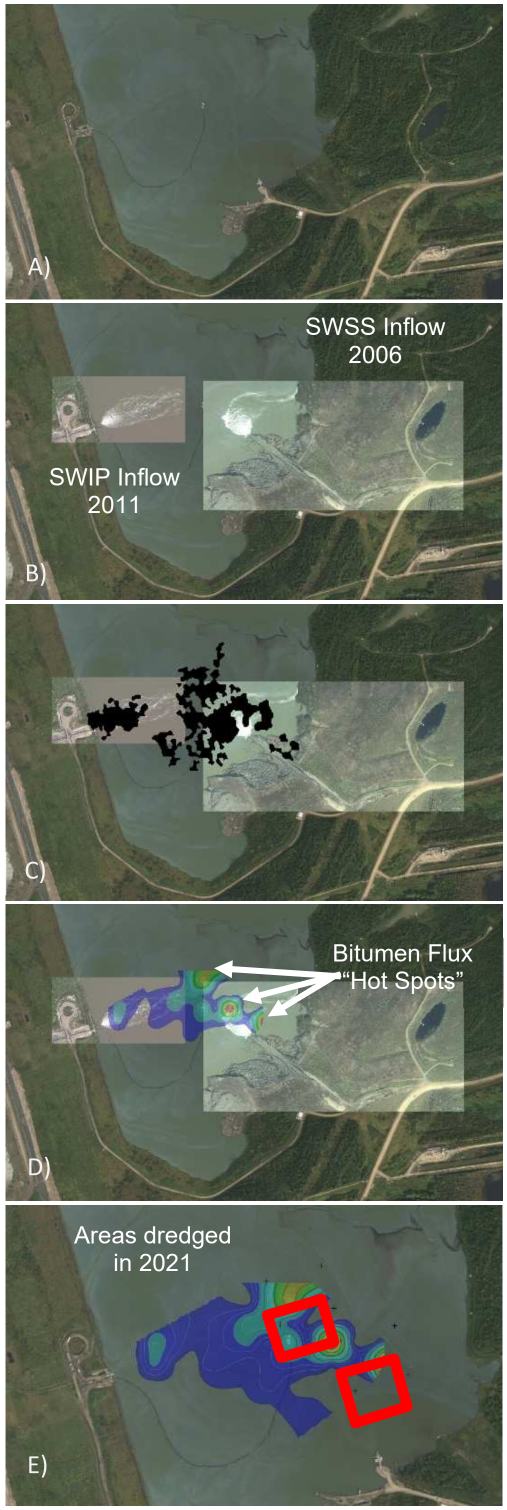


Figure 4-4: Demonstration of bitumen mat and flux hotspots in relation to tailings pour locations: A) BML SW corner, B) image of pouring locations, C) bitumen mat locations detected with ponar sampling, D) bitumen flux hotspots detected through ice core analysis, E) focus of dredging activities in 2021

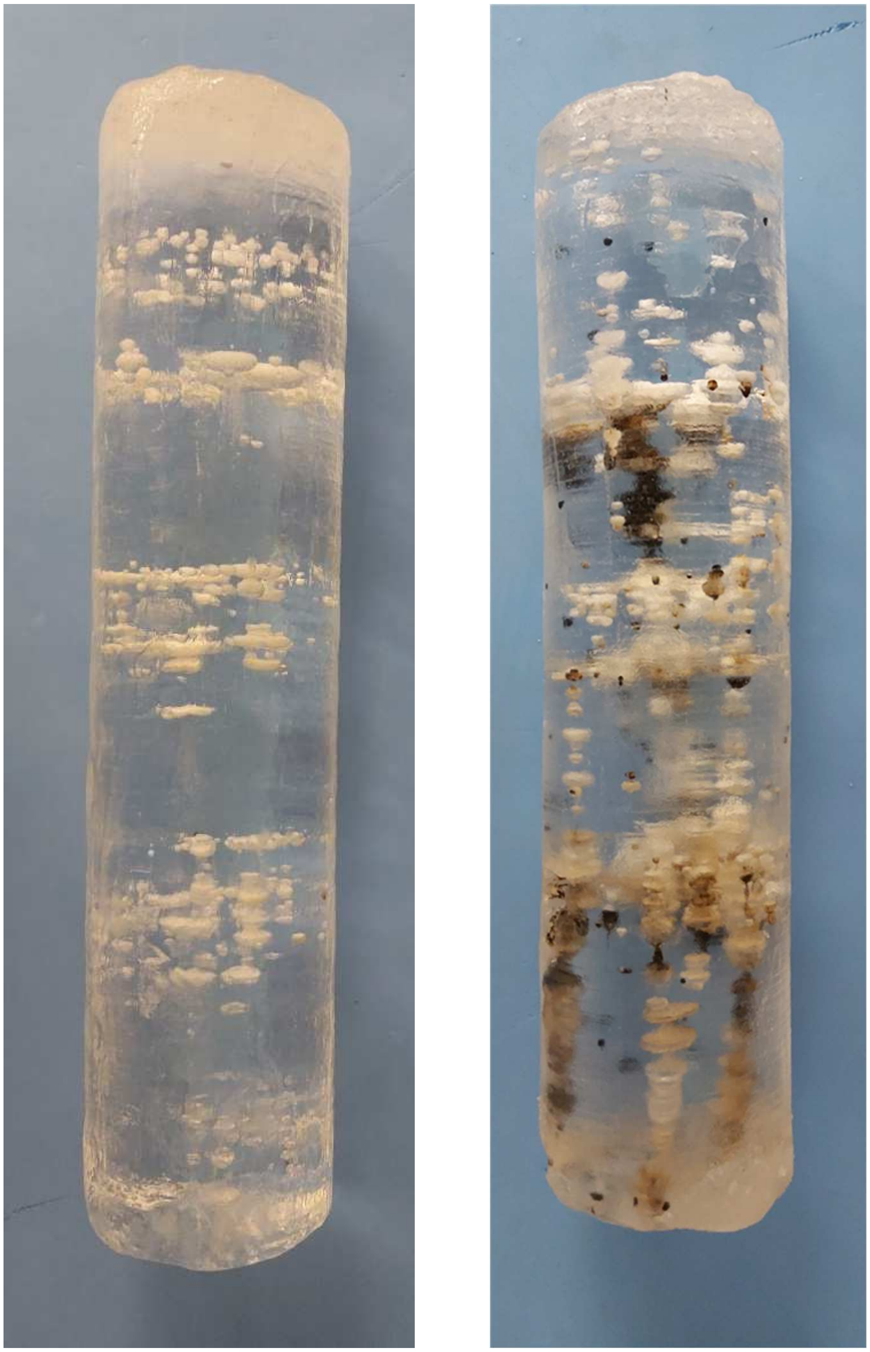


Figure 4-5: Ice core samples from two different areas in BML with gas and no visible bitumen on left and bitumen and gas on right

Figure 4-6: 2021 Clamshell dredge operation method A) material handler on dredge collects bitumen and FFT and water from mudline of BML, B) material handler deposits contents of clamshell into hopper barges until full, C) hopper barges are pushed to shore using tugboats, and D) on-shore excavator moves material from hopper barge into wiggle wagons for disposal

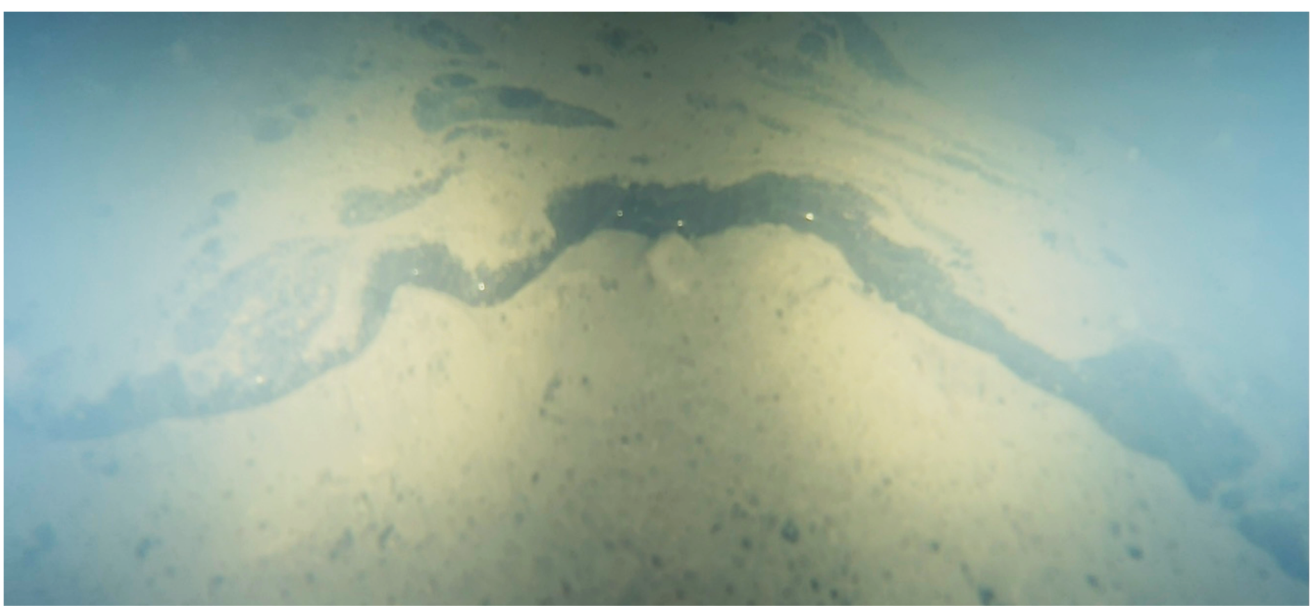


Figure 4-7: Visible edge of bitumen mat on FFT surface after dredge has cut through; note the clean edge and clear water column

Figure 4-8: Ice cores taken from same location before dredging (2021, on left) and after dredging (2022, on right) demonstrating reduction in bitumen flux post-dredging

5 Summary of Key Performance Results for BML: Shorter-term performance indicators to validate Water-Capped Tailings Technology

As described in section 4.3.1.2.1, validation of Water-Capped Tailings Technology requires demonstration that the fines are physically sequestered beneath the water cap and that the lake water quality is improving with time. The following sections describe results associated with shorter-term performance indicators.

5.1 The lake should have all solids in place and be filled to design elevation with a water cap sufficient to prevent wind-wave driven resuspension of fines

For the Base Mine Lake demonstration, placement of fluid tailings into the mined-out pit began in 1995 and was completed in late 2012. The facility was removed from Syncrude's active tailings network when it was commissioned as Base Mine Lake on December 31, 2012. During 2013, additional fresh water and process-affected water were added to the existing upper water layer to attain the final design water elevation of 308.7masl.

The depth of water required to prevent wind-wave driven resuspension of sediments (e.g., FFT) is a function of four factors: the threshold velocity, wind velocity, fetch and a factor of wave heights (Lawrence et al. 1991). Using the expression derived by Lawrence et al. (1991) for BML, a water cap depth of 6 m would prevent wind driven resuspension of fines from the sediment (i.e., below the mudline). The average water cap depth 10 months after commissioning was ~8 m and has been consistently deeper than 9 m since May 2015 (Lawrence *et al.* 2016). There has been no evidence of wind-wave driven resuspension of sediment since BML was commissioned (see section 7.3). It is also expected that densification resulting from FFT consolidation and increasing water cap depth with time will further reduce or eliminate the likelihood of wind-wave driven resuspension of FFT (Dunmola *et al*. under review).

5.2 The fluid tailings should be settling as it dewaters with time

Since commissioning BML, and as expected from modelling (Dunmola *et al.* under review), the FFT has been settling as indicated by decreasing mudline over time (Figure 5-1), releasing pore water into the water cap. The rate of FFT settlement is gradually decreasing over time, from ~ 1.1 m in 2012 – 2013 to 0.24 m in 2018 – 2019 (Dunmola *et al.* under review). Contours of cumulative FFT settlement between October 2012 and October 2021 highlight the spatial variability of observed settlement (Figure 5-2). The total settlement ranges from 0.3 to 7.3 m, with the largest settlement recorded in the northeastern portion of the lake. The least settlement was observed near the BML shoreline where the initial FFT thickness was the smallest. The total volume of FFT in BML has decreased from 196.0 Mm^3 in 2012 to 169.08 Mm^3 in 2021, a volumetric deformation of 13.7 %.

Numerical modelling of FFT consolidation was completed in 2007 and was updated in 2019. The 2019 numerical predictions generally agree with the field data. The earlier model predicted a higher cumulative settlement because the assumed fines tonnage was higher (6.2 Million tonnes higher) than actual conditions in BML at commissioning. Settlement predictions for the updated model compared to field measurements are shown in Figure 5-3. Also, the FFT settlement is complemented by profile increases in solids content, indicating FFT dewatering and densification with time (Figure 5-4). The transition in geotechnical properties at the mudline is also getting distinct over time, as shown by Figure 5-5. Features in the FFT surface (e.g., cracks, pock marks) are further evidence that the mudline distinct and the FFT is densified (Figure 5-5). These are multiple lines of evidence that the fines are physically isolated below the water cap.

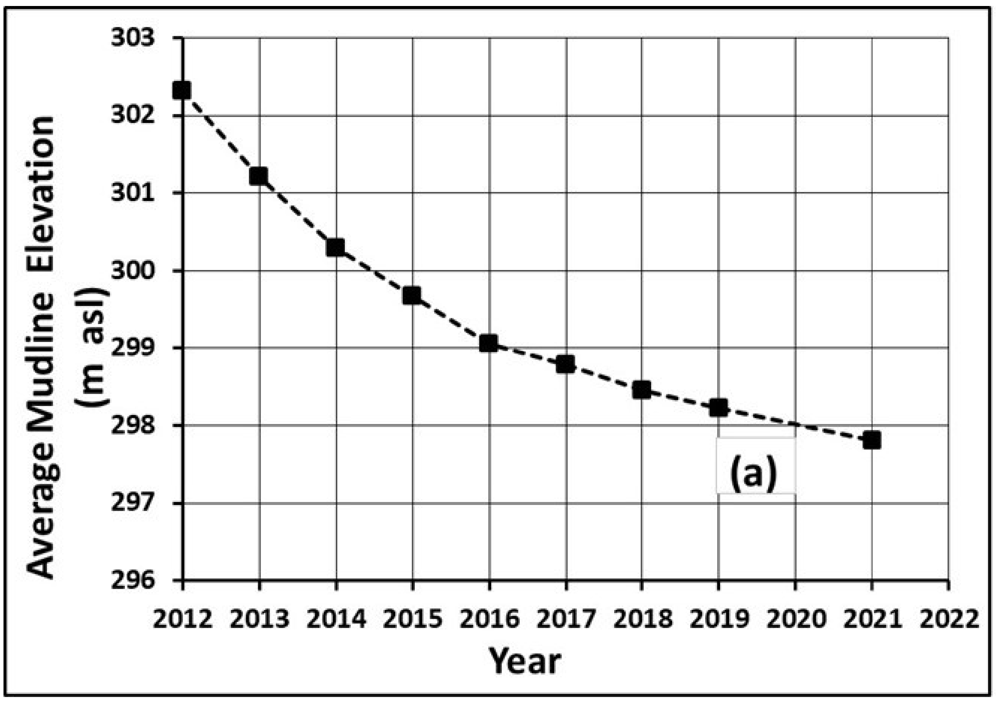


Figure 5-1: Field measurement of average FFT mudline elevation in BML from 2012-2019 (Dunmola *et al.* under review).

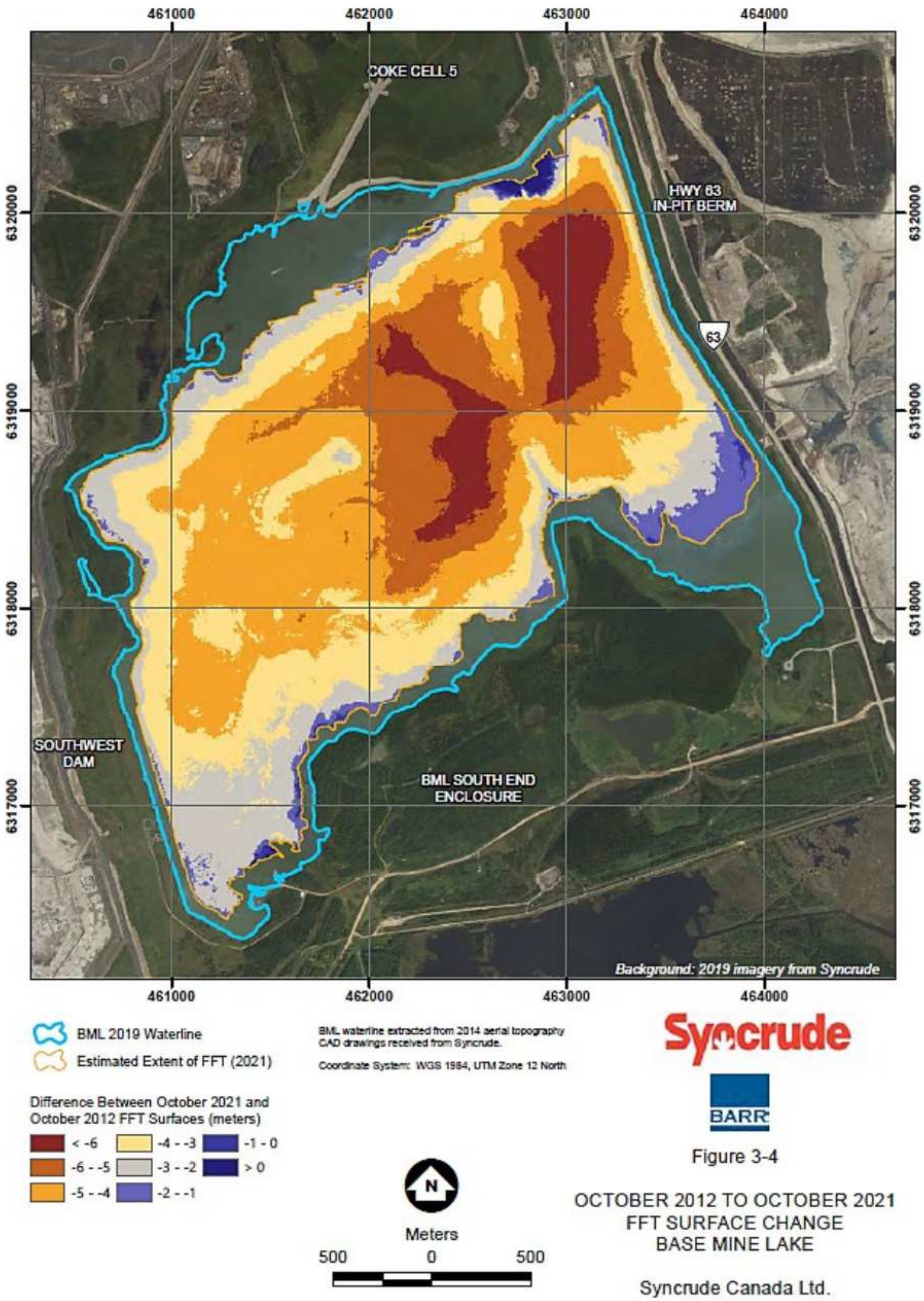


Figure 5-2: October 2012 to October 2021 FFT surface elevation change in Base Mine Lake.

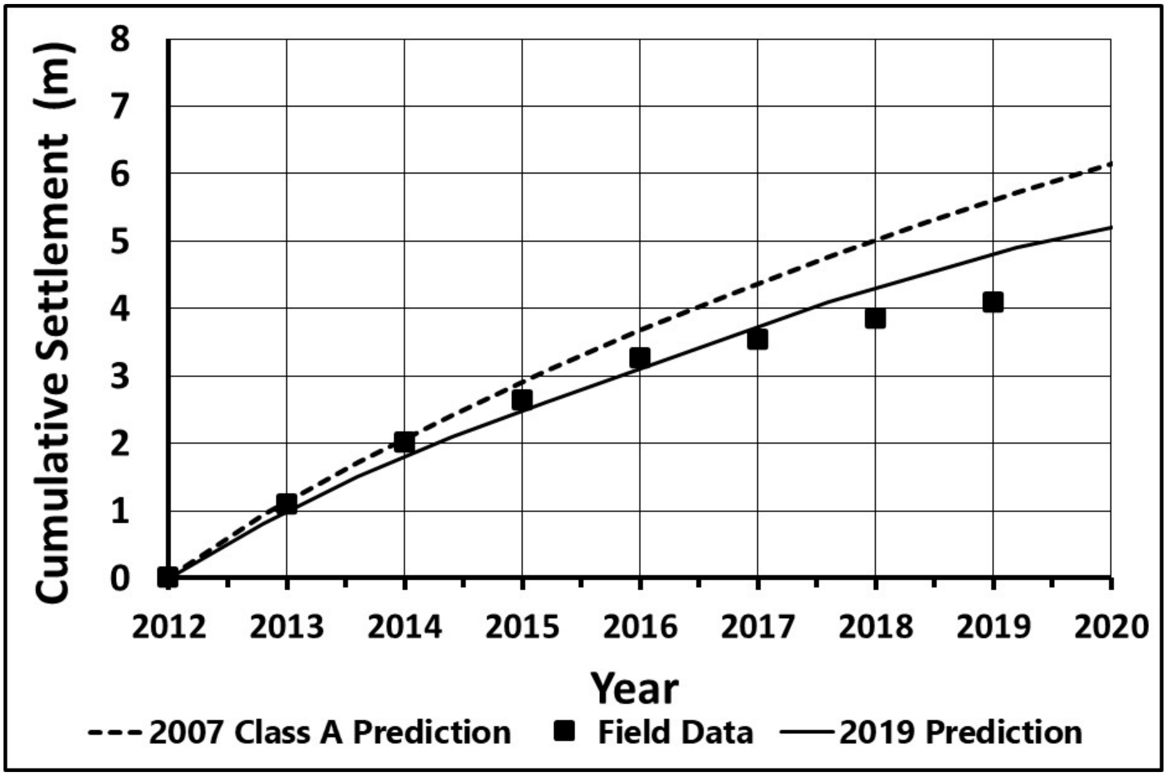


Figure 5-3: Field measurement of cumulative FFT settlement shown with numerical predictions in 2007 and 2019 (Dunmola *et al.* under review).

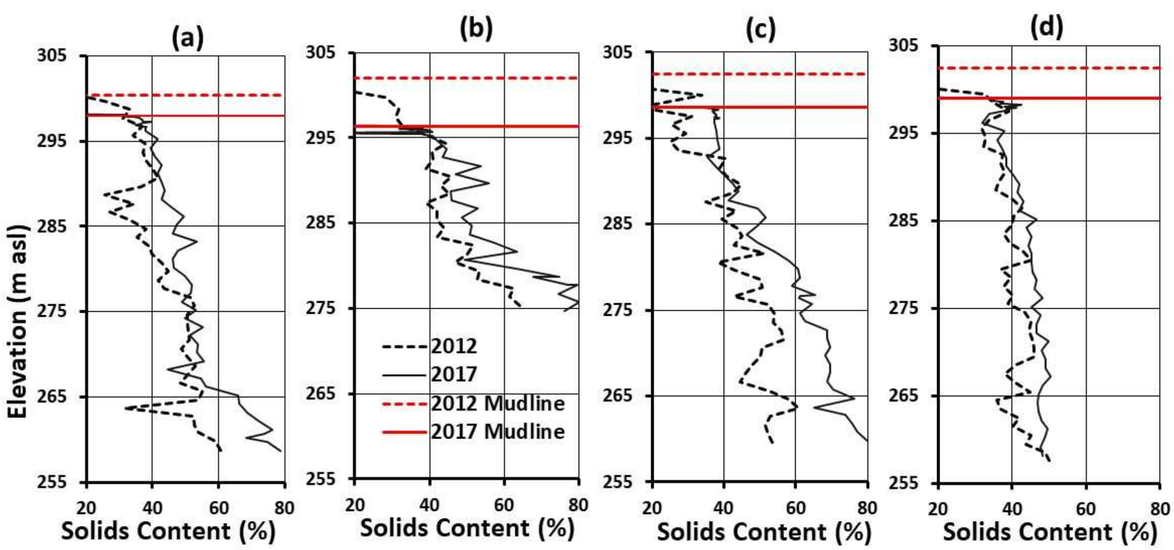


Figure 5-4: Profiles of solids content in 2012 and 2017 at sampling locations: (a) D11; (b) Platform; (c) D08; and (d) D38. Also shown are the respective mudlines.

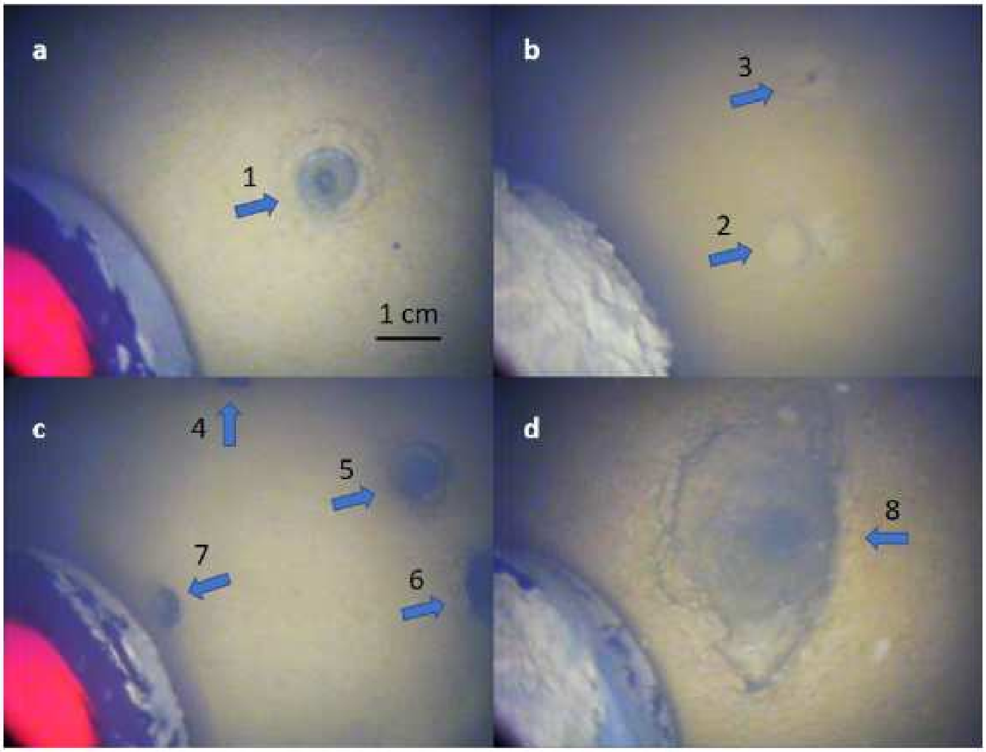


Fig. 4. Photographs taken from a camera suspended approximately 5 cm above the water-mud interface on 03 October 2019. (**a**) An active pockmark (#1) with a narrow conduit within. (**b**) Two pockmarks (#2–3) located close to each other. Pockmark 2 is backfilled with sediment, indicating bubbles did not rise through it in recent ebullition events. Pockmark 3 is particularly small, potentially because few bubbles have passed through it. (**c**) Four pockmarks (#4–7) in close proximity. (**d**) One large pockmark (#8). The instrument (red and black color) on the bottom-left corner of each image is an RBR concerto data logger. The rim of the black guard has a diameter of 8.6 cm. In (**b**) and (**d**), the instrument is covered by mud. The location of pockmark 1 is marked as white diamond in Fig. 1a; whereas, the location of pockmarks 2–8 is indicated with a white square in Fig. 1a.

Figure 5-5: Photographs taken from a camera suspended approximately 5 cm above the water-mud interface on 03 October 2019 (after Zhao *et al.* 2021).

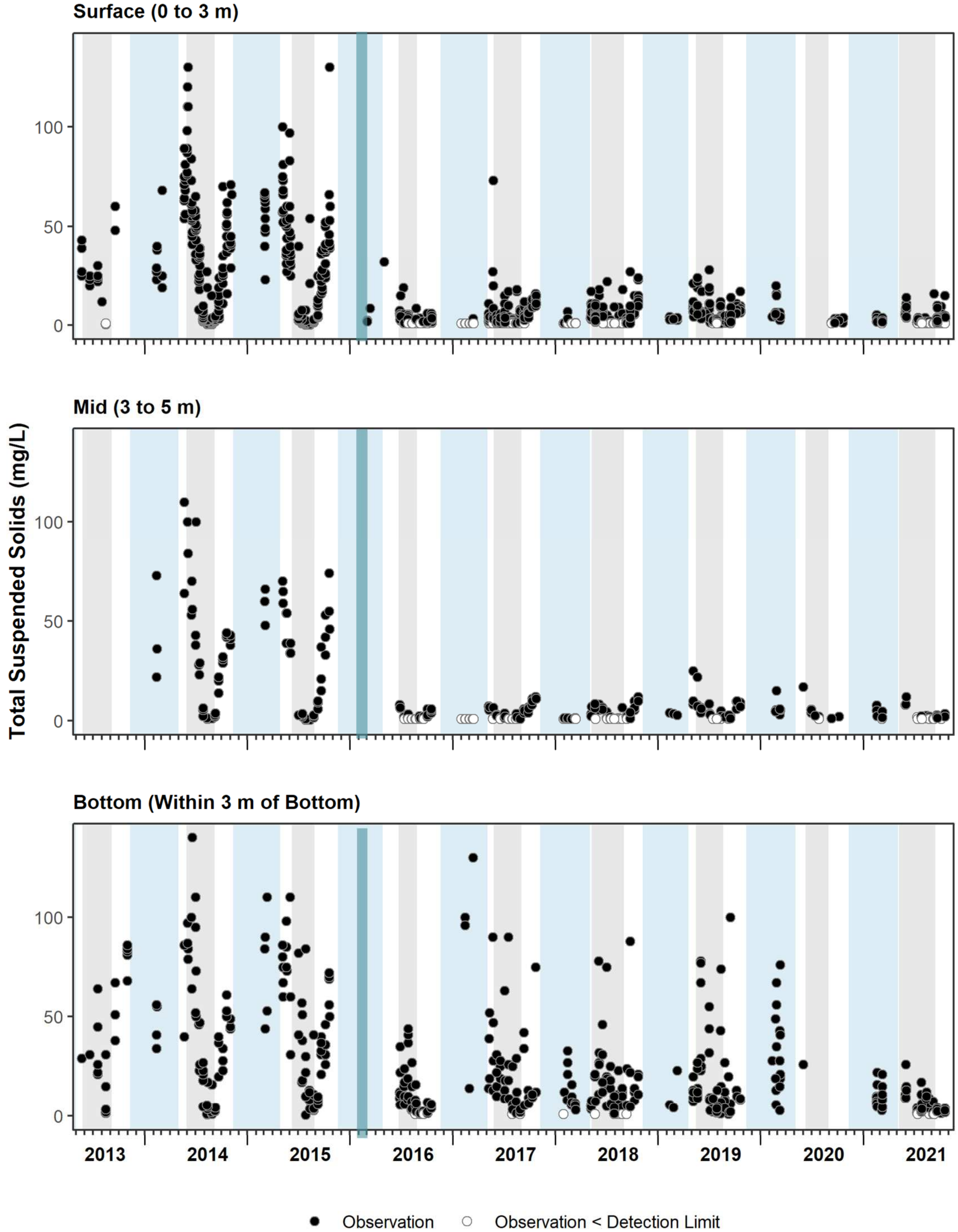
5.3 Total Suspended Solids (TSS) should show improvements over time or be in the range of natural variability

TSS concentrations in BML remained relatively high, but declining in annual peak concentrations slightly from 2013 through 2015, before decreasing and becoming more stable after the 2016 alum treatment (Figure 5-6). The fines in the water cap were residual fines liberated to the water cap during tailings deposition. If fines are re-suspended from below the mudline, the TSS concentration in the water cap would be expected to increase with time. Both pre- and post-alum addition, the peak TSS concentrations are generally declining with time or are stable (Figure 5-6). Seasonal trends in TSS concentrations connected to lake mixing events are evident, but are dampened post-alum treatment. These seasonal dynamics represent residual fines in the water cap, not fines re-suspended from beneath the mudline, because there is no evidence of net increases over time. Before the alum addition, the TSS concentrations would peak during spring turnover, and when the lake was thermally stratified in summer the TSS concentration in the water cap generally declines as fines settle. The fines did not settle out of the water cap completely before fall turnover. These seasonal dynamics are present, but dampened post-alum treatment.

Seasonal variations in TSS concentrations were less apparent in BML in 2021, with median concentrations highest in winter (3.9 mg/L), followed by summer (1.9 mg/L), and fall (1.6 mg/L). Because of COVID related delays in sampling, TSS concentrations were not measured during the spring of 2021. Median TSS concentrations in summer and fall 2021 were lower than the historical post-alum treatment medians (2.45 and 4.85 mg/L, respectively), while the winter 2021 median was higher (2.5 mg/L).

Historically, TSS concentrations have varied vertically, with slightly higher concentrations near the bottom of the lake (Figure 5-6). Greatest median concentrations were found near bottom (within 3 m; 6 mg/L), with lowest median concentrations found at the surface (1.6 mg/L). The vertical variations in TSS concentrations are influenced by near-bottom sampling close to the water-FFT interface.

In 2021, TSS concentrations in Beaver Creek Reservoir (BCR), the fresh water source for BML import, had a median concentration of 1.9 mg/L during the summer and 1.6 mg/L during the fall, which both were lower than the historical medians (7.8 and 9.3 mg/L, respectively) but still within the historical range. These are comparable to concentrations in BML in 2021.



Ice-covered (blue) and stratified (grey) periods shown as filled areas on each panel.
Green interval shows the period of the alum treatment.
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 5-6: Total Suspended Solids (TSS) in BML water cap in mg/L from 2013-2021.

5.4 The water cap should not be acutely toxic

Toxicity tests measure the biological response of test organisms exposed to a water or sediment sample for a controlled time period. Organisms are exposed to BML whole-water at various concentrations (serially diluted), and also to clean laboratory controls to determine differences in the biological responses to any toxicants present. Acute toxicity is determined by organism survival. Lethal responses are reported as LC50, which is the estimated concentration of exposure medium, diluted with a non-toxic control medium, that is lethal to 50% of the organisms in the short-term test period (usually within 96 hours).

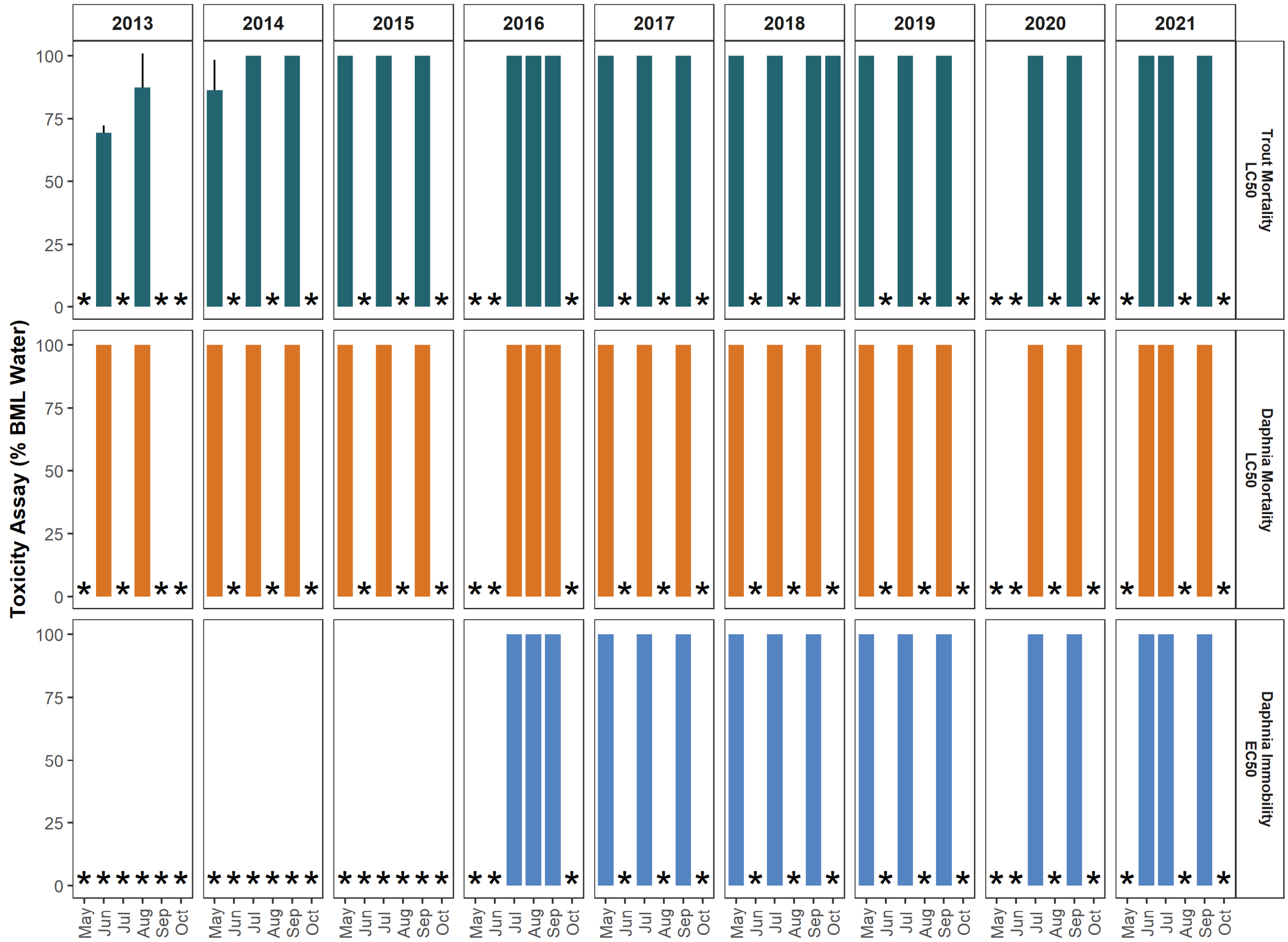
Water toxicity samples are collected during the open water season. Each sample consists of a composite of multiple grabs from two discrete depths in the field-estimated euphotic zone (twice the Secchi depth), collected with a 4L horizontal Van Dorn sampler. The grab samples were composited in clean laboratory-supplied 20L carboys. At each of the three platform stations, 70 L of water was collected for testing. Samples were shipped immediately, unpreserved, to Nautilus Environmental (Nautilus) in Calgary, Alberta. Two standard acute toxicity tests were used:

- EPS 1/RM/13: Biological Test Method: Reference Method for Determining Acute Lethality of Effluents to Rainbow Trout (Environment Canada 2000, 2nd Edition); and
- EPS 1/RM/14: Biological Test Method: Reference Method for Determining Acute Lethality of Effluents to *Daphnia magna* (Environment Canada 2000, 2nd Edition).

The 96-hour static acute test on rainbow trout (*Oncorhynchus mykiss*) did not show any effect on survival resulting from exposure to BML water in 2021, with all LC50 values >100% v/v BML water (Figure 5-7). Historically, rainbow trout exposure to BML water resulted in a mortality response until May 2014, with LC50 values ranging from 69% to 87% v/v; no survival effect has been observed in any subsequent rainbow trout test.

The 48-hour acute *Daphnia magna* test on BML water has shown no survival effect since monitoring began in 2013, with all LC50 values >100% v/v BML (Figure 5-7). The 48-h *D. magna* acute test conducted since 2016 has similarly showed no toxicity of BML water on *D. magna* mobility, with EC50 values >100% v/v BML in all three years.

Using the Rainbow Trout and *Daphnia magna* tests, there has been no evidence of acute toxicity in BML water cap since early 2014.



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

Figure 5-7: Rainbow trout and Daphnia magna acute toxicity results for BML whole water 2013-2021, showing absence of acute toxicity since early 2014.

5.5 The water should also pass appropriate Canadian Water Quality (acute) Guidelines for the Protection of Aquatic Life (CCME 2014c) and Environmental Quality (acute) Guidelines for Alberta Surface Waters (AEP 2018)

Of all parameters measured in the water cap during the open water season with acute PAL guidelines, only the F2 hydrocarbons exceed acute guidelines. A study is underway though COSIA to assess the relevance of the interim F2 guideline for use in aquatic systems.

6 Summary of Key Performance Results for BML: Progress towards longer-term performance indicators to validate Water-Capped Tailings Technology

As described previously, the longer term objective for Base Mine Lake is reclamation certification, which 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. Key existing guidelines that may be appropriate as performance indicators to support certification of Base Mine Lake include Environmental Quality (chronic) Guidelines for Alberta Surface Waters (AEP 2018) and Canadian Water Quality (chronic) Guidelines for the Protection of Aquatic Life (PAL) (CCME 2014c).

The 2021 analytical results for the discrete water quality samples collected from BML were screened against GoA (2018) 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 (2018) and CCME (2007) guidelines, or acute and chronic guidelines). Site-specific (e.g., hardness-dependent) guidelines were calculated for each sample, as applicable.

One metric that historically has been used to track lake performance over time is the proportion that a water quality variable exceeds its guideline relative to the total number of samples collected in a year. Table 6-1 summarizes the proportion of each analyte that exceeded guideline values in each monitoring year; however, caution should be taken when interpreting the 2020 results due to adjustments to the sampling design. Specifically, a higher proportion of winter samples were collected relative to open-water and a higher proportion of surface samples were collected relative to at-depth in 2020. A lower percentage of samples exceeded the GoA chronic water quality guideline relative to the historical record, with chloride, sulphide, total ammonia, total boron, and F2 hydrocarbons exceeding guidelines consistently every year.

Table 6-1: Proportion (as %) of surface water quality samples from Base Mine Lake that exceeded GoA chronic guidelines for surface water quality, 2013 to 2021

Group/Variables	Year[a]								
	2013	2014	2015	2016	2017	2018	2019	2020	2021
Conventional Physico-Chemical Variables, Ions, and Nutrients									
Total Alkalinity (as $CaCO_3$)	0	0	0	0	0	0	0	0	0
Chloride	100	100	100	100	98	100	100	100	100
Sulphate	25	0	0	0	0	0	0	0	0
Sulphide[b]	71	55	66	68	57	69	66	81	87
Nitrate (as N)	0	0	0	0	0	0	0	0	0
Nitrite (as N)	29	19	3.5	4.0	0	0.3	0	0	0
Total Ammonia (as N)	84	88	68	48	61	55	58	10[c]	51
Dissolved and Total Metals									
Dissolved Aluminum	21	5.6	1.0	33	39	1.0	4.3	22	15
Dissolved Iron	2.3	0.4	2.0	0	0.3	0	6.2	7.8	1.0
Total Arsenic	0	1.6	0.8	0.5	1.4	0.6	0	2.5	0
Total Boron	100	100	95	86	96	100	95	83	67
Total Cadmium	0	0.4	0.4	0	0.6	0.6	0	2.5	0
Total Chromium	25	61	100	42	14	45	49	70	18
Total Cobalt	23	90	62	35	15	41	10	6.2	0.3
Total Copper	0	1.6	0	0	0.9	0.9	0	3.7	0
Total Lead	0	2.0	0.4	0	1.7	1.2	0	0	0
Total Mercury	7.5	3.6	0.7	1.0	1.3	0	0.9	0	0
Total Methyl Mercury	-	3.8	0	0	1.3	6.7	0	0	0
Total Molybdenum	9.1	0	0	0	0	0	0	0	0
Total Nickel	0	0	0	0	0.3	0	0	0	0
Total Selenium	51	1.2	0	0	0.3	0.3	0	0	0
Total Silver	0	0	0	0	0.3	0.3	0	0	0
Total Thallium	0	0	0	0	0	0.3	0	0	0
Total Uranium	0	0	0	0	0	0.3	0	0	0
Total Zinc	0	2.4	0.4	0	0.6	0.9	0	9.0	0.5
Organics									
Total Phenolics	100	71	52	50	15	79	46	35	11
Benzene	-	0.6	0	0	0	0	0	0	0
Ethylbenzene	-	0	0	0	0	0	0	0	0
F1 (C6-C10)	-	4.0	0.7	0	0.6	1.1	0	0	0
F2 (C10-C16)	-	100	99	100	100	97	99	98	100

Table 6-1 (continued)

Group/Variables	Year[a]								
	2013	2014	2015	2016	2017	2018	2019	2020	2021
Organics (cont'd)									
Toluene	-	1.7	0	0	0.6	0	0	0	0
Total Xylenes	-	0.6	0	0	0	0	0	0	0
PAHs									
Acenaphthene	0	0	0	0	0	0	0	0	0
Acridine	0	0	0	0	0	0	0	0	0
Anthracene	0	0	0.7	0	5.7	1.1	0.7	0	0.6
Benzo(a)anthracene	0	4.2	1.4	1.0	1.3	0	0	0	0
Benzo(a)pyrene	0	3.5	1.4	1.0	0.6	0	0	0	0
Fluoranthene	0	4.2	0.7	0	0.6	0	0	0	0
Fluorene	0	0	0	0	0	0	0	0	0
Naphthalene	0	0	0	0	0	0	0	0	0
Phenanthrene	0	3.5	0	0	0.6	0	0	0	0
Pyrene	54	61	67	15	23	17	10	14	3.6
Quinoline	0	0	0	0	0	0	0	0	0

Note: Percent exceedance values calculated across all locations, seasons, and depths; zero values presented in grey text to increase readability.

– = Variable not analyzed in a given sampling year.

[a] Based on calendar year.

[b] Sulphide guideline was equal to or less than the analytical DL from 2013 to 2020; the calculated proportion of exceedances includes measurable results only (i.e., values greater than DL).

[c] TAN exceedances have historically occurred most frequently in deep samples, while 2020 open-water sampling focused on shallow- to mid-water depths.

7 Summary of Key Performance Results from the Base Mine Lake Monitoring Program

To date, the results from the monitoring and research program indicate that the fine tailings is settling as forecasted by model predictions, the mudline is declining over time, 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 water layers. The lake exhibits conventional boreal dimixis. These and other typical lake physical dynamics are important drivers of both the chemical and biological response in the lake. The water balance is dominated by pore water flux and fresh water import from Beaver Creek Reservoir. Bitumen sheen may have an effect on water evaporation from the lake surface. Surface water quality is also improving with time in Base Mine Lake, as expected to demonstrate the viability of the WCTT. The lake water is not acute toxic and has some residual chronic toxicity.

7.1 Physical Components of the Base Mine Lake Monitoring Program

The physical components of the Base Mine Lake monitoring program primarily relate to understanding trends in fluid tailings consolidation and conventional lake mixing dynamics. The physical components of the lake are the key drivers of the lake chemistry (especially with respect to lake water and chemical mass balance) and lake biology. An understanding of key physical limnological aspects in the lake is crucial for putting the lake chemistry and biology into context. Monitoring the fluid tailings mudline provides an understanding of the fluid tailings consolidation behaviour, and pore water volume and chemistry flux from the fluid tailings into the water cap. This monitoring provides support for the shorter-term performance indicators associated with demonstrating physical isolation of the fines beneath the water cap.

7.1.1 Fluid Tailings Settlement

FFT Settlement Assessment Key Findings
• *The top of the FFT surface is not flat. There is considerable variability in the mudline surface across the lake that generally corresponds to the original pit topography.*
• *FFT is settling, up to approximately 7.3 m between October 2012 and October 2021.*
• *The volume of FFT in BML has decreased from 195.97 Mm^3 in October 2012, to 169.08 Mm^3 in October 2021.*
• *The FFT surface changes observed in the 2021 FFT program are consistent with historic changes since 2012.*
• *The rates and magnitude of the FFT settlement are consistent with the expected self-weight consolidation as modelled by finite-strain consolidation theory (Carrier et al. 2019, and Dunmola et al. under review).*

A complete sonar survey of BML was conducted in October 2021. Since the fall of 2012, complete sonar surveys have been completed in the fall of each year, with the exception of 2020 due to COVID-19 pandemic site restrictions. FFT surface contour maps were completed for each fall sonar survey. FFT surface contour maps for 2012 and 2021 are shown in Figure 7-1. A map of cumulative settlement since commissioning is presented in Figure 5-2.

The FFT surface shows more bathymetric variation than in the early years since commissioning. This is a result of several factors, including:

- Single beam sonar methods and patterns of data acquisition were improved between 2012 and 2015,
- During the first sonar assessment in October 2012, tailings were still actively being deposited and this may have affected detection of mudline settlement,
- In 2016, sonar methods switched from single beam echosounder to swath bathymetry (multi-beam) providing full bathymetric coverage at high resolution,
- Cumulative FFT settlement in BML from 2012-2021, including differential settlements, variation in pit-bottom topography, and varying initial thicknesses of FFT creates variation in the mudline elevation.

The FFT surface is not flat across BML. As shown on Figure 7-1, the FFT surface in October 2021 generally varies spatially by over 7 m, from elevation 294.8 m in the northeast portion of BML to approximately 301.4 m off the south shore. Based upon the sonar survey isopachs, the FFT settled between 0 m and approximately 7.3 m between October 2012 and October 2021. Minimal settlement is observed around the perimeter (shoreline) of BML, where underlying FFT thickness is generally lower, and the pit surface is generally higher.

Cumulative FFT settlement across the lake between 2012 and 2021 is not constant but varies across the lake generally based upon the underlying thickness of FFT. To illustrate this, a scatterplot of the original 2012 FFT thickness versus the cumulative FFT settlement from 2012 through 2021 is provided in Figure 7-2. The individual scatterplot points are spaced at 5 m. These points are referenced and summarized within 100 m x 100 m grid ‘cells.’ The overall trend of this dataset is that settlement increases with increasing FFT thickness throughout the lake. There is quite a bit of scatter in the data for several factors, in addition to original FFT thickness, which may include variations in the physical characteristics of the FFT. Samples were collected in 2021 to assess FFT physical parameters.

The maximum settlement is approximately 7.3 m in the vicinity of Platform 2. The northeast section of BML is where the most recent transfer of FFT into WIP, now BML, occurred and therefore represents the freshest (lowest solids content) FFT within WIP/BML. Consolidation/ dewatering of FFT is thought to occur more rapidly in the early years following deposition and generally slows with time.

A cross-section through the three permanent platforms (P1, P2, and P3) in BML showing both the 2012 and 2021 water elevations and the 2012 and 2021 FFT surfaces, demonstrates that overall settlement is in part related to FFT thickness, as discussed above (Figure 7-3).

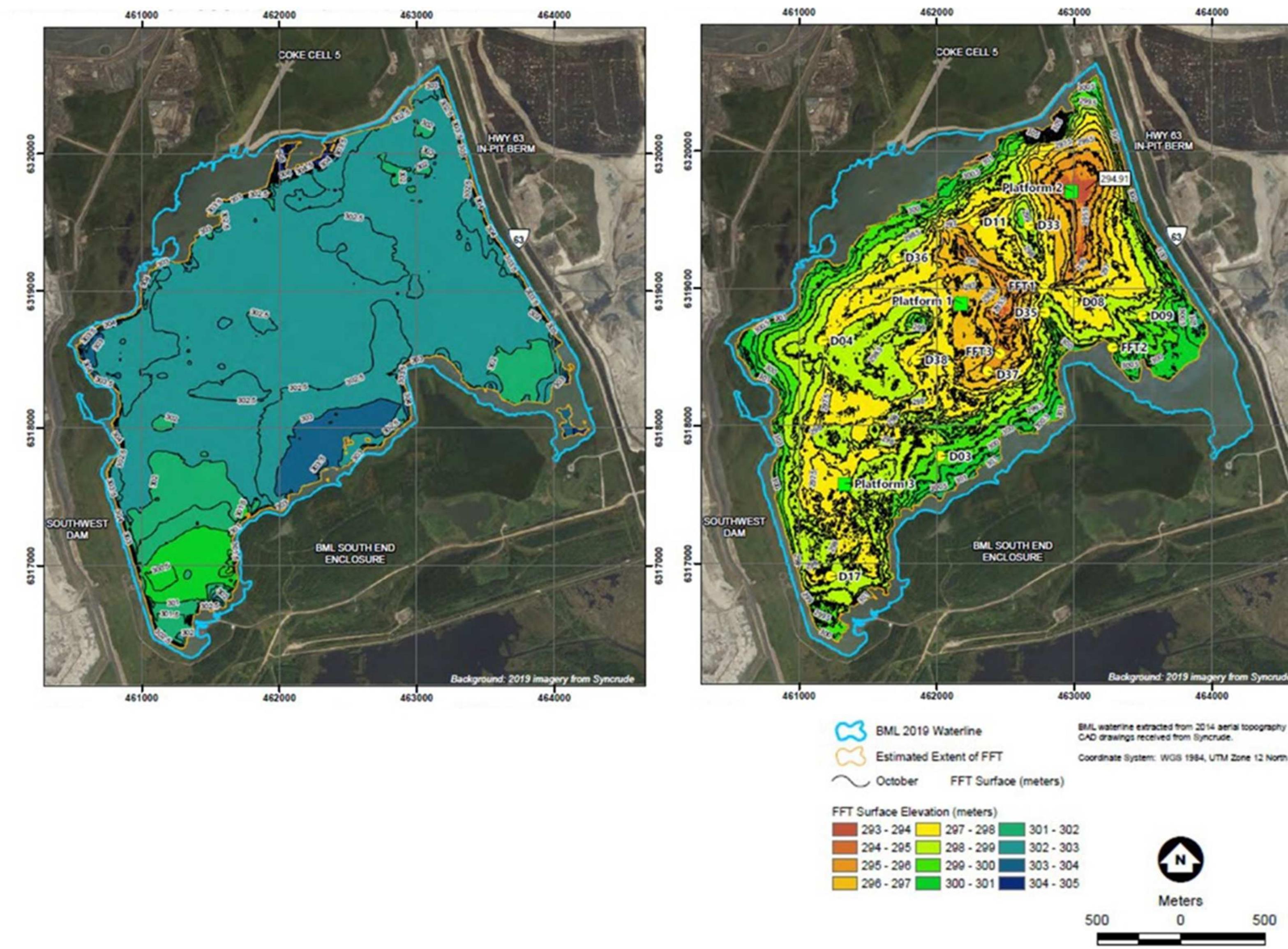


Figure 7-1: Surface contour maps of FFT mudline from October 2012 (at left) and October 2021 (at right) showing variation in mudline bathymetry.

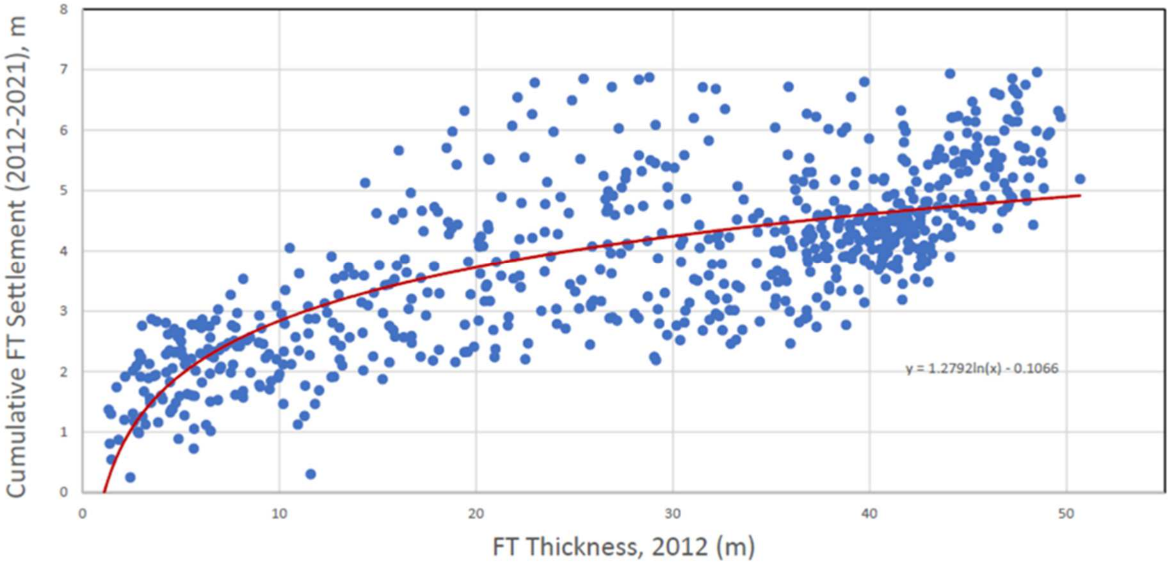


Figure 7-2: Scatterplot of cumulative FFT settlement in metres (2012-2019) against FFT thickness in 2012.

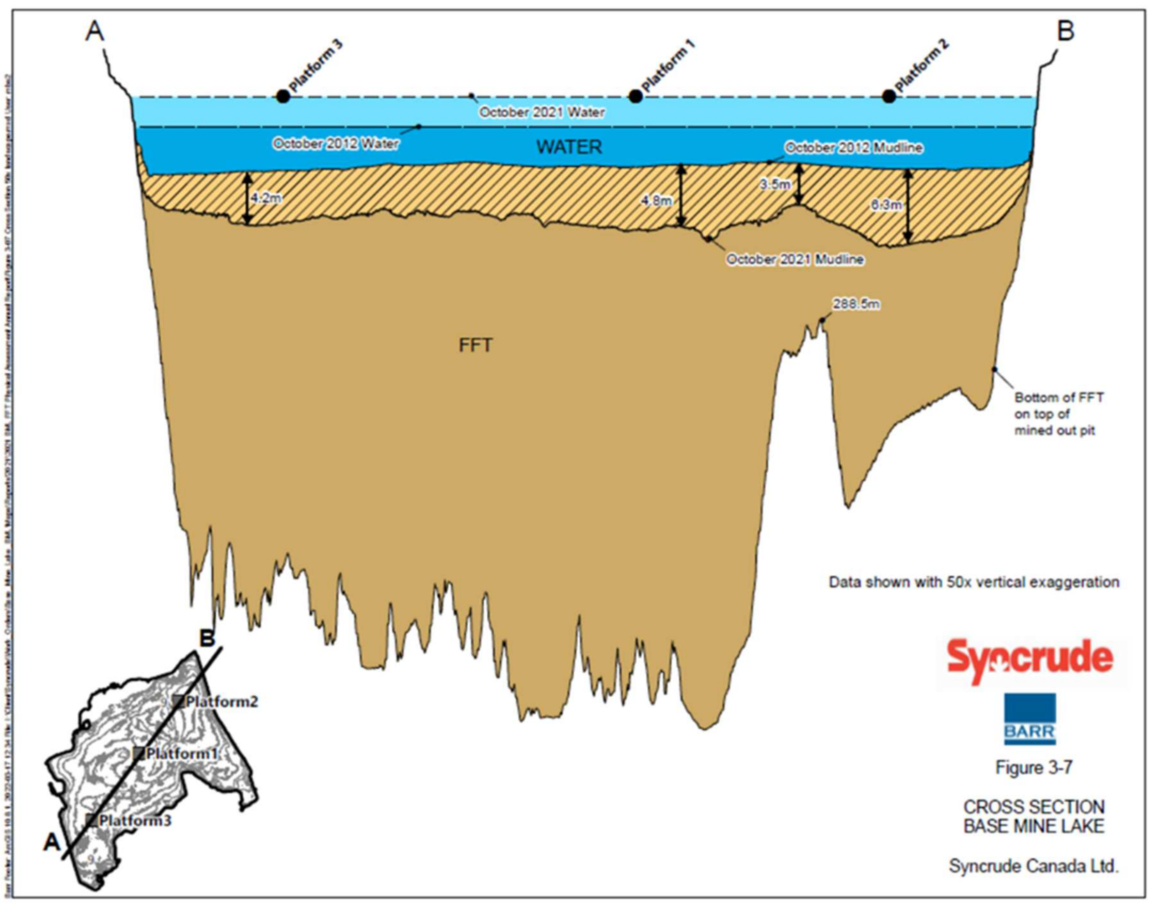


Figure 7-3: Cross-section of BML showing mudline elevation changes since 2012.

7.1.2 Fluid Tailings Physical Assessment

In October of 2021, at the same time as the sonar survey, ball penetrometer testing, physical FFT profile sampling, and vane shear testing were completed in BML. The samples are in the process of laboratory analysis, including pore water geochemistry analysis, and results will be shared in the 2022 BML Research and Monitoring Annual report, due June 2023.

7.1.3 Physical Limnology Assessment

Physical Limnology Assessment Key Findings
Physical Limnological processes that were similar in 2021 to 2014-2020
• *Similar to previous years, 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 a nearly 10% increase in water salinity under the ice.*
• *As the winter progressed, dissolved oxygen concentrations gradually declined at both 2 and 6 m depths, from 75% to 30% saturation.*
• *Turbidity increased throughout in late spring and early summer (May and June).*
• *Gradually declining turbidity during the second half of the summer thermal stratification period.*
• *In the summer, weekly wind events that cause large oscillations of the thermocline (internal seiches) and large fluctuations in turbidity and oxygen within and below the thermocline (when wind > 4 m/s).*
• *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 mudline).*
Physical Limnological processes that were varied from previous years or newly observed
• *The onset of turnover (September 14) was later than previously recorded and resulted in a longer summer stratified period (109 days) than most years.*
• *The turbidity in 2021 was generally less than the turbidity in previous years.*
• *Due to limited fresh water inflow, specific conductivity (salinity) was more constant and spatially uniform than previous years.*

Physical Limnology Assessment Key Findings
• *Profiles collected before alum dosing (September 2016) often indicated the presence of a region at the base of the water column up to approximately 0.5 m thick with very high turbidity that was intermediate in temperature between the temperature of the FFT and the water above (e.g., this layer was warmer than the water above in the fall and cooler than the water above in the spring. This region has become less apparent*

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. BML has consistently exhibited conventional boreal lake physical processes since commissioning. Annually, during the winter, the lake forms ice. When 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 temperatures and wind. This results in the lake mixing again, or fall turnover. Key lake events since commissioning are indicated in the table below.

Table 7-1: Summary of ice-on, ice-off, stratification (whole lake) and turbidity extremes from moored sensors at Platform 3 (P3) at 2.5 m depth

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

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

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

[d] Based on platform P3 at 7.5m (winter turbidity is uniform down to this depth).

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

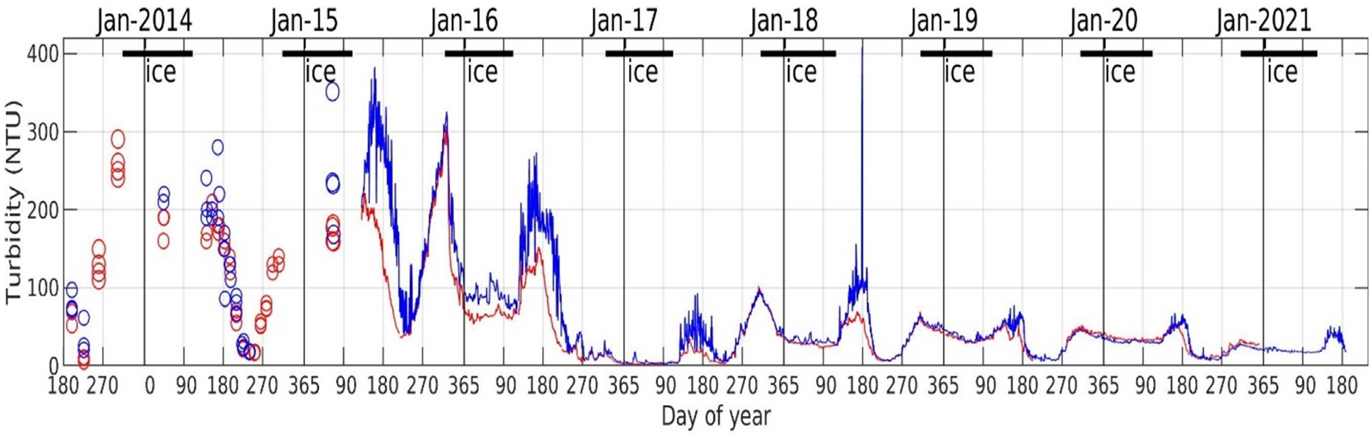


Figure 7-4: Turbidity measured from March 2014 to December 2021.

7.1.3.1 Ice and Winter Reverse Thermal Stratification in 2021 (Nov. 10, 2020 – May 6, 2021)

Air and water temperature, turbidity, specific conductivity, and dissolved oxygen concentration (as a percentage of saturation concentration) from Base Mine Lake before, during and after the period of ice-cover in 2021 is presented in Figure 7-5. Once ice cover occurred (day = - 47, November 10, 2020) notable changes were observed in the water column: the water temperature continued to decrease in the top 7m but increased below 7m (Figure 7-5b); the conductivity increased due to salt exclusion from the ice (Figure 7-5d) (day –53 to day 110, November 4, 2020 to April 20, 2021); the oxygen concentration declined from approximately 75% to 30% (Figure 7-5e).

Ice-on was not as clearly defined as previous years with different measures indicating different dates ranging from the November 4, 2020 to November 10, 2020 (day -53 to -47 in Figure 7-5), suggesting ice may have formed over all or part of the lake and then broken up and then reformed. Following ice-on, reverse temperature stratification (warm water below cool water) was established, indicating that mixing associated with atmospheric forcing (wind and solar radiation) was not occurring (Figure 7-5b). The patterns in the water temperature under ice are qualitatively similar to what is observed in many natural lakes and nearly identical to previous winters in BML; the near bottom water is gaining heat from the bottom FFT/sediment and the near surface water is losing heat through the ice to the cold atmosphere.

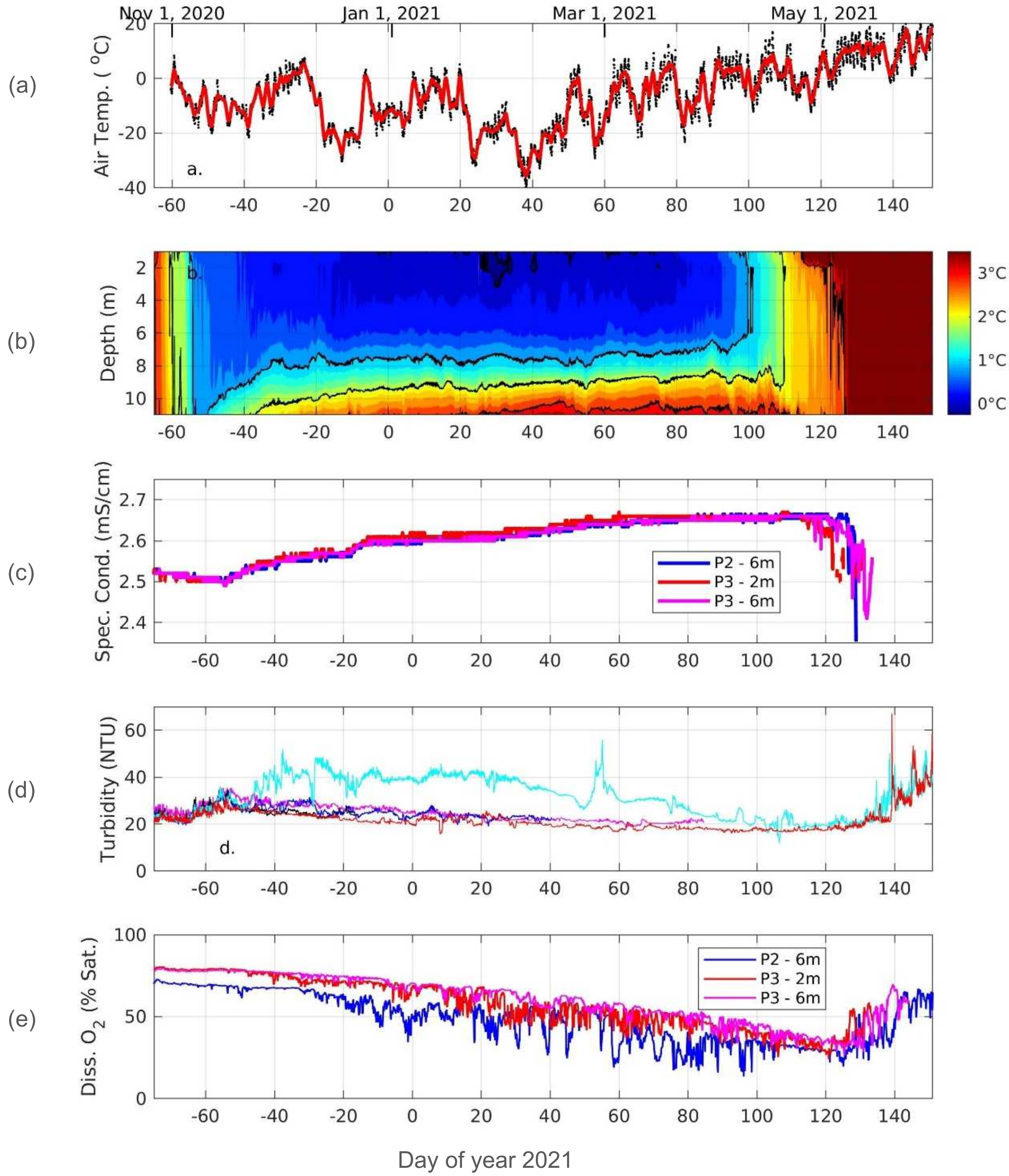


Figure 7-5: Measurements during winter 2020-2021. (a) Air temperature at P1. (b) Water temperature profiles measured at P2, the black contours are at 1, 2 and 3C. (c) Turbidity measured at P2 and P3. (d) Specific conductivity (mS/cm) measured at various locations indicated. (e) Oxygen concentration expressed as a percentage of the saturated concentration i.e., adjusted for water temperature.

7.1.3.2 Under-Ice Turbidity

There are four noteworthy features in the under-ice turbidity data:

1. Similar to previous winters, the highest turbidity at occurs at P2.

2. Except for the turbidity measured below 7.5m, the maximum turbidity occurred at the end of fall turnover, coincident with the initial formation of ice.

3. The peak in turbidity at 9.5 m at P2 occurred approximately four to five weeks after ice-on. This is similar to measurements made below 7.5 m during previous winters.

4. The turbidity throughout the ice-covered period was lower than previous years (other than 2017 immediately following alum dosing) and fell to a winter minimum of approximately 16 NTU (at 2.5 m).

7.1.3.3 Under-Ice Profiles of Temperature, Specific Conductivity and Turbidity

Profiles during the winter were collected at P1, P2, P3 and D04 on March 2 and 3. The vertical profiles of temperature are consistent with those observed in natural lakes under ice: water temperature increases with depth (reverse thermal stratification). Similar to previous winters, most of the profiles exhibit a homogeneous water-layer that is approximately 2 m thick at the top (Figure 7-6a and b). Below this homogeneous layer, temperature increases toward the bottom. Salinity decreases with depth until a depth of approximately 8 m where it then increases until the full depth of the water column is reached. The decrease in salinity with depth is relatively uniform across the lake and throughout the upper 8 m and from year to year (approximately 0.2 to 0.3 mS/cm). The source of the additional near bottom salinity is not yet known; it may be expressed from the FFT or excluded from the ice. This near bottom increase in salinity is becoming more conspicuous from year to year. Turbidity is relatively homogeneous throughout the water column, with some profiles displaying gradual increases with depth (1-5 NTU). A notable feature in the winter profiles at P3 is the presence of slightly clearer water near the bottom (Figure 7-6c).

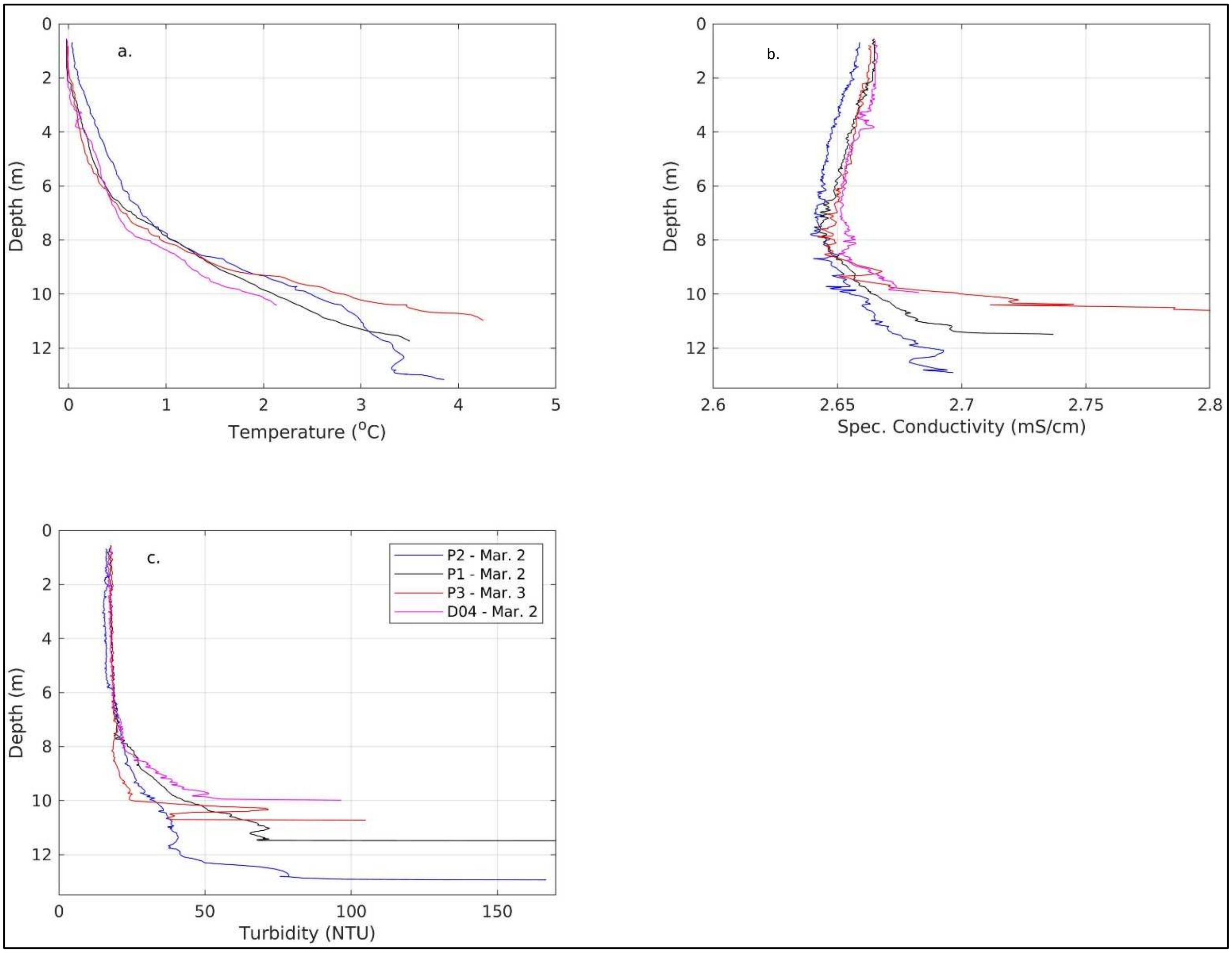


Figure 7-6: Winter 2021 Seabird profiles of (a.) temperature, (b.) specific conductivity and (c.) turbidity.

7.1.4 2021 Spring Turnover (May 6 – May 28, 2021)

Once the ice melts, solar heating warms the near surface water that is cooler than the temperature of maximum water density (TMD). For BML the TMD is ~ 3.6 °C for a specific conductivity of 2.7 mS/cm. This heating of the cool near-surface water increases the water density near the air-water interface, destabilizing the water column (dense water on top of less dense water) and drives convection. In the absence of salinity or suspended solids, the unstable water column will continue to warm from top to bottom until the temperature of maximum density is reached. If a lake is as saline as BML, melted ice and snow can leave a fresh water cap at the surface. The fresh, less dense, water at the surface tends to stabilize the water column and, provided there are no large wind events, can prevent complete spring turnover. A wind event at the end of May resulted in complete turnover in 2021; temperature, turbidity and oxygen (Figure 7-7b, c, d, and e) were all homogenized. This mixing lasted only a few days with all of these parameters diverging after the winds calmed on May 28 (day 148).

7.1.5 2021 Summer Stratified Period (May 28 – Sept. 14, 2021)

Like previous summers, Base Mine Lake exhibited summer thermal stratification that is typical of temperate and northern lakes. In this section, the evolution and structure of temperature, turbidity and dissolved oxygen are described.

7.1.5.1 Wind Forcing and Thermal Evolution During the Summer Period

In Figure 7-7, wind speed is plotted with the water temperature records from P2 and P3, turbidity from P3 and dissolved oxygen (as a percentage of the saturation concentration) from P3. The heavy blue line in Figure 7-7a is a low pass filtered representation of the scalar wind speed. This filter removes the wind variance at frequencies faster than 8 cycles per day (periods less than 3 hours) to emphasize winds that are persistent enough to have a lake-wide impact on the thermocline (i.e., upwelling of deeper cold water at the upwind end of the lake and downwelling of warmer near-surface water at the downwind end of the lake). It takes at least 3 hours of sustained winds in the same direction to begin to significantly impact the thermocline lake-wide.

The period of persistent summer thermal stratification began on approximately day 148 (May 28) and ended on approximately day 257 (September 14). The epilimnion (the upper water layer above approximately 3 m depth as shown by the red line in Figure 7-7b and c) warmed from the beginning of this period until approximately day 198 (July 17). A cool (10 ^{o}C average air temperature on day 198) and calm weather system on days 197 to 201 (July 16 to 20) resulted in deepening of the epilimnion below 5 m throughout the lake. A period of somewhat elevated winds from day 167 to 175 (June 16-24) caused mixing that cooled the surface water and slightly warmed the bottom water (the near-bottom water is shown by the magenta line, P2, 11 m in Figure 7-7b.). Following this windy period, the near bottom water maintained a nearly constant temperature for about 30 days (days 173-203) when, following the cooling period mentioned earlier, there was another wind event.

7.1.5.2 Turbidity in BML During the Summer Period

By the time ice came off of BML in early May only two of the moored turbidity instruments were fully functional, P2 at 9.5 m and P3 at 7.5 m. Both locations showed increasing turbidity in May. At P2 at 9.5 m the turbidity continued increasing until mid June. These changes are similar to those observed in May and June of previous years. Once the majority of the instruments were serviced at the beginning of July, turbidity is observed to be below 20 NTU throughout most of the water column until the end of the summer stratified period in early September.

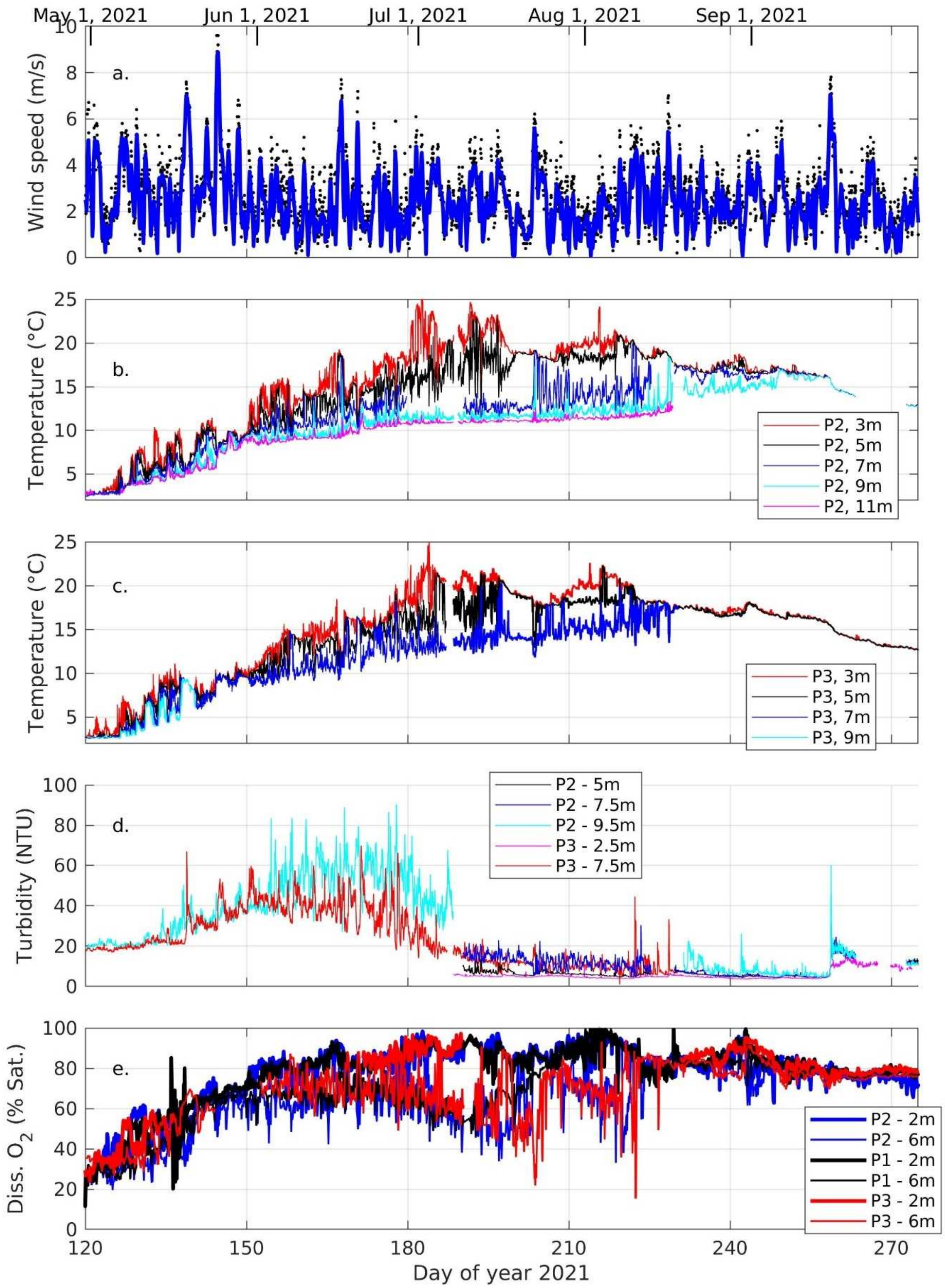


Figure 7-7: (a.) Wind speed at Sandhill Fen (Fen 3). (b.) Water temperature in BML at P2. (c.) Water temperature at P3. (d.) Turbidity measured at P2 and P3. (e.) Dissolved oxygen concentration in percent of saturation concentration.

7.1.5.3 Examination of Summer Profiles

Vertical and horizontal variability of temperature, specific conductivity, and turbidity collected on day 229 (August 17) at P2 are compared with previous years in Figure 7-8. The thermal stratification during this period is typical of BML or any other temperate lake on a mid-summer day. There are three layers within the water column as indicated in Figure 7-8a; an upper layer (epilimnion), a middle layer (metalimnion, also called the thermocline), and a lower layer (hypolimnion). The temperature and specific conductivity profiles from August, 2021 are noticeably different from previous years. In the case of temperature, the epilimnion is deeper than previous summers and, with the exception of 2019, the epilimnion is cooler than previous summers. The deeper and cooler may be related to the cool weather in mid-July discussed in section 9.1.5.1. In the case of the specific conductivity, the August 2021 profile indicates an almost perfectly uniform profile. This is primarily due to the lack of fresh water pumped in 2021.

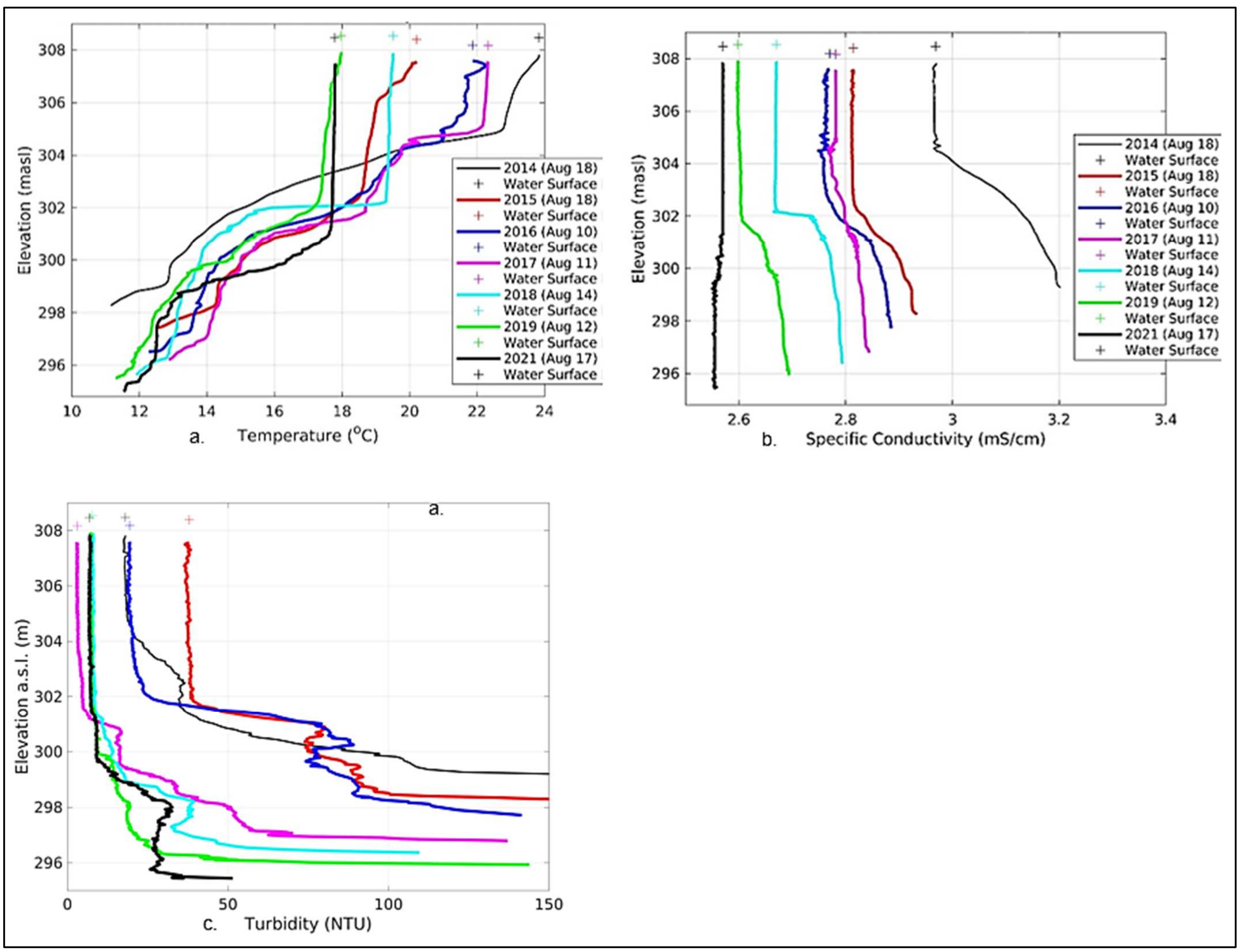


Figure 7-8: Seabird profiles at platform 2 indicated in the legend of (a.) temperature, (b.) specific conductivity and (c.) turbidity.

7.1.6 2021 Fall Turnover (Sept. 14 – Nov. 21, 2021)

7.1.6.1 Temperature and Turbidity Evolution

Fall turnover in BML started on approximately day 257 (September 14). The 2021 fall turnover in BML exhibited similarities to previous fall turnover periods, and the thermal evolution in 2021 was similar to that of a natural lake. The lake was homogenized both horizontally and vertically (Figure 7-7b and c). Calm winds and mild temperature in September resulted in late turnover (Figure 7-7b). The gradually increasing depth compared to early years also contributed to the late turnover. At the onset of turnover, the turbidity spike upward at the deepest instruments but then quickly fell back down (day 257 in Figure 7-7d). At shallower instruments (e.g., 2.5 m at P3, magenta in Figure 7-7d at day 257) the turbidity steps up from approximately 5 NTU to 10 NTU. This series of changes at the onset of turnover suggest a source of relatively turbid water in the deepest parts of the lake (>9.5 m) is mixed upward, first causing a spike at the deepest instruments when mixed with a small volume of relatively clear water and then a small step at the shallowest instruments when mixed with the total volume of the lake.

7.1.6.2 Fall Profiles

In Figure 7-9a, b and c the profiles of temperature, specific conductivity and turbidity collected on day 291 (October 18) are plotted. In general, all three parameters are quite uniform from top to bottom at all five stations with evidence of the instrument entering either an intermediate region or the FFT.

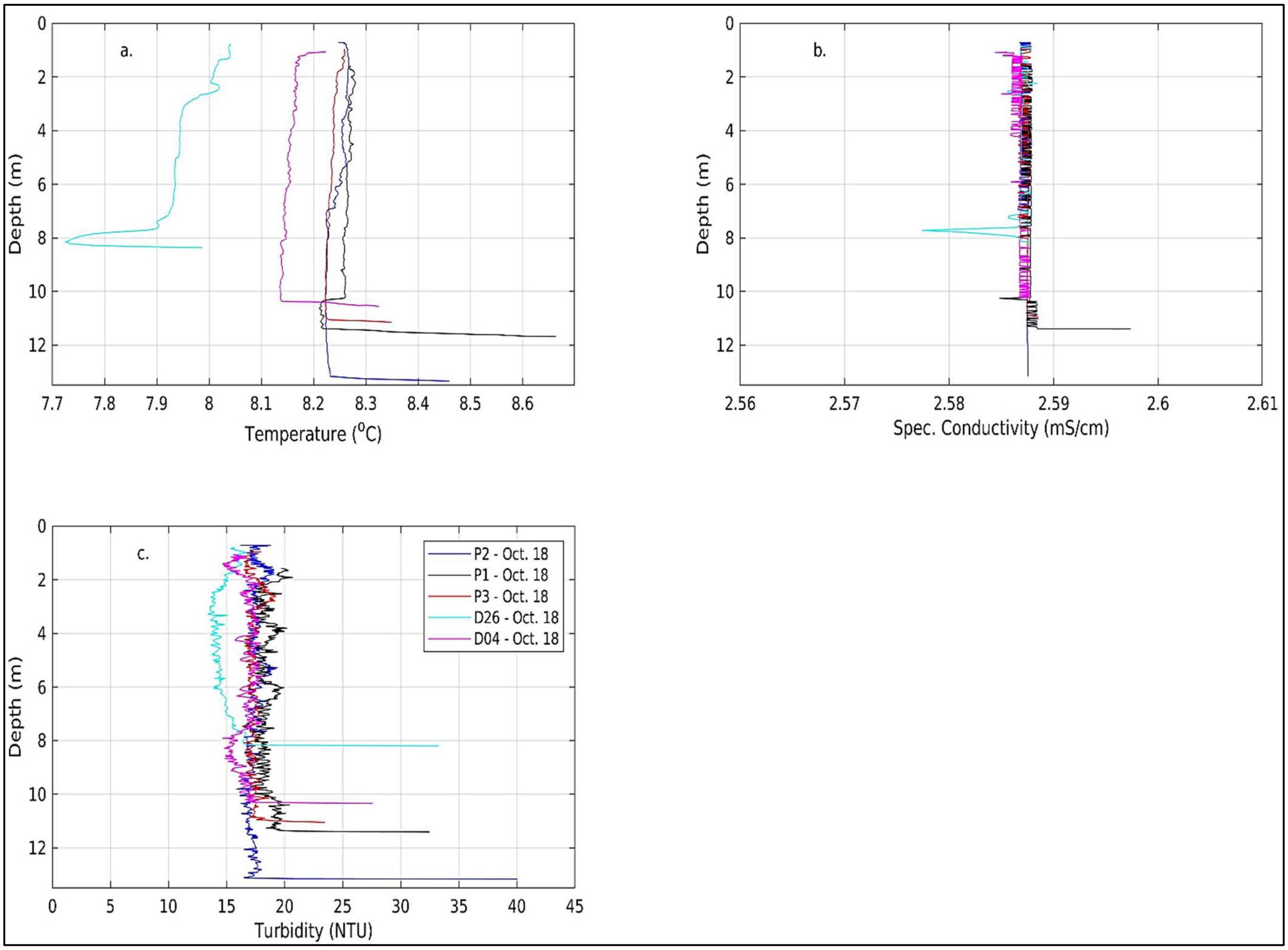


Figure 7-9: Fall 2021 Seabird profiles at the 5 locations indicated in the legend of (a) temperature, (b) specific conductivity and (c) turbidity.

7.2 Chemical Components of the Base Mine Lake Monitoring Program

The chemical components of the Base Mine Lake monitoring program focus on understanding surface water quality and changes through time. These monitoring components contribute to the validation of the shorter-term expectation of water quality improvements over time. Understanding the lake water balance is important for developing the water column chemical mass balance.

7.2.1 Water Balance Assessment

Water Balance Assessment Key Findings
• *The primary drivers of the water balance since commissioning have been inflows in and out of the lake, and pore water release to the water cap.*
• *There is an influence of hydrocarbon sheen on suppressing evaporation.*
• *The water balance is being closed and is well constrained.*
• *Runoff has been challenging to measure, and an estimation is required to close the water balance. Rules of thumb were imposed based on historical data to help provide a number.*
• *Methane and carbon dioxide fluxes have declined from the initial years post-commissioning.*

Estimating the water balance of BML has important implications for the chemical, energy and constituent mass balance of the lake, and provides information to support modelling of pit lakes in the closure landscape. The water balance for Base Mine Lake was revised in 2021. There are several changes to previous estimates that have arisen from data quality analysis and evaluation of longer-term estimates now that eight years of measurements have occurred. The water balance is complete from January 1, 2014 to December 31, 2021 on a daily basis in terms of both volumes of water and mm of water (depth per unit area). New approaches have been made to better estimate runoff contributions from the terrestrial areas.

7.2.1.1 Air Temperature

Since commissioning, air temperatures at BML have fluctuated by approximately 4 degrees in the open water season on an annual basis with the exception being an anomalously cool September 2018 (Figure 7-10). Open water air temperatures were above the 30-year Fort McMurray climate normal (1981-2010) whereas winter temperatures were above/below normal during ice-on periods.

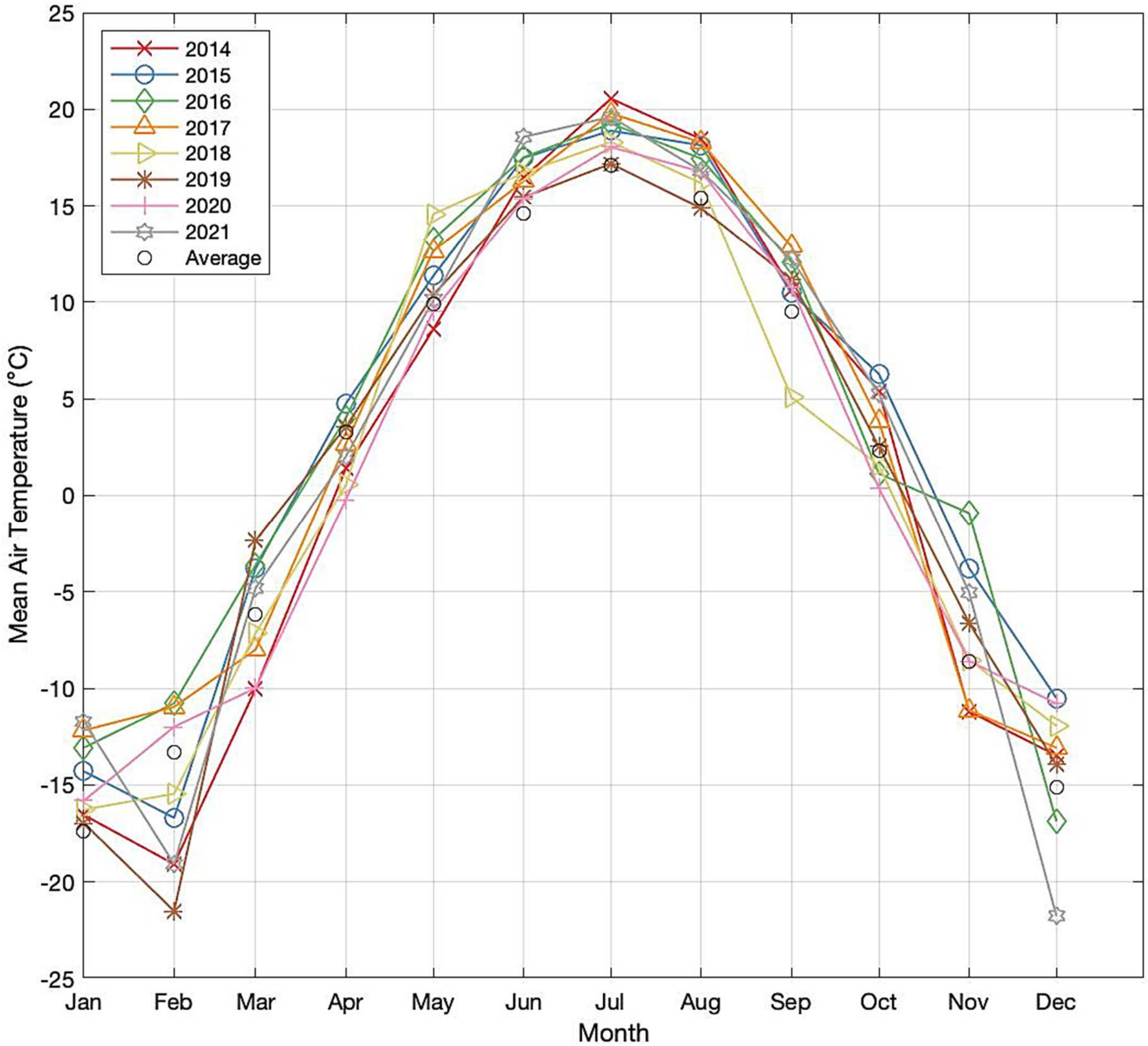


Figure 7-10: Air temperature from 2014-2021. Black circles are the 30-year climate normal for Fort McMurray.

7.2.1.2 Total Precipitation

Annual total precipitation has ranged from approximately 300 mm in 2015 to 600 mm in 2020, highlighting the considerable variability in local climate conditions. The climate normal for Fort McMurray A is ~420 mm, suggesting that there are approximately equal years above/below average. As discussed further, this variance is largely a result of rainfall as opposed to snow.

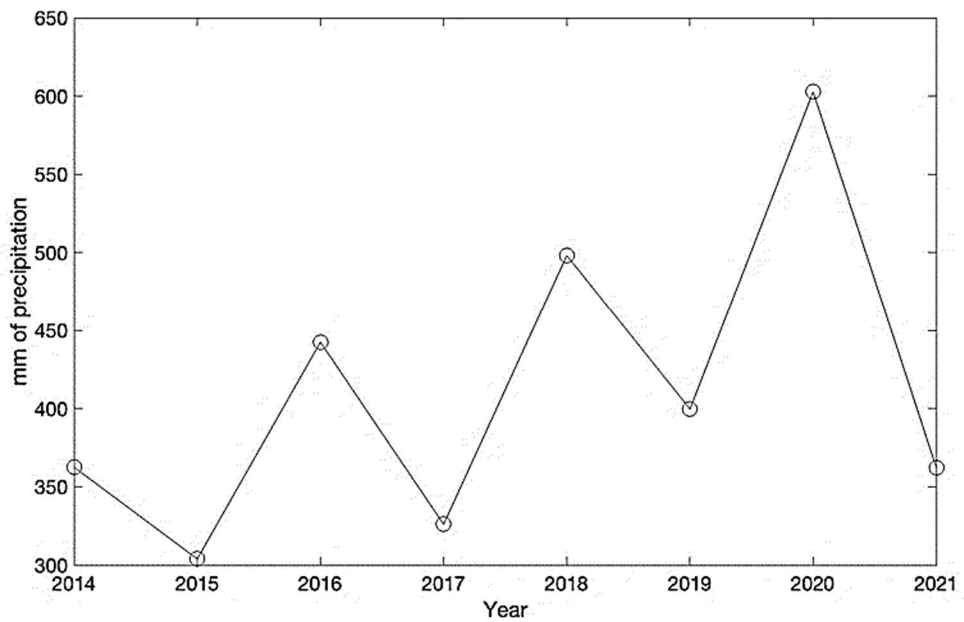


Figure 7-11: Total precipitation from 2014 to 2021.

7.2.1.3 Snow

The input of snow to BML is handled in a rudimentary manner. Each year snow surveys at BML and other sites are compared with total SWE gauges at the Sandhill Fen. There is considerable correspondence among these measurements, and a 'representative' BML snow water equivalent (SWE) is determined. This SWE is then added to the lake on the day the lake estimated to become ice-free. While there are obvious errors in this (most notably snowmelt will contribute to the lake water budget prior to ice-off), it is a reasonable estimate on a monthly basis yet may result in storage variances in the April and May. In all years, cumulative melt expressed as SWE is lower than the Fort McMurray average SWE of 102 mm. 2015 and 2017 were exceptionally low-snow years, whereas 2021 was the only year with a snowpack approaching normal. Note that SWE is taken as the maximum measured via surveys and continuous measurements.

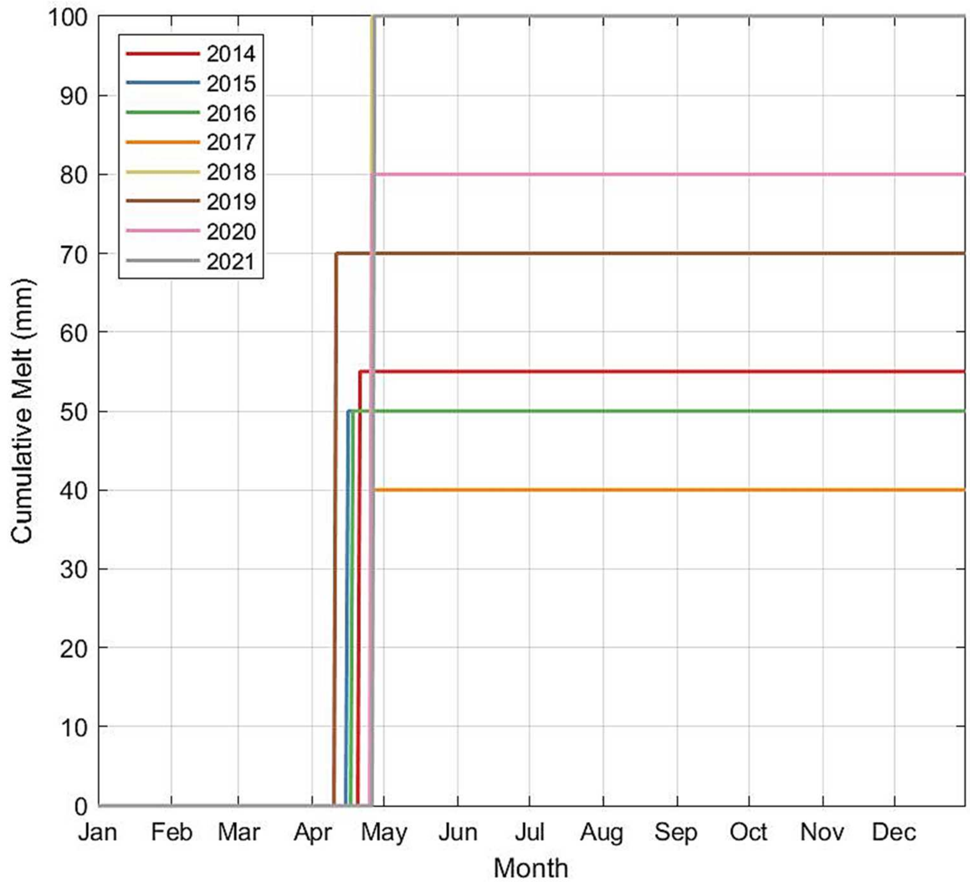


Figure 7-12: Cumulative melt added to the BML on the day of ice-off.

7.2.1.4 Rain

Rainfall is obtained by comparing daily totals from five gauges adjacent to BML and the tipping bucket gauge on Platform 1 for quality assurance. Gaps are filled and under-catch is assessed based on windspeed and gauge type. Daily cumulative rainfall (Figure 7-13) indicates that approximately half the years are below and half above the 30-year climate normal. Cumulative rainfall in the 8 years of study appears to lag the climate average, and in wet years late-summer large intensity events are responsible for considerable gains in water. In terms of total precipitation, rainfall is responsible for much more water, and a much greater variance in the water balance compared with snow.

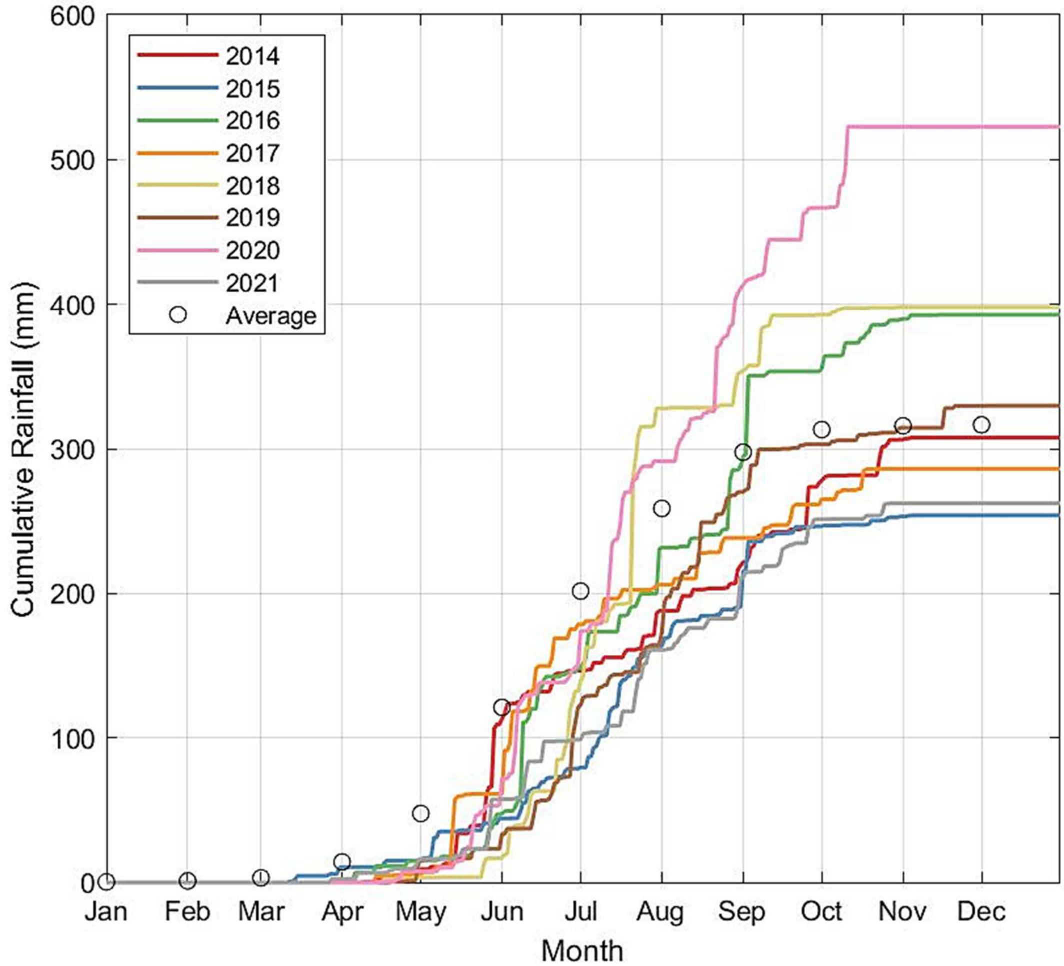


Figure 7-13: Cumulative daily rainfall. Open circles are the Fort McMurray cumulative monthly rainfall normals.

7.2.1.5 Runoff

In previous years, runoff was calculated from the Golden Pond weir on South Bison Hill and scaled to the terrestrial area contributing into BML. However, after 2015 the weir reported almost no water entering BML. This low value was attributed to the very high storage capacity of reclamation soils and near-zero values were entered into the annual balance. However, after 8 years, it has become clear that there was 'extra' water in the lake that could not be accounted for. There were many potential sources of errors, yet poor runoff estimation or groundwater fluxes were considered the two likeliest sources as all other fluxes were directly measured (with varying degrees of confidence). Firstly, over-winter changes in pressure in the lake during periods of minimal snowfall was examined. There is little evidence for increasing or decreasing pressure associated with gains/loss from groundwater, which would occur in winter, therefore net gains/losses in groundwater were assumed negligible (Figure 7-14).

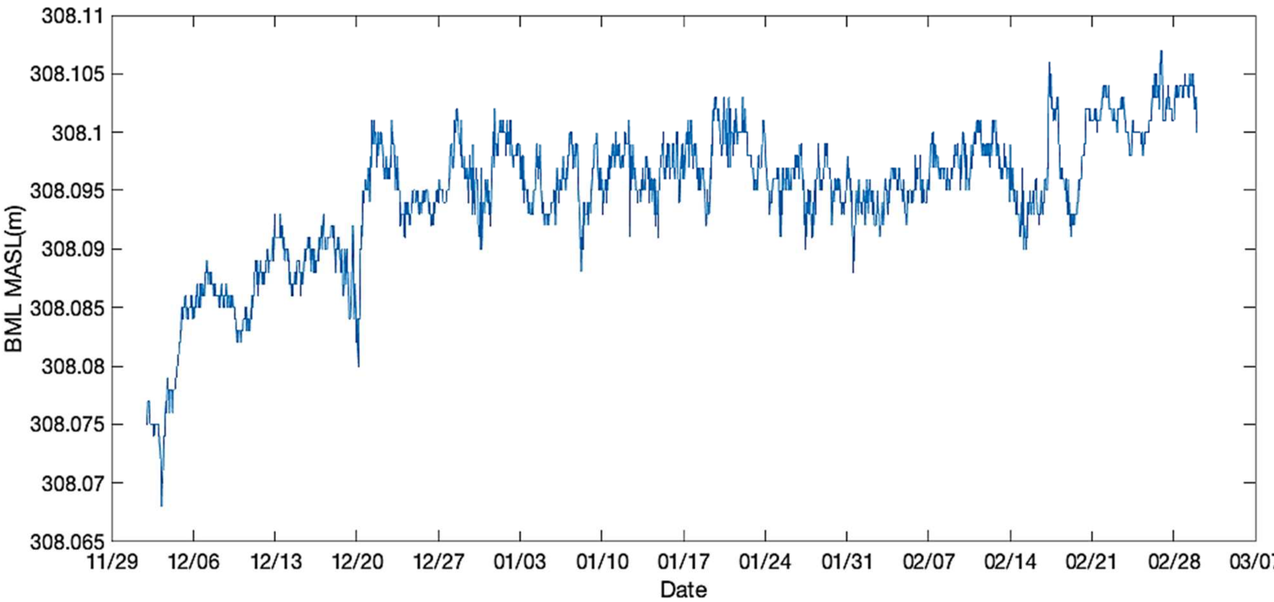


Figure 7-14: Over-winter water pressure in 2017 showing minimal changes during a largely snow-free January.

Previous runoff data from the weir prior to 2014 was reviewed, and a 'rule of thumb' developed to estimate runoff from precipitation events. A literature review helped to place this in context of previous reviews of runoff ratios form the boreal plains. The rule of thumb is:

For a given day:

- If Precipitation is < 10 mm, there is no runoff
- If Precipitation is > 10 mm and < 20 mm, the runoff ratio is 0.05
- If Precipitation is > 20 mm and < 40 mm, the runoff ratio is 0.1
- If Precipitation is > 40 mm, the runoff ratio is 0.2

These rules are applied for both rain and snow and occur the day of precipitation without lag. As discussed later, without this rule, there was a gradual decrease of water over the 8 years. Figure 7-15 shows the annual estimated runoff, and while total fluxes were small, they ranged from 17 to 52 mm. It is important to note that there are years with very high summer precipitation events that were previously assumed to be zero, yet could have addition of up to 18 mm of water (as in 2018).

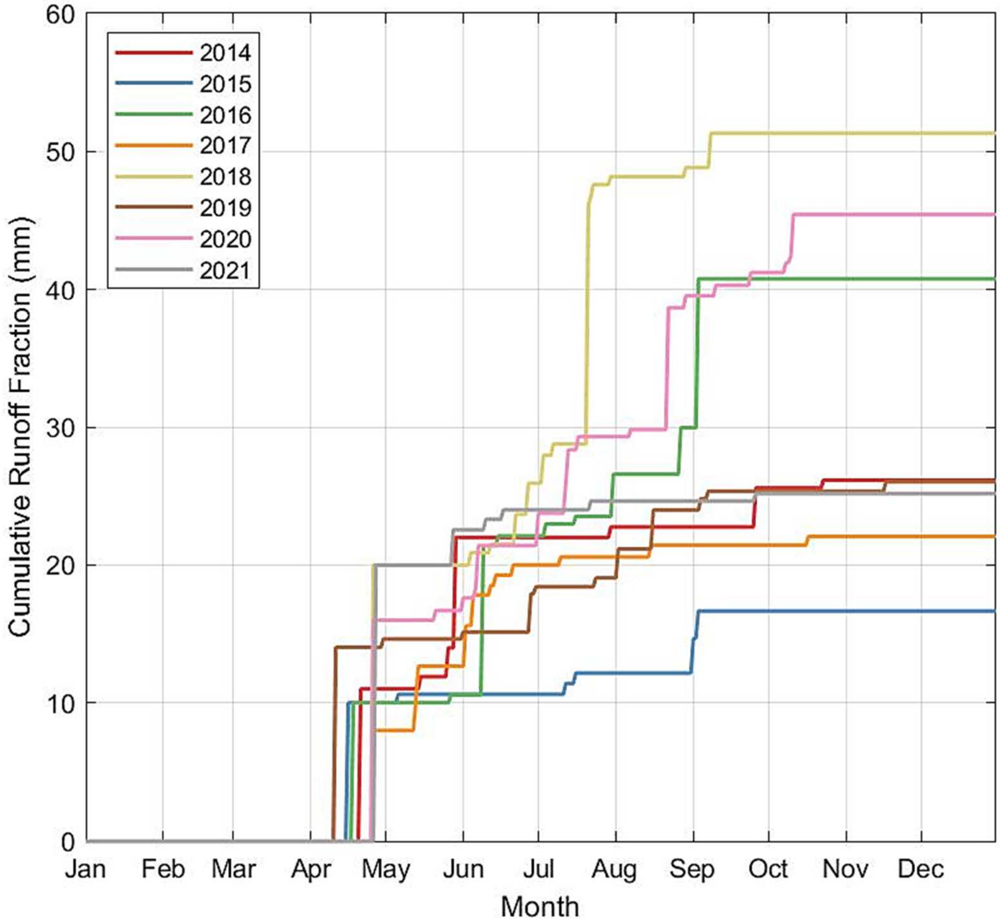


Figure 7-15: Cumulative calculated daily runoff.

7.2.1.6 Pumping

When there is inflow or outflow, volumes of both the additions (Figure 7-16) and removals (Figure 7-17) of water from BML from pump operation are determined on a daily basis. In the early years of commissioning, there were very large inputs/outputs from BML which have gradually declined over time. In 2019, dredging of bitumen removed water estimated as 45 mm. In 2021, to support operational water management on-site, no water was added to BML and very little (~23 mm) was removed.

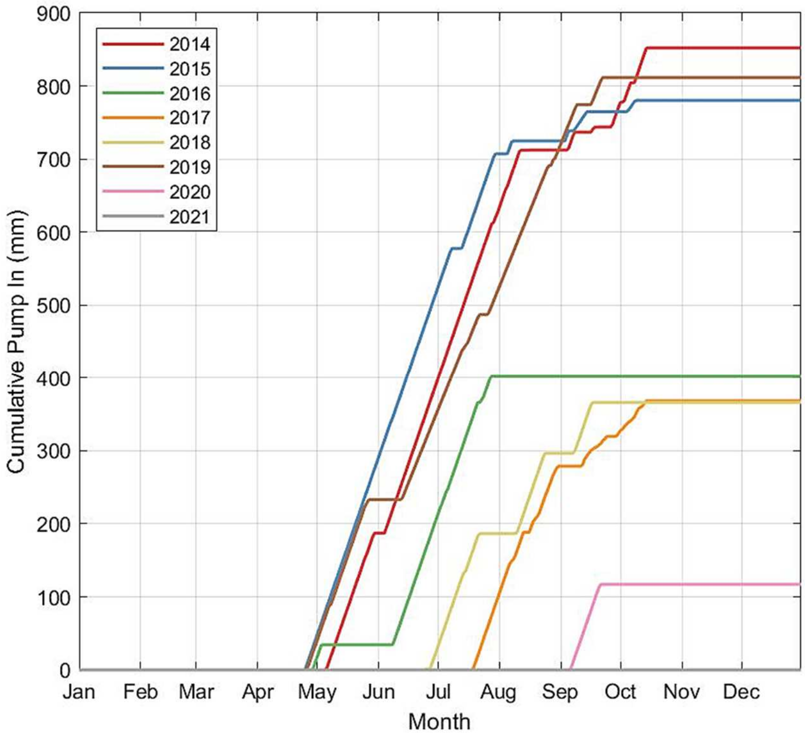


Figure 7-16: Total pump volume in from Beaver Creek Reservoir.

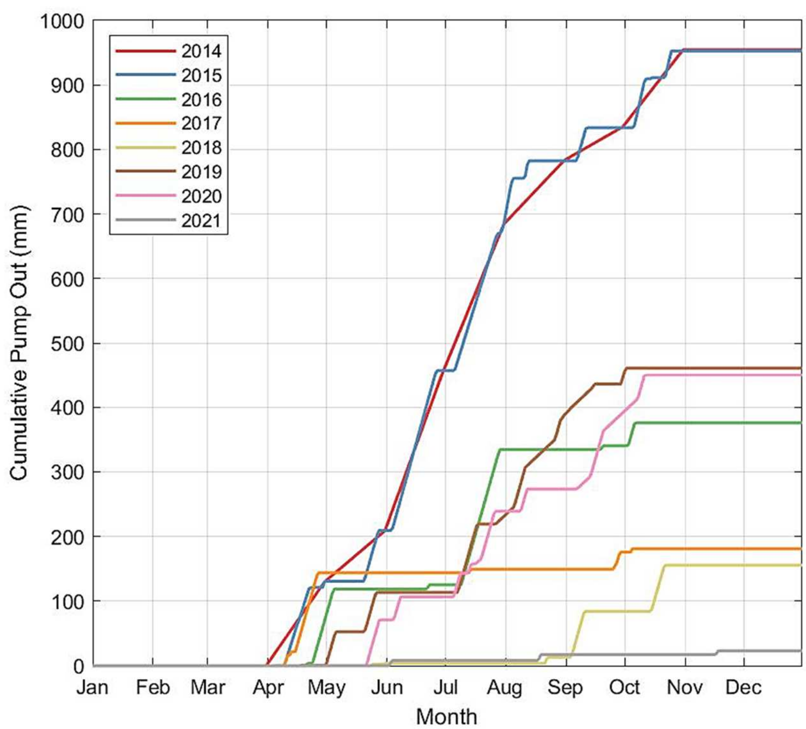


Figure 7-17: Total pumped removal of water from BML.

7.2.1.7 Evaporation

Evaporation is measured typically during the open water season (setup is in February/March and takedown in October). To interpolate missing data, artificial neural networks are now trained using BML data. This is also compared with the publicly available air-sea toolbox to in-fill evaporation rates and compare actual rates with those of large open water bodies (Figure 7-18).

Evaporation from BML appears suppressed compared to other northern lakes. This will be more fully confirmed using data collected in 2022 as new local lake-based instruments provide data. Evaporation values were particularly low in 2014 and have gradually increased (coinciding with the onset of bitumen mitigation activities, including surface sheen skimming) and range between 430 and 480 mm. It is uncertain as yet, the exact role of the hydrocarbon sheen, yet expected evaporation is over 100 mm higher than BML evaporation for the open water season.

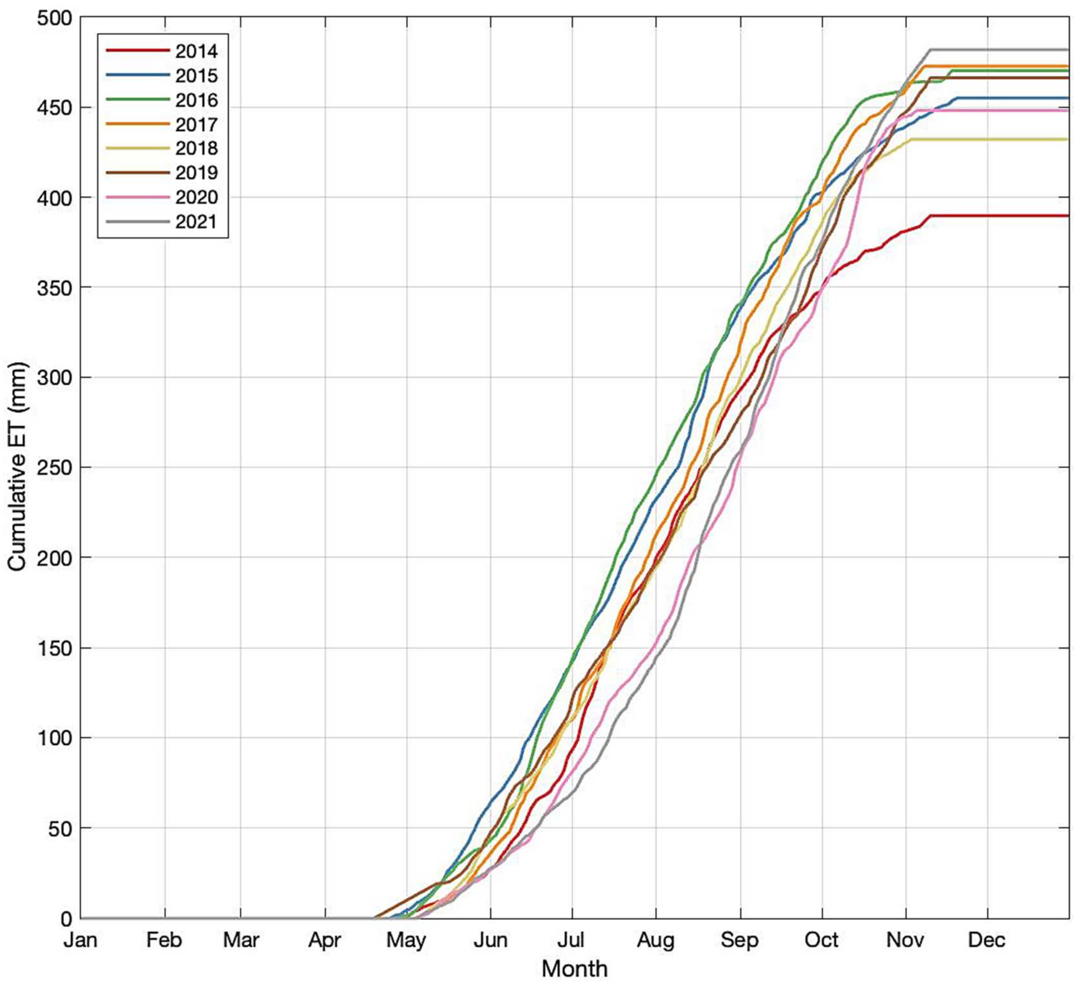


Figure 7-18: Cumulative evaporation from Base Mine Lake measured at Platform 1.

7.2.1.8 Multi-year Water Balances

Cumulative monthly totals in terms of mm and Mm^3 of water are presented in Figures 7-19 and 7-20; annual totals are presented in Tables 7-2 and 7-3. The volumetric totals include the water expressed from the FFT as determined by the annual FFT mudline elevation surveys.

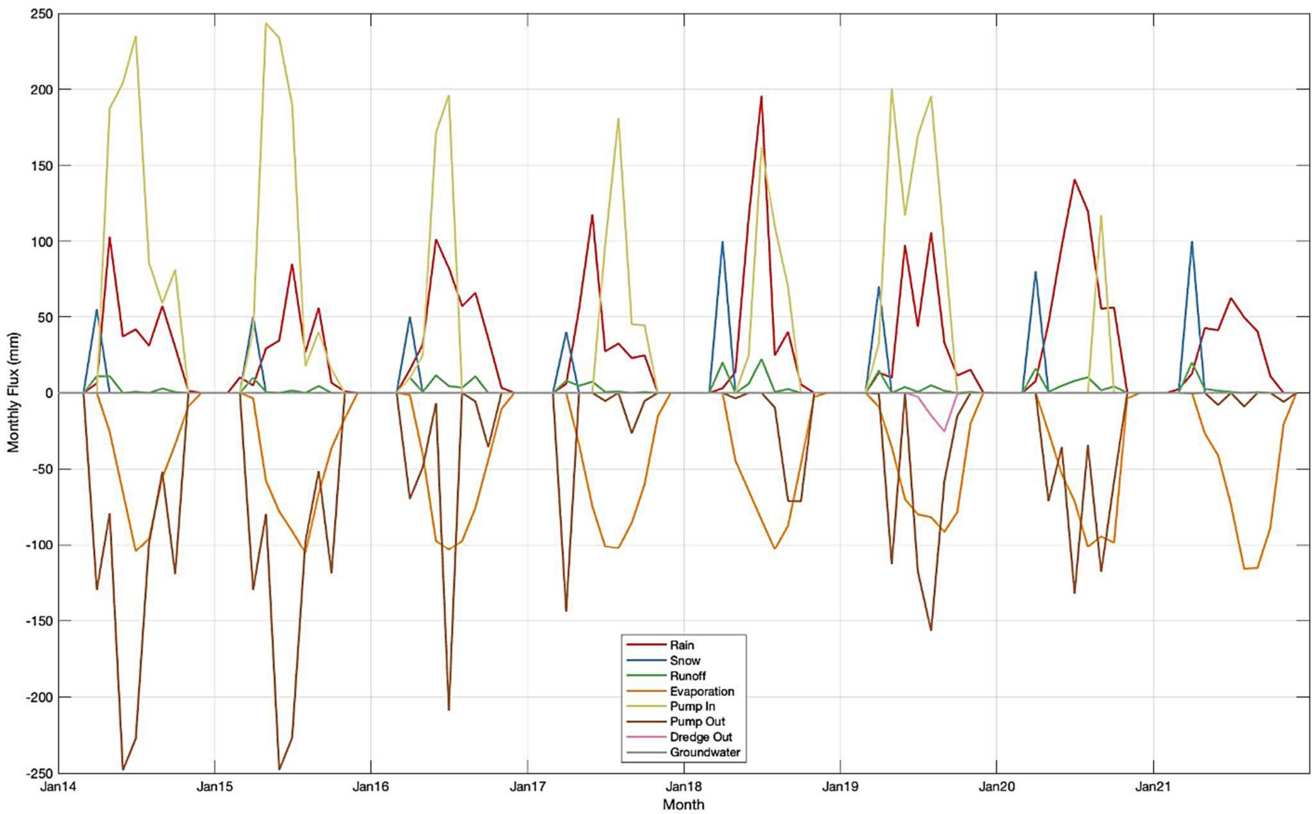


Figure 7-19: Monthly BML water balance in mm.

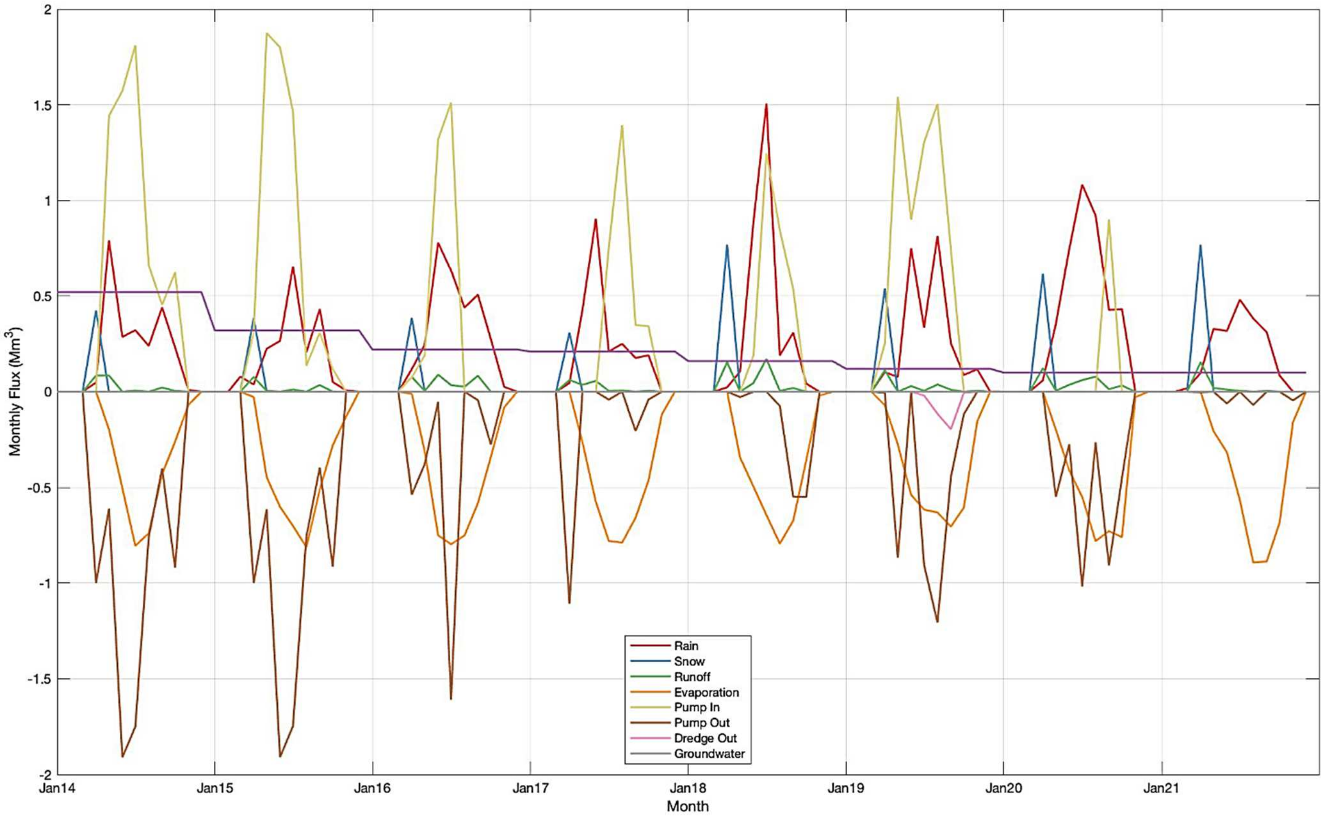


Figure 7-20: Monthly BML water balance in Mm^3.

Table 7-2: Annual BML water balance (in mm)

Year	Rain	SWE	Runoff	Evap	Pump_In	Pump_Out	Dredge_Out
2014	307.6	55.0	26.1	389.7	852.0	954.5	0.0
2015	254.0	50.0	16.7	455.2	780.2	952.6	0.0
2016	392.5	50.0	40.8	470.3	402.1	375.9	0.0
2017	286.1	40.0	22.1	472.8	368.4	181.2	0.0
2018	398.1	100.0	51.3	432.2	366.1	155.6	0.0
2019	329.7	70.0	26.0	466.3	811.4	461.1	43.6
2020	522.6	80.0	45.4	448.2	117.1	450.0	0.0
2021	262.2	100.0	25.2	481.9	0.0	23.1	0.0

Table 7-3: Annual BML water balance (in Mm^3)

Year	Rain	SWE	Runoff	Evap	Pump_In	Pump_Out	Dredge_Out	FFT Settlement
2014	2.37	0.42	0.20	3.00	6.56	7.35	0.00	6.24
2015	1.96	0.39	0.13	3.50	6.01	7.34	0.00	3.84
2016	3.02	0.39	0.31	3.62	3.10	2.89	0.00	2.64
2017	2.20	0.31	0.17	3.64	2.84	1.40	0.00	2.52
2018	3.07	0.77	0.40	3.33	2.82	1.20	0.00	1.92
2019	2.54	0.54	0.20	3.59	6.25	3.55	0.34	1.44
2020	4.02	0.62	0.35	3.45	0.90	3.47	0.00	1.20
2021	2.02	0.77	0.19	3.71	0.00	0.18	0.00	1.20

7.2.1.9 Change in Storage

The cumulative change in storage as calculated monthly versus the lake level change in storage suggests that with the inclusion of a new runoff calculation, that over 8 years the water balance is well constrained. Short-term differences occur, and much of this has to do with the artificial nature of water additions when calculating the water balance (i.e., all snowmelt runoff in one month with no lag).

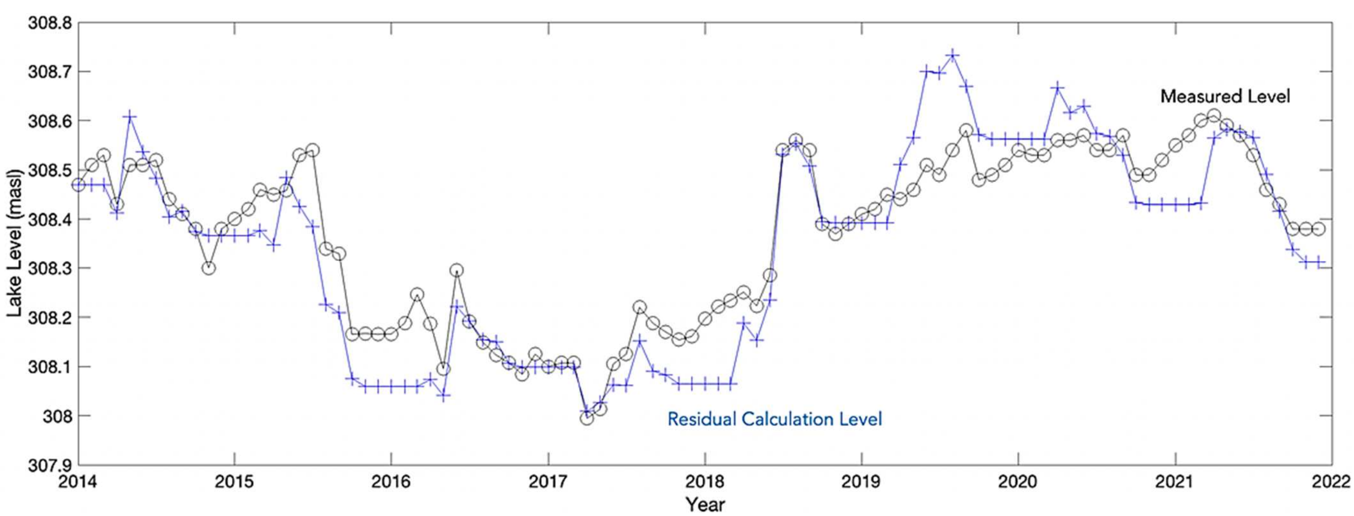


Figure 7-21: Long term measured change in storage (blue) versus measured water level of BML over 8 years.

7.2.1.10 Methane and Carbon Dioxide fluxes

CO_2 and CH_4 fluxes from BML continue to be measured. There has been considerable challenge in obtaining high quality CH_4 data for 2020 and 2021. In 2020, the COVID-19 pandemic limited access for data collection, and also in 2021 the platform became unmoored and the solar panels that power the CH_4 analyzer faced north. There was insufficient power to report comprehensive CH_4 for 2021 analysis is underway on the data for when the panels were oriented south. CO_2 and CH_4 figures with data to date are presented in Figures 7-22 and 7-23. The uptick in CH_4 in 2022 should be viewed with caution due to the limited data available.

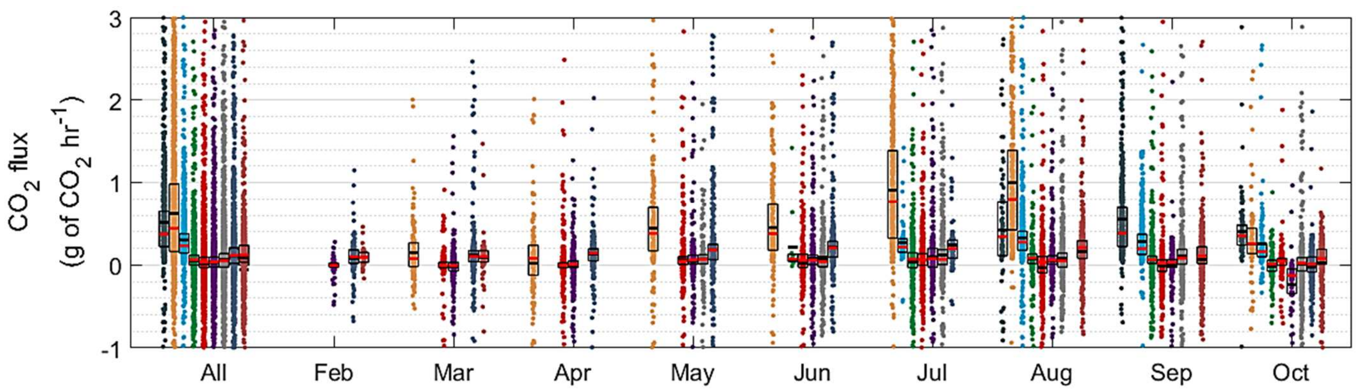


Figure 7-22: Annual and monthly binned CO_2 fluxes from BML.

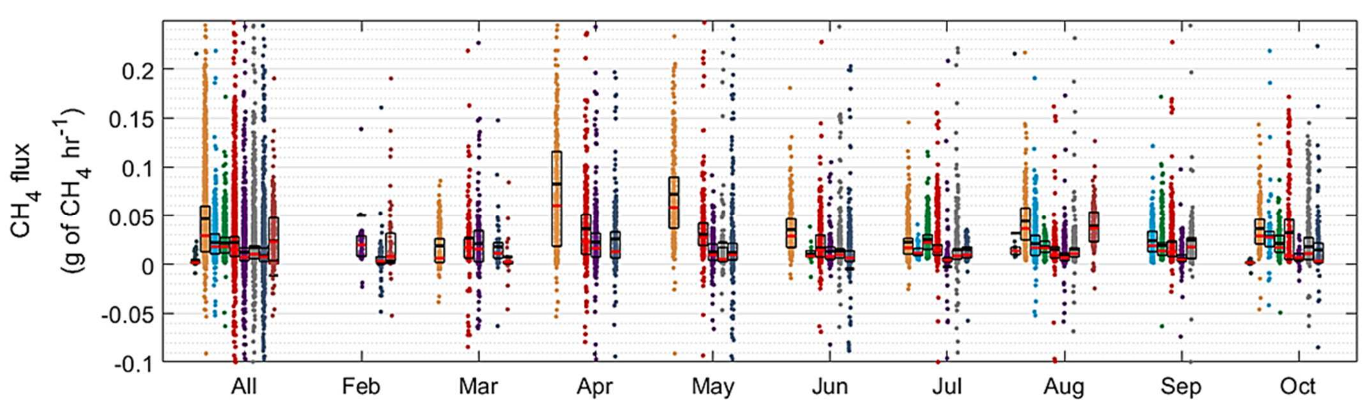


Figure 7-23: Annual and monthly binned CH_4 fluxes from BML.

7.2.2 Surface Water Quality Assessment

BML Surface Water Quality Assessment Key Findings	
In-situ and Conventional Physico-Chemical Variables	
Summary of 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 fresh water.* • *Slightly alkaline pH.*
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. Concentrations of TSS are also decreasing at bottom depths.*
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.*
Nutrients	
Summary of 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.*
Temporal Trends	• *Seasonal variations of ammonia, nitrate, and phosphorus observed.* • *Lower nutrient concentrations in 2021 relative to the previous monitoring years.*
Spatial Trends	• *Depth-related variation in nutrient concentrations:*

BML Surface Water Quality Assessment Key Findings	
	• *BML bottom layer potential source of ammonia.* • *Total phosphorus concentrations greater within the surface and bottom depth strata.*
Guideline Exceedances (long-term)	• *Ammonia and nitrite concentrations greater than guidelines, however, the frequency of exceedances has decreased since 2013.*
Metals	
Summary of Observations	• *Concentrations of total and dissolved bismuth, cadmium, silver, thallium, and tin, and dissolved beryllium, chromium, and titanium were often near or below analytical detection limits.* • *Seasonal variability present, with concentrations generally higher in winter.*
Temporal Trends	• *Concentrations of most metals have decreased in BML.* • *Metals that showed the steadiest declines are molybdenum, antimony, selenium, and sulphur.*
Spatial Trends	• *Metal concentrations were relatively homogenous through the water column, except for total chromium and manganese, which were greater in the bottom depth strata*.
Guideline Exceedances (long-term)	• *Boron concentrations consistently greater than long-term guidelines.* • *Sporadic observations of concentrations greater than long-term guidelines for several metals, including: dissolved aluminum, and iron, and total cobalt and zinc.* • *Many metals display decreasing trends, with concentrations moving towards guideline compliance or more frequently falling within guideline compliance compared to historical proportions of sample exceedances.*
Organics	
Summary of Observations	• *Some petroleum-associated compounds continued to be measurable in BML:* ○ *Naphthenic acids, alkylated and parent PAHs, and F2 and F3 hydrocarbons.* • *Most volatile organics (e.g., benzene, xylene, toluene) were near or below analytical detection limits.*
Temporal Trends	• *Highest concentrations of PAH were in summer, F2 and F3 hydrocarbons were in fall, and NA were in winter 2021.*

BML Surface Water Quality Assessment Key Findings	
	• *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.*

The surface water quality component of the 2021 program consisted of both winter and open-water sampling events (Tables 7-4 and 7-5). The open water program did not start until June 2021 (usual kick-off of sampling is May) due to COVID related site restrictions. In winter, because of safety concerns resulting from heavy snow load and freeboard issues, the sampling locations and frequencies were adjusted from plans. Because of this, the number of samples collected in 2021 were less than historical, pre-pandemic tallies (Table 7-6). In situ profile data were collected using a YSI multi-meter probe, water clarity was measured using a Secchi disk, and light penetration profiles were completed using a Li-Cor light sensor.

Some key results from the surface water quality are presented below.

Table 7-4: Locations, analyses, and frequency of snow, ice, and water quality sampling at Base Mine Lake, winter 2021

Media Sampled	Station ID	Sample Type and Frequency									
		In Situ Water Quality[1] and PAR[2]	Conventional Variables	Ions	Nutrients and Biological Indicators	General Organics	Total and Dissolved Metals	Total and Methylmercury	Hydrocarbons	PAHs	Dissolved Gasses
		Bi-Weekly Sampling[3,4]					Monthly Sampling[3,4]				
Water (💧)	BML12_PLATFORM 1_C	💧	💧❄◊	💧❄◊	💧❄◊	💧❄	💧❄◊	💧❄◊	💧❄	💧❄	💧
Ice (◊)	BML12_PLATFORM 2_NE	💧	💧❄◊	💧❄◊	💧❄◊	💧❄	💧❄◊	💧❄◊	💧❄	💧❄	💧
Snow (❄)	BML12_PLATFORM 3_SW	💧	💧❄◊	💧❄◊	💧❄◊	💧❄	💧❄◊	💧❄◊	💧❄	💧❄	💧
	BML13_D04[5]	💧	❄	❄	❄	❄	❄	❄	❄	❄	-
	BML15_D26[5]	💧	❄	❄	❄	❄	❄	❄	❄	❄	-

Note: Station coordinates are provided in Appendix A1

[1] Temperature, pH, specific conductivity, dissolved oxygen concentration and saturation, and turbidity depth profiles

[2] Photosynthetically active radiation depth profile using Li-Cor.

[3] Surface water quality sample collection frequency

[4] Ice samples collected during the weeks of February 17 and March 8. Snow samples collected the weeks of February 16, February 24, and March 9.

[5] D04 and D26 were not accessible until the week of February 24.

- = not sampled

Table 7-5: Locations, analyses, and frequency of surface water sampling at Base Mine Lake, open-water 2021

Station Type	Station ID	Sample Type and Frequency									
		In Situ Water Quality[1]	PAR[2]	Conventional Variables	Ions	Nutrients and Biological Indicators	Total and Dissolved Metals	General Organics	Hydrocarbons and PAHs	Oil and Grease	Total and Methylmercury
		Weekly		Bi-Weekly					Monthly		
Deep Stations	BML12_PLATFORM 1_C	♦	♦	♦	♦	♦	♦	♦	♦	-	♦
	BML12_PLATFORM 2_NE	♦	♦	♦	♦	♦	♦	♦	♦	-	♦
	BML12_PLATFORM 3_SW	♦	♦	♦	♦	♦	♦	♦	♦	-	♦
	BML13_D04	♦	♦	-	-	-	-	-	-	-	-
	BML15_D26	♦	♦	-	-	-	-	-	-	-	-
Littoral Stations	BML14_S06	♦	-	♦	♦	♦	♦	♦	♦	-	♦
	BML14_S07	♦	-	♦	♦	♦	♦	♦	♦	-	♦
	BML14_S08	♦	-	♦	♦	♦	♦	♦	♦	-	♦
	BML14_S09	♦	-	♦	♦	♦	♦	♦	♦	-	♦
	BML14_S10	♦	-	♦	♦	♦	♦	♦	♦	-	♦
Lake Pump-out[3]	BML_PUMP_OUT	♦	♦	♦	♦	♦	♦	♦	-	♦	-
Reservoir Pump-in[3]	BCR_PUMP_IN	♦	-	♦	♦	♦	♦	♦	-	-	-

Note: Station coordinates are provided in Appendix A1

[1] Temperature, pH, specific conductivity, dissolved oxygen concentration and saturation, turbidity, and light penetration depth.

[2] Photosynthetically active radiation depth profile was measured using a Li-Cor unit during the open-water season.

[3] Sample collection occurred July – October 2021.

♦ = water sample collection

- = not sampled

Table 7-6: Total number of analytical water quality samples collected from Base Mine Lake and Beaver Creek Reservoir, 2013 to 2021

Sample location and season	Number of samples collected per year								
	2013	2014	2015	2016	2017	2018	2019	2020	2021
Winter sampling									
Base Mine Lake	0	26	30	3	63	79	21	72	48
Open-water sampling									
Base Mine Lake	74	356	358	223	349	335	339	56	272
Beaver Creek Reservoir	19	26	22	29	37	25	23	2	8

7.2.2.1 Trends in conductivity profiles through time

Lake-wide specific conductivity has decreased progressively in BML (Figure 7-24); median specific conductivity at the BML platform and deep stations in 2013 was approximately 3,600 µS/cm, which has decreased to a median value of approximately 2,494 µS/cm in 2021.

7.2.2.2 Sodium

Sodium has remained the dominant cation in BML since monitoring began in 2013, although concentrations have declined slightly in recent years (Figure 7-25). The seasonal median concentrations of sodium in 2021 ranged from 520 mg/L in winter to 540 mg/L in summer, which were slightly lower than the historical seasonal medians (540 to 610 mg/L). Sodium has remained evenly distributed throughout the water column since 2014.

7.2.2.3 Chloride

Chloride has remained the dominant anion in BML since monitoring was initiated in 2013, with absolute concentrations showing a decreasing trend over time. Median chloride concentrations in 2021 were slightly higher in winter (425 mg/L) than the open-water seasons (spring to fall; 370 mg/L), while falling below the historical seasonal median range of 390 mg/L in fall to 430 mg/L in winter (Figure 7-26). Chloride concentrations have exceeded the GoA (2018) long-term surface water quality guideline for the protection of aquatic life since 2013. Consistent with previous years, there were no vertical concentration gradients of chloride in BML in 2021 (Figure 7-26).

7.2.2.4 Sulphate

Sulphate continued to be the second-most abundant anion in BML in 2021, exhibiting only minor variation among seasons and across depth strata (Figure 7-27). Seasonal median sulphate concentrations in 2021 ranged from 160 to 180 mg/L, which were slightly lower than the season medians from previous years (median of 190 mg/L for each season). Sulphate concentrations were below the surface water quality guideline for the protection of aquatic life in 2021 (Figure 7-27).

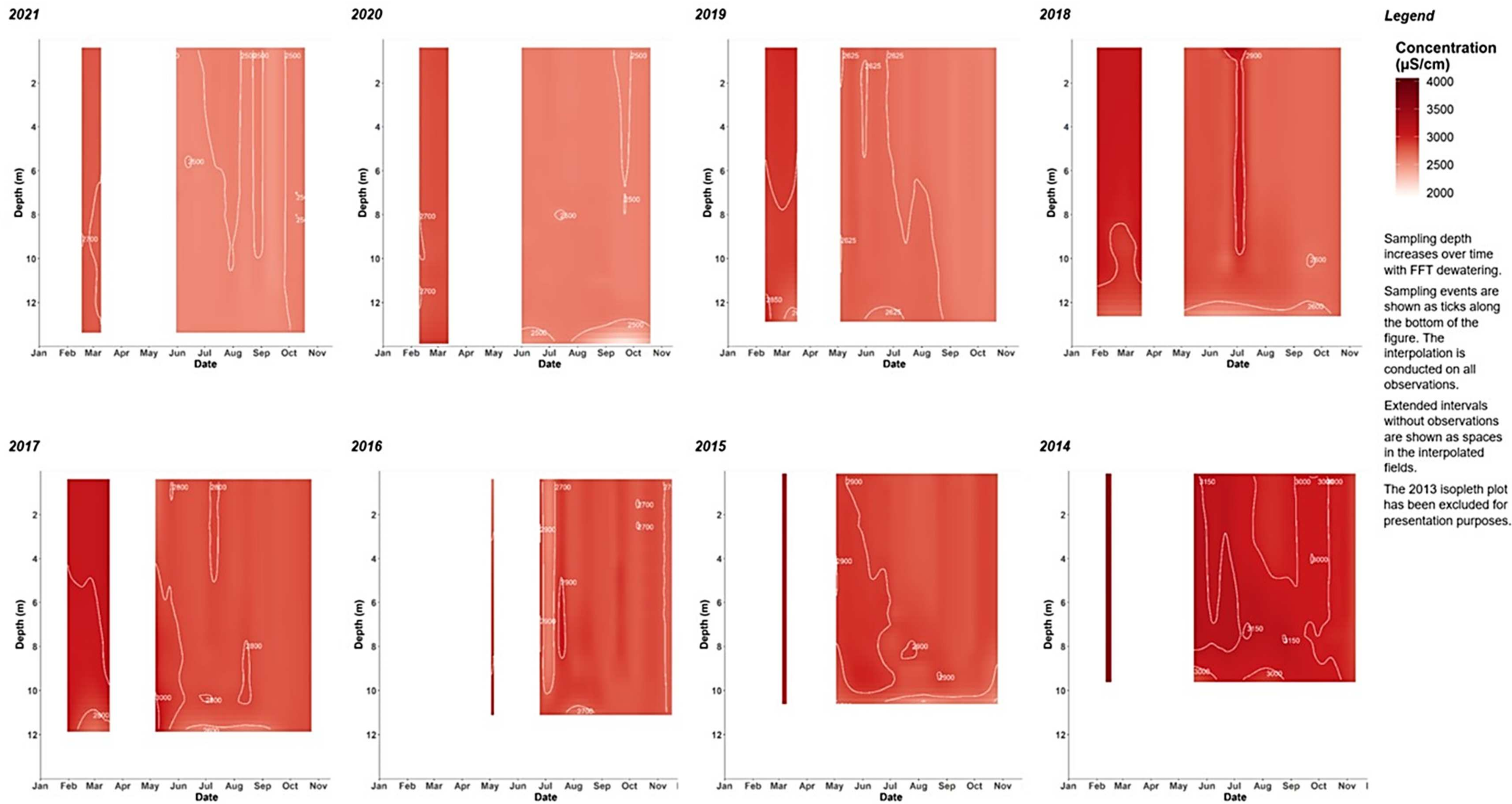
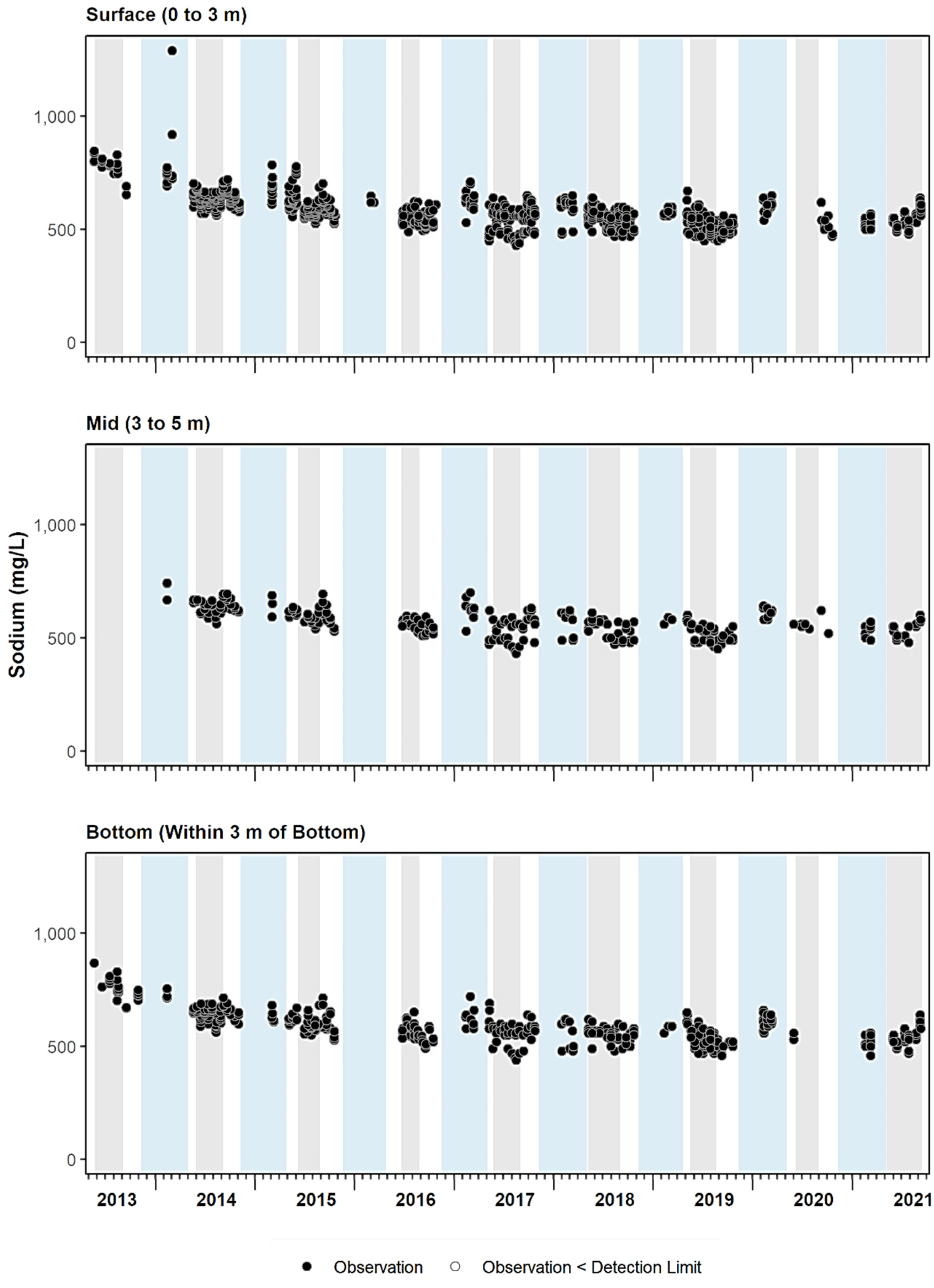
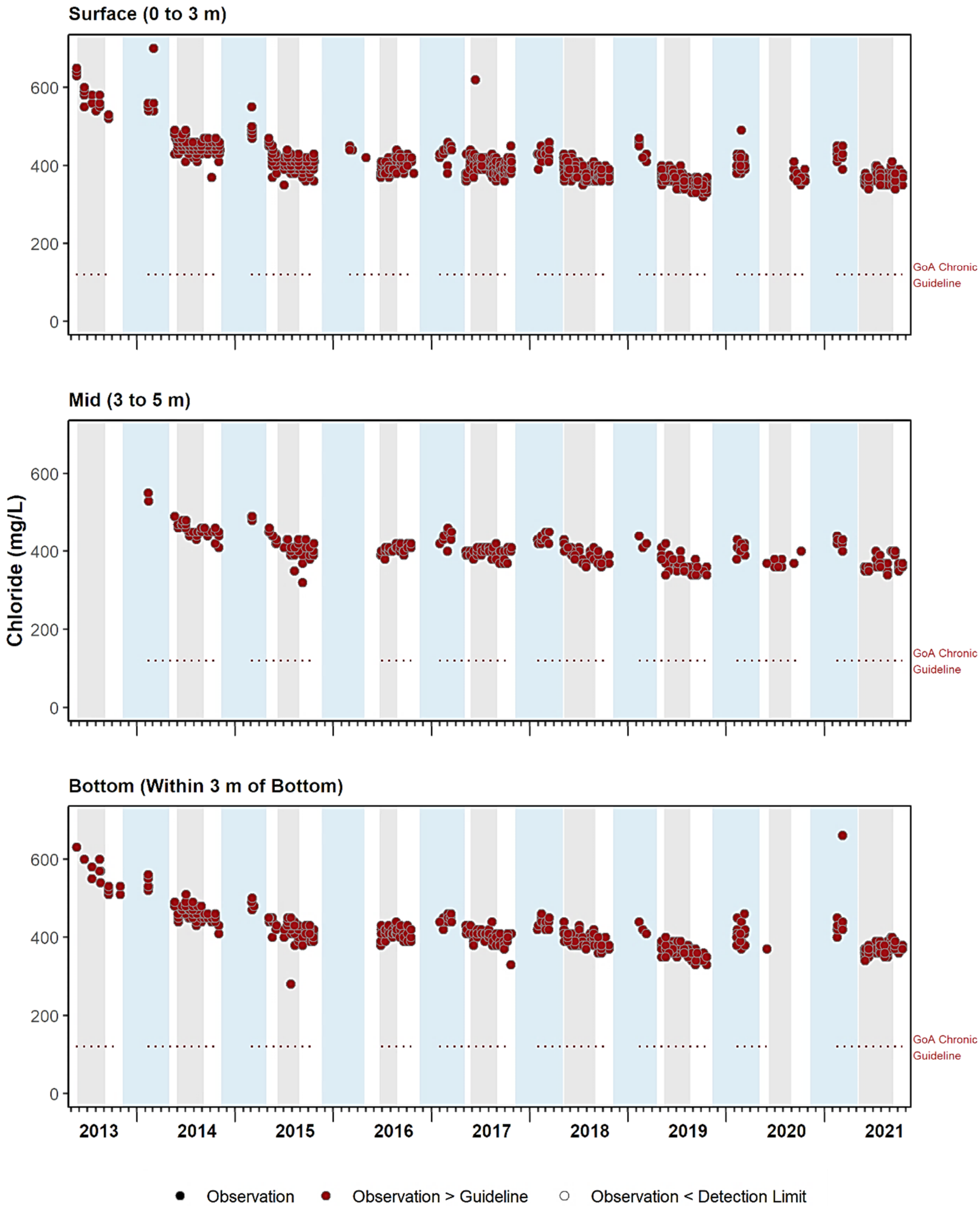


Figure 7-24: In situ specific conductivity (μS/cm) profiles measured at Base Mine Lake platform and deep stations, 2014 to 2021.



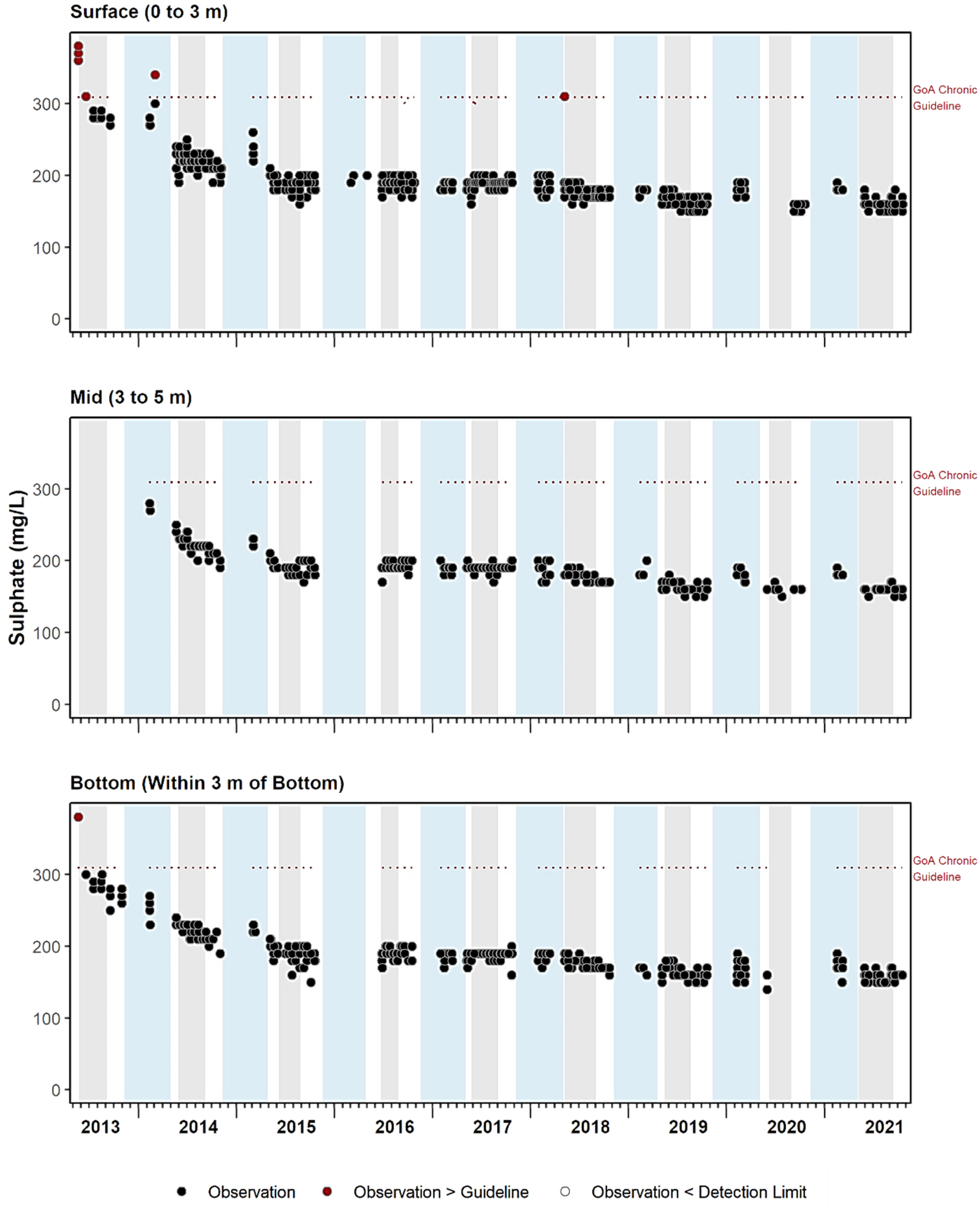
Ice-covered (blue) and stratified (grey) periods shown as filled areas on each panel.

Figure 7-25: Sodium in Base Mine Lake, 2013 to 2021.



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 7-26: Chloride in Base Mine Lake, 2013 to 2021.



Ice-covered (blue) and stratified (grey) periods shown as filled areas on each panel.
Mean weekly sulphate guideline values shown as dotted red line and are hardness dependent.
Scale adjusted to focus on overall trends; full-scale plot presented in Appendix A5.9.

Figure 7-27: Sulphate in Base Mine Lake, 2013 to 2021.

7.2.2.5 BML Ionic Composition

The ionic composition of BML has been relatively stable since 2013 (Figure 7-28) and continues to be dominated overwhelmingly by monovalent cations, with sodium contributing approximately 92% of the cation composition. In contrast, anion ratios of chloride, sulphate, and bicarbonate indicate no dominant water type given their percent compositions of 43:13:44, respectively. Cation and anion ratios in BML have shifted gradually over the years, while remaining comparable to oil sands process-affected water (OSPW) originating from the WIP; the ionic signatures of OSPW and BML have been, and continue to be, substantially different than BCR (Figure 7-28).

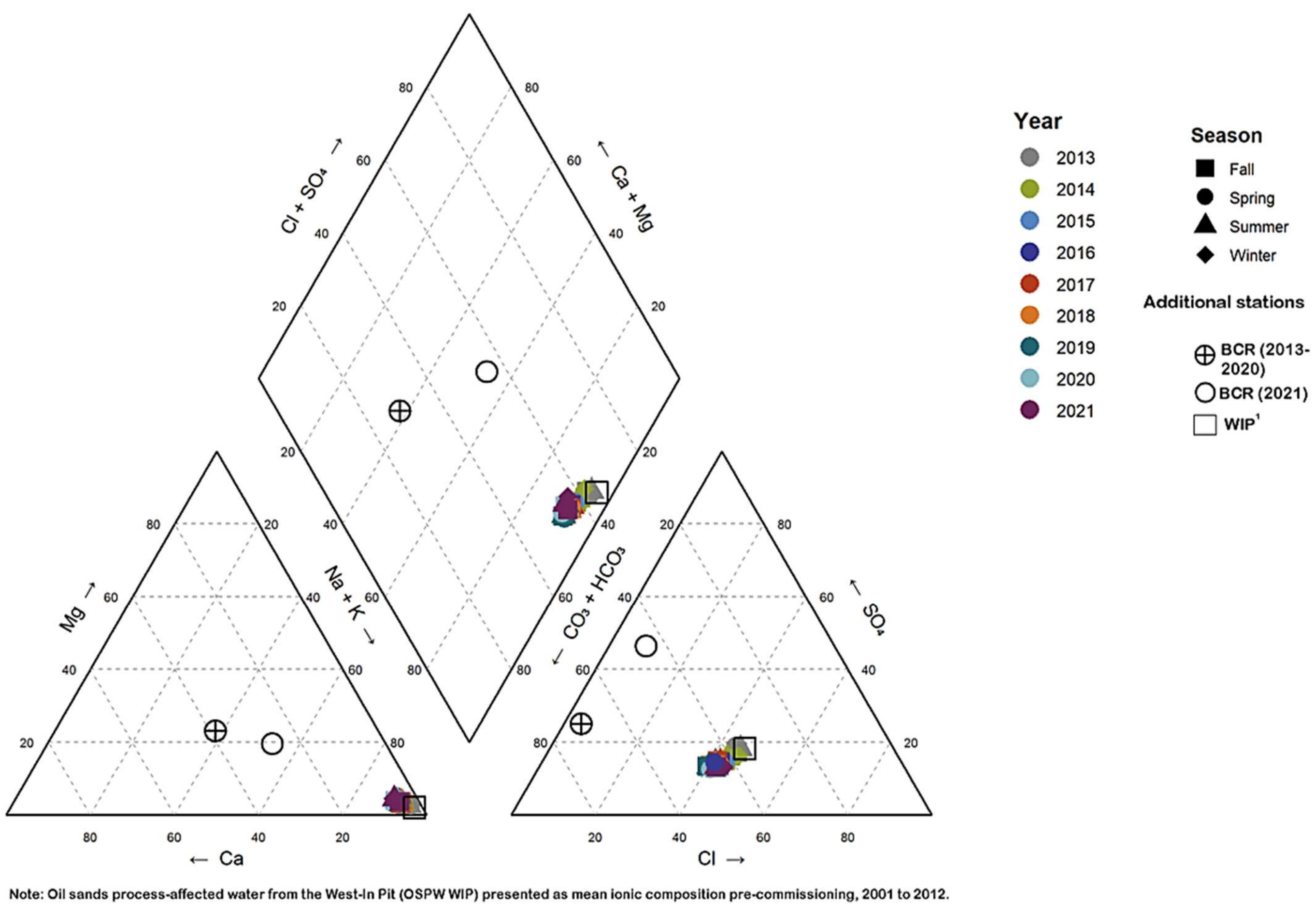


Figure 7-28: Piper plots of major ion composition in Base Mine Lake, 2013 to 2021.

7.2.2.6 Metals

Total and dissolved forms of 29 metals, total ultra-low-level mercury, and methylmercury were analyzed in support of the 2021 program. Temporal trends among individual metals vary, but focusing on those with detectable concentrations in >50% of the collected samples, the following dominant temporal patterns have been observed in BML over the past nine years:

- Concentrations of most metals have declined at varying rates since lake monitoring began in 2013, except for the following analytes: dissolved species of aluminum, iron, lead, zinc, zirconium, and total species of methyl mercury and copper. Total nickel and dissolved chromium have remained relatively stable from year-to-year.
- Metals that showed the steadiest declines are molybdenum, antimony, selenium, and sulphur.
- Dissolved aluminum increased in response to the September 2016 alum treatment but returned to pre-treatment levels the following year and remained stable through 2021.

Metal concentrations were relatively homogenous through the water column in 2021, except for total chromium and total manganese, which were present in higher concentrations in the bottom 3 m of the lake. Most metals also exhibited some seasonal variability, with median concentration generally highest during winter in 2021; this result was consistent with the historically higher medians observed during winter and spring. Some representative metal data is shown in the following graphs.

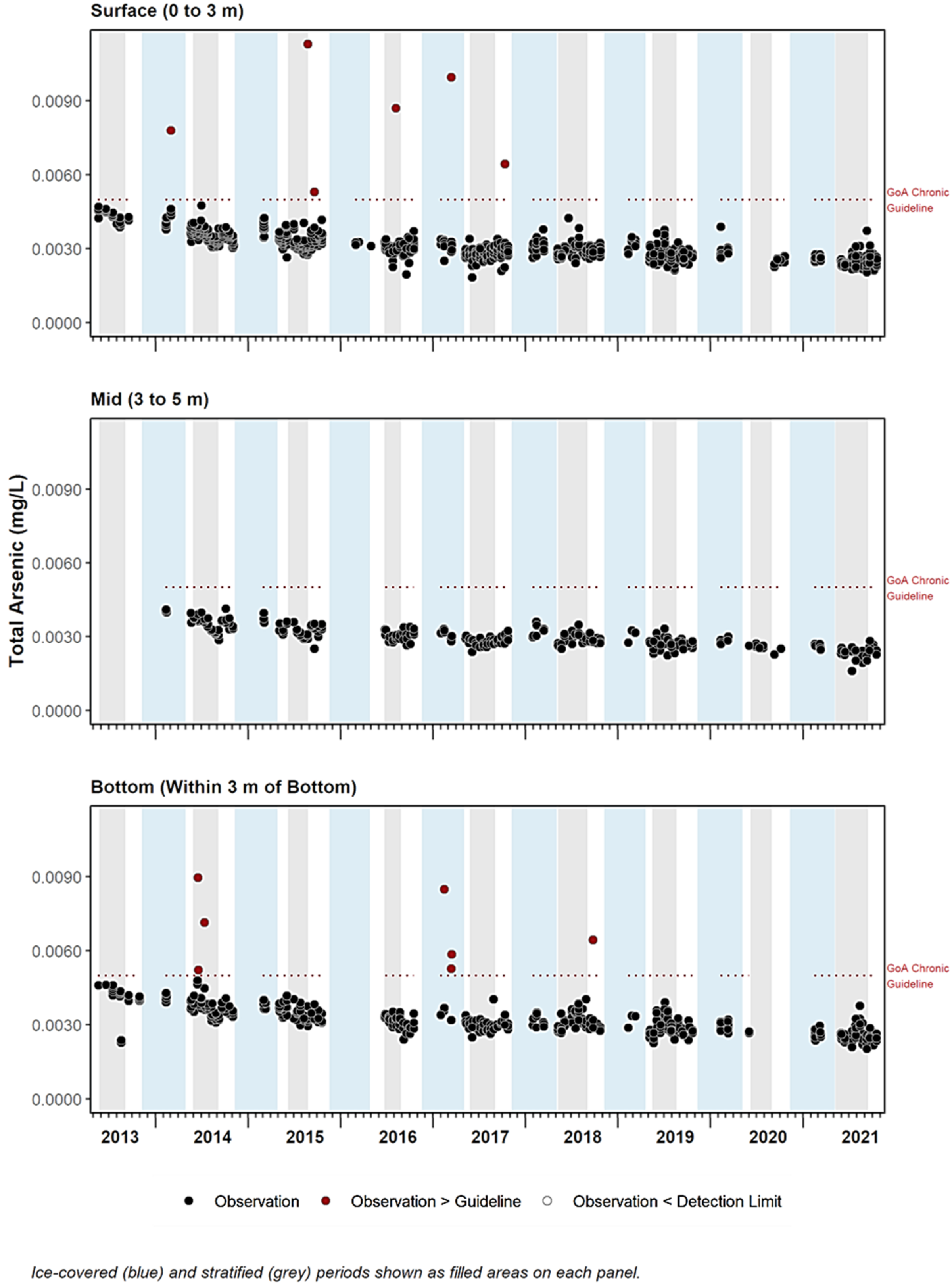
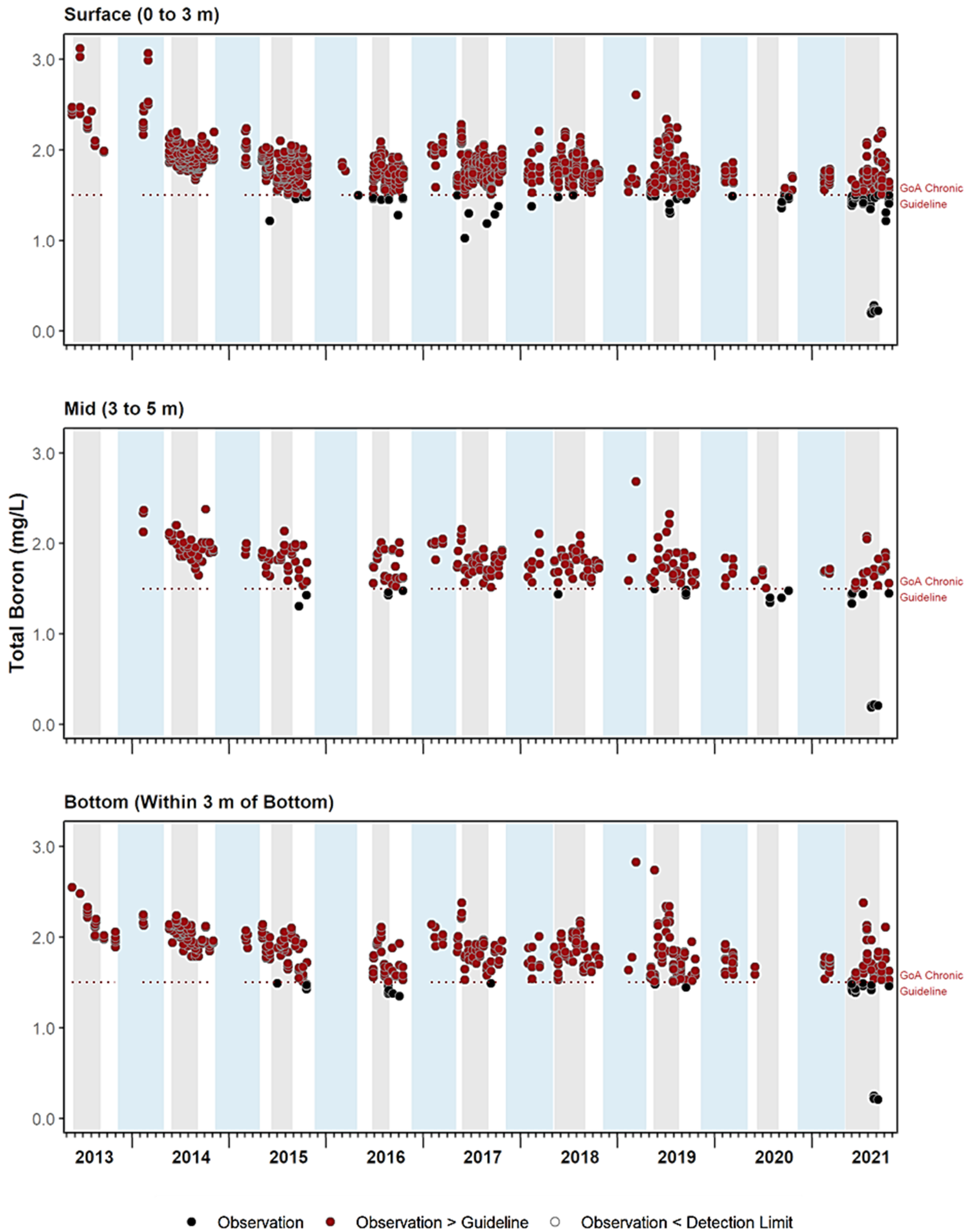
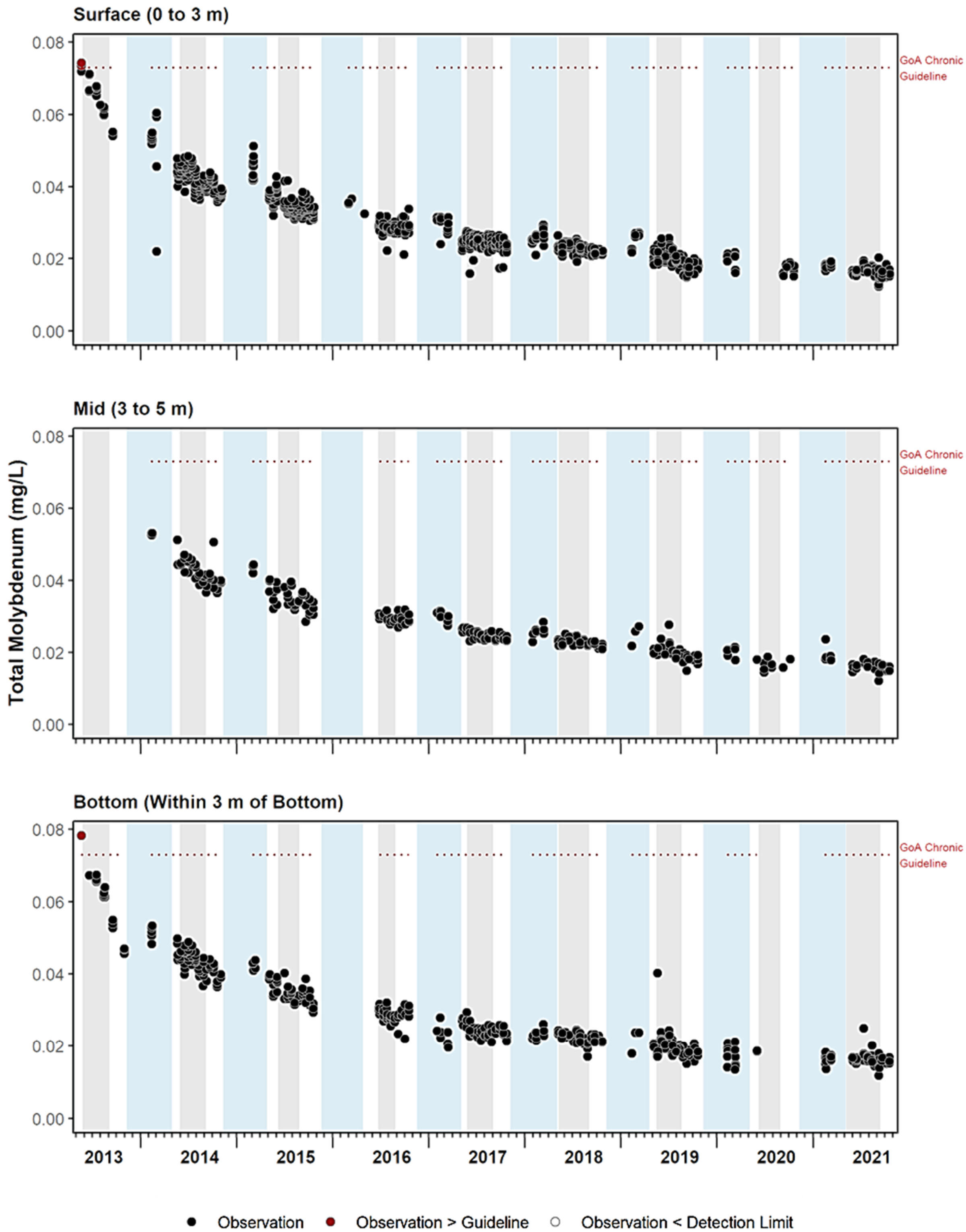


Figure 7-29: Total arsenic in Base Mine Lake, 2013 to 2021.



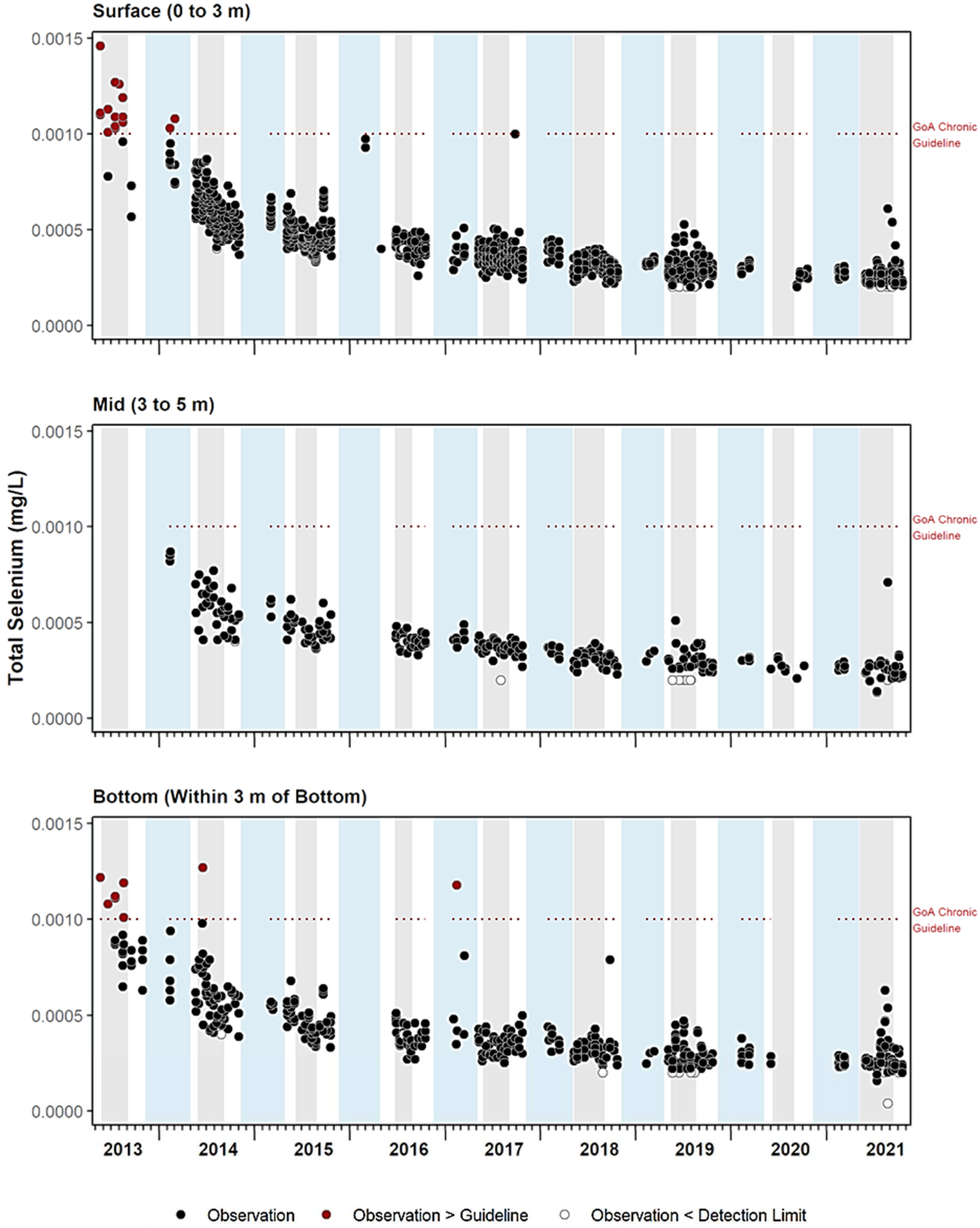
Ice-covered (blue) and stratified (grey) periods shown as filled areas on each panel.

Figure 7-30: Total boron in Base Mine Lake, 2013 to 2021.



Ice-covered (blue) and stratified (grey) periods shown as filled areas on each panel.

Figure 7-31: Total molybdenum in Base Mine Lake, 2013 to 2021.



Ice-covered (blue) and stratified (grey) periods shown as filled areas on each panel.
Scale adjusted to focus on overall trends; full-scale plot presented in Appendix A5.49.

Figure 7-32: Total selenium in Base Mine Lake, 2013 to 2021.

7.2.2.7 Organics

Oil sands extractable acids, more commonly known as naphthenic acids (NA), are one of the principal components of OSPW and are associated with OSPW toxicity (Allen 2008). Classic naphthenic acids are limited to those compounds with the formula $C_nH_{2n+z}O_2$, but OSPW also consists of related compounds containing sulphur and nitrogen. Given the high diversity of acid extractable organic acids, quantification is challenging and method dependent. Analysis and reporting of NA results were adjusted in 2016, which should be considered when comparing observations from 2016 onwards with previous years. Specifically, discrepancies between NA concentrations analyzed by the Syncrude R&D Analytical Services laboratory and those reported by the contracted commercial laboratory (BV Labs) during a 2016 review of concurrently analyzed NA samples (Ripmeester and Duford 2019). This review determined that all BV Labs analyses conducted prior to 2016 had used a method that deviated from the requested Syncrude 1995 method[8]. The change in NA concentrations that are apparent between the pre-2016 and 2016-to-present results (Figure 7-33) are an artifact of the laboratory adjustment to the correct Syncrude 1995 method.

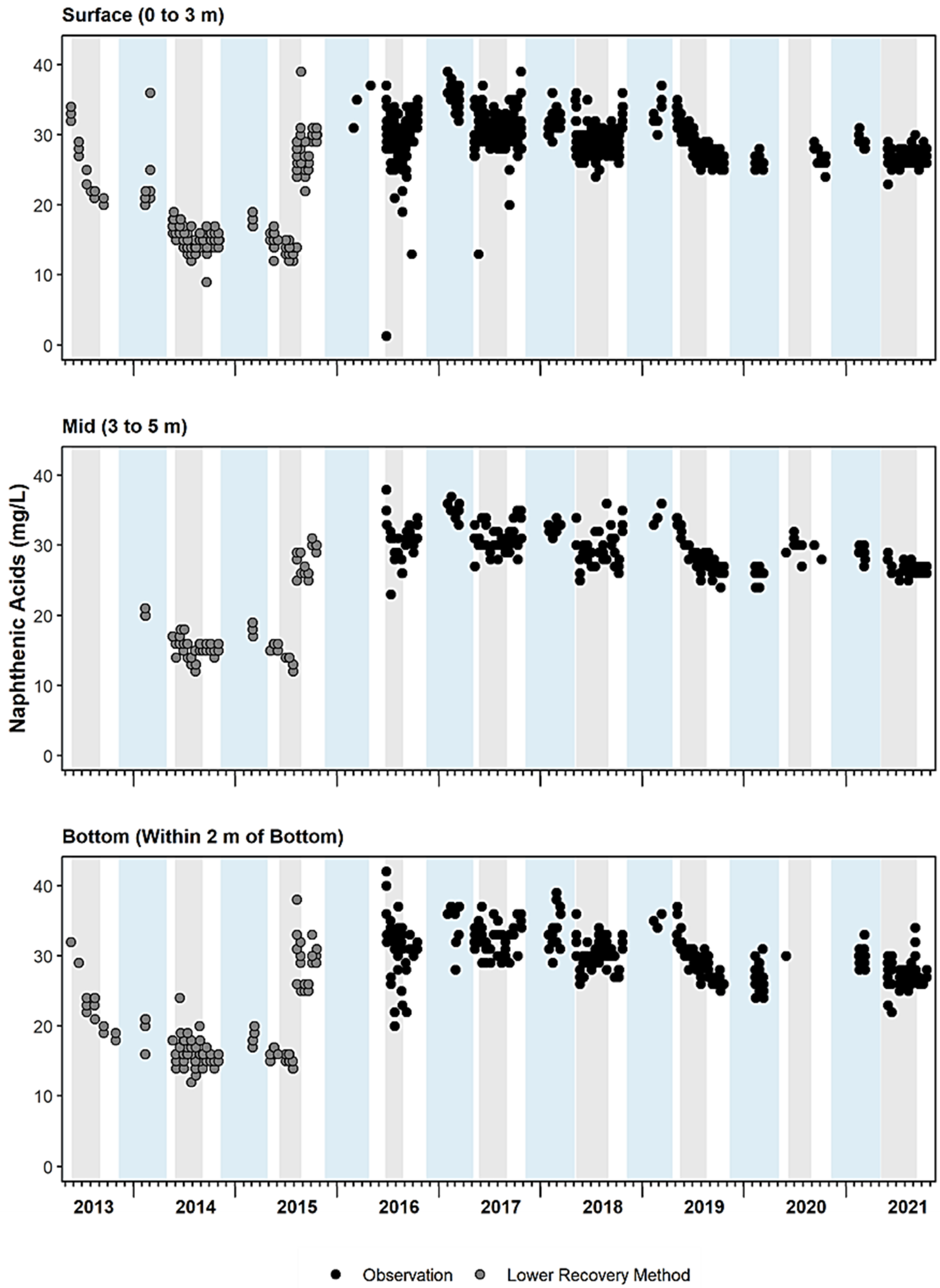
The NA median concentrations in 2021 have remained relatively stable since 2013 (Figure 7-33). The greatest seasonal median concentration in 2021 was recorded in winter (29 mg/L) while the lowest seasonal medians were observed in summer and fall (27 mg/L). This seasonal trend of marginally higher winter medians was consistent with the historical dataset. No discernible vertical variations in NA concentrations have been observed in BML to date.

Total polycyclic aromatic hydrocarbons (PAH) concentration is calculated by summing concentrations of 27 parent and 28 alkylated PAH species. Approximately 89% of the total PAH in BML consisted of alkylated species in 2021, whereas most of the parent PAH species were below detection limits (<0.005 µg/L) in over 50% of all samples; exceptions include pyrene and quinoline, which were present in measurable quantities. Total PAH concentrations in BML have shown a relatively high degree of the annual, seasonal, and vertical variation (Figure 7-34). Historically, seasonal median concentrations of total PAH were highest in spring (median concentration 3.7 µg/L); however, no PAH sampling was undertaken in the spring of 2021. From the available 2021 data, median concentrations of total PAH were highest in summer (0.98 µg/L) and lowest in winter (0.66 µg/L). Median PAH concentrations in all three seasons were lower than the corresponding historical medians, but within the range of historically observed concentrations.

Of the 10 parent PAH species with guidelines, only pyrene and anthracene exceeded the GoA (2018) surface water quality guidelines for the protection of aquatic life in 2021. Pyrene was one of the most frequently detected parent PAH species in 2021 (only 32% of samples below RDL), while anthracene was detectable in only 2% of samples. Exceedance frequencies of pyrene and anthracene were 3.6% and 0.6%, respectively, which are both less than the historical frequency of exceedances (Table 6-1).

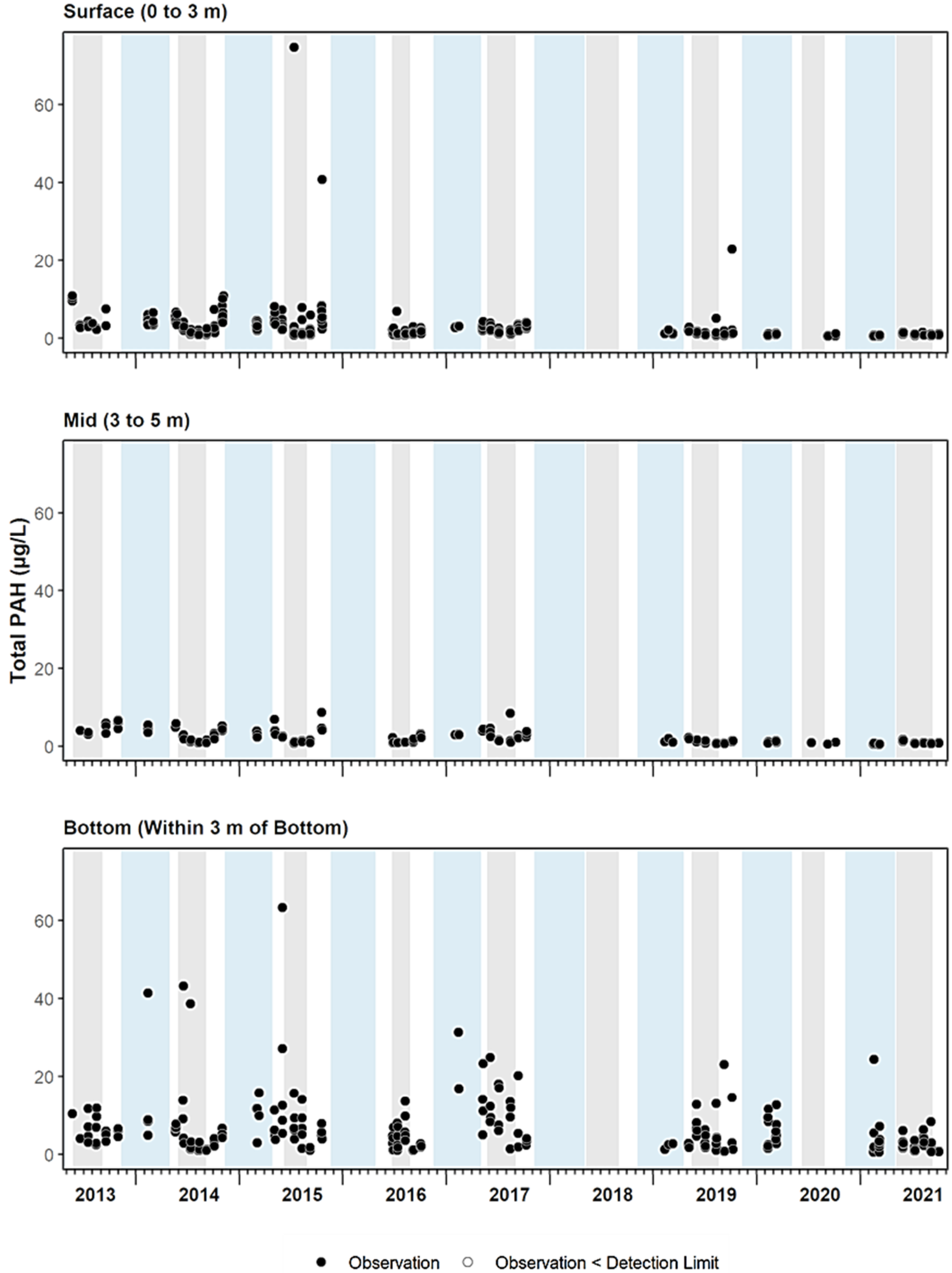
---

8 Syncrude 1995 method (Jivraj et al. 1995) requires acidification of the water sample followed by extraction in dichloromethane (DCM), while commercial laboratory methods use hexane for extraction; the use of hexane results in a less efficient extraction process that does not recover all acid extractable organics from the water sample.



Ice-covered (blue) and stratified (grey) periods shown as filled areas on each panel.

Figure 7-33: Naphthenic acids in Base Mine Lake, 2013 to 2021.



Ice-covered (blue) and stratified (grey) periods shown as filled areas on each panel.
Scale adjusted to focus on overall trends; full-scale plot presented in Appendix A5.161.

Figure 7-34: Total polycyclic aromatic hydrocarbons in Base Mine Lake, 2013 to 2021.

7.2.3 Groundwater Quality Assessment

BML Groundwater Assessment Key Findings
• *Overall, groundwater level and quality results for 2021 appear to be following consistent trends with, or fall within previously measured ranges of the historical data collected between 2013 and 2020.*
• *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.*
• *Comparison with site-wide data suggest that the BML lake level of about 308.5 masl and currently recorded BML area groundwater levels, which are in the 280 to 325 masl range, are overall relatively low compared to immediate surrounding areas (i.e., the BML area acts as a zone of groundwater convergence) which likely reflects residual effects from historical mine operations (i.e., groundwater level recovery).*
• *Once groundwater levels have fully equilibrated, it may be expected that groundwater inflows to BML will occur from the south and west and that groundwater losses from BML may occur towards the northeast. In the shallow zone, the rate of these groundwater exchanges with the fresh water cap may be controlled by the hydraulic conductivity of overburden deposits and/or shallow bedrock while in the intermediate and deep zones these groundwater exchanges are likely limited by the low hydraulic conductivity of the FFT (i.e., are likely small).*
• *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 ionic composition (piper diagrams) and isotopic plots indicate distinct groundwater geochemical differences between the shallow, intermediate, and deep sediments around BML. There were no notable changes in the ionic composition of the groundwater from prior years.*
o *Among the monitoring wells, there were 54 statistically significant trends detected among 20 water quality variables (particularly for major ions).* o *Major ions (bicarbonate, calcium, chloride, magnesium, sodium, and sulphate) comprise 36 of the 54 identified trends.*
• *The monitoring program results suggest that the infilling of the lake has altered subsurface pressures and groundwater flows, and that there is ongoing evolution in groundwater geochemistry. The evolution in chemistry is likely related to chemical evolution processes (e.g., ion exchange) which may be associated with groundwater movement.*
• *Groundwater levels appear to be stabilizing over time (i.e., rates of change are diminishing in recent monitoring) and significant geochemical change may be occurring in only about 13% of instances (i.e., the significant trends) while 87% of the 410 trend analyses conducted suggest relatively stable groundwater quality.*

From 2013 to 2020, groundwater monitoring has been conducted at 27 wells in 11 well nests on the north, east, and west sides of BML. In October 2021, 14 groundwater wells in 4 existing Syncrude well nests on the southern edge of BML (South Bison Hills) were inspected and 8 were added to the Groundwater program to provide a more complete picture of groundwater levels and quality around BML. There are now 41 monitoring wells in the BML network which are classified as shallow, intermediate, or deep (Figure 7-35). The monitoring well location information, formations, and well status in 2021 are indicated in Table 7-7. Fourteen of the 41 wells cannot be sampled due to gas concerns, obstructions, bitumen presence, damage or insufficient water. Groundwater wells are classified as active if sufficient water is available to fill sampling bottles to the minimum volume required for laboratory testing. Continuous groundwater elevations are being recorded at seven deep well locations with dataloggers. For 2021, the groundwater component of the BML program included semi-annual monitoring and sampling activities in July and November.

The summer (July 2021) groundwater monitoring event consisted of verifying the status of the 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 in active wells. There were 19 wells classified as active and sampled during this event (i.e., 8 are classified as inactive).

In the fall (October 2021), the 14 groundwater wells in 4 nests south of BML were assessed for their suitability for the groundwater program. Out of those, 6 were discarded due to bitumen presence (1 well) or insufficient water column for sampling (5 wells), leaving 8 active monitoring wells. The 8 active wells were added to the November monitoring and sampling activities.

The fall (November 2021) event consisted of conducting groundwater level measurements and collecting groundwater samples in the active wells historically sampled and new active wells in South Bison Hills. There were 25 wells sampled during this event (19 historically sampled BML wells and 7 new South Bison Hills wells). One of the new South Bison Hills wells, SP990127, was frozen; however, attempts will be made to sample this well in the future.

Monitoring and sampling activities at the active wells included:

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

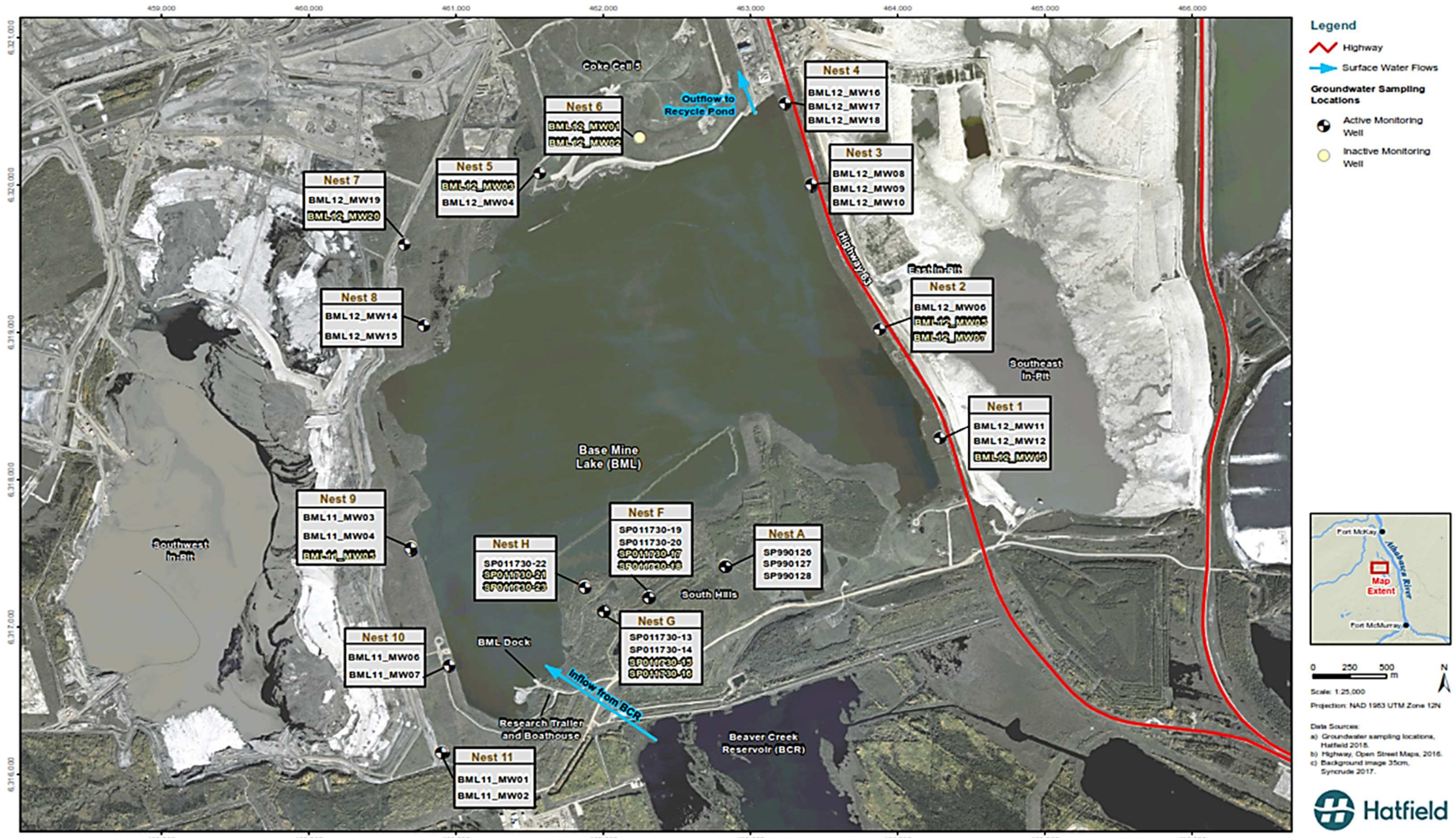


Figure 7-35: Groundwater sampling locations for the 2021 Base Mine Lake Monitoring Program.

Table 7-7: Groundwater sampling locations for the 2021 Base Mine Lake Monitoring Program

Nest	Location	Monitoring Well ID	Well Grouping	Screened Unit	Ground Elevation (masl)	Screen Elevation (masl)		Location (UTM NAD 83 12V)		Well Status and Water Level Logger Installation
						Top	Bottom	Easting	Northing	
1	Hwy 63 Berm	BML12_MW13	Shallow	Dam Core	311.6	293.2	290.1	464285	6318277	Inactive[1]
		BML12_MW12	Intermediate	Dam Core	311.7	272.1	269.0	464286	6318282	Active
		BML12_MW11	Deep	Basal Water Sands	311.6	251.0	247.9	464286	6318284	Active & Logger Installed
2	Hwy 63 Berm	BML12_MW06	Shallow	Dam Shell	311.5	296.6	293.6	463878	6319022	Active
		BML12_MW07	Intermediate	Dam Core	311.3	272.8	269.7	463880	6319013	Inactive[2]
		BML12_MW05	Deep	Basal Water Sands	311.5	245.7	242.6	463879	6319017	Inactive[2]
3	Hwy 63 Berm	BML12_MW10	Shallow	Dam Shell	311.0	295.1	292.1	463415	6320002	Active
		BML12_MW08	Intermediate	Dam Core	311.0	274.4	271.4	463413	6319991	Active
		BML12_MW09	Deep	Basal Water Sands	311.1	245.6	242.5	463414	6319997	Active & Logger Installed
4	Hwy 63 Berm	BML12_MW18	Shallow	Dump	310.7	287.9	284.8	463234	6320561	Active
		BML12_MW17	Intermediate	Dump	310.9	267.8	264.8	463236	6320557	Active
		BML12_MW16	Deep	Km Pond Mud	310.8	241.7	238.6	463237	6320553	Active & Logger Installed
5	Coke Cell 5	BML12_MW04	Shallow	Dragline Rejects	319.3	284.4	281.3	461567	6320080	Active
		BML12_MW03	Deep	Dragline Rejects	319.3	265.9	262.9	461571	6320082	Inactive[2]
6	Coke Cell 5	BML12_MW02	Shallow	Dragline Rejects	331.5	305.9	302.8	462247	6320317	Inactive[3]
		BML12_MW01	Deep	Dragline Rejects	331.5	267.5	264.4	462242	6320320	Inactive[3]
7	Southwest Dam	BML12_MW20	Shallow	Dump	326.4	300.6	297.5	460654	6319600	Inactive[4]
		BML12_MW19	Deep	Devonian Limestone	326.6	256.6	253.6	460648	6319603	Active & Logger Installed
8	Southwest Dam	BML12_MW15	Shallow	Kc Fill	313.7	303.6	300.6	460782	6319045	Active
		BML12_MW14	Deep	Devonian Limestone	313.7	246.8	243.8	460782	6319048	Active & Logger Installed
9	Southwest Dam	BML11_MW05	Shallow	Dam Shell	309.5	290.6	287.6	460697	6317546	Inactive[5]
		BML11_MW04	Intermediate	Dam Shell	309.7	281.4	278.3	460693	6317537	Active
		BML11_MW03	Deep	Dragline Rejects	309.8	265.5	262.4	460696	6317526	Active
10	Southwest Dam	BML11_MW07	Shallow	Dam Shell	308.9	295.8	292.7	460955	6316740	Active
		BML11_MW06	Intermediate	Dam Core	309.0	275.3	272.3	460952	6316732	Active & Logger Installed

Table 7-7 (continued)

Nest	Location	Monitoring Well ID	Well Grouping	Screened Unit	Ground Elevation (masl)	Screen Elevation (masl)		Location (UTM NAD 83 12V)		Well Status and Water Level Logger Installation
						Top	Bottom	Easting	Northing	
11	In-situ south of Southwest Dam	BML11_MW02	Shallow	In-situ Kc	333.7	316.3	313.3	460901	6316150	Active
		BML11_MW01	Intermediate	In-situ Kcw	333.7	305.8	302.8	460917	6316153	Active & Logger Installed[6]
A	South Bison Hills Shore	SP990126	Shallow	Kc Fill	325.8	313.0	311.5	462832	6317411	Active
		SP990127	Shallow	Kc Fill	324.9	321.9	320.4	462830	6317416	Active
		SP990128	Shallow	Kc Fill	325.4	317.8	316.3	462832	6317413	Active
F	South Bison Hills Mid-East	SP11730_17	Shallow	Kc Fill	328.9	325.5	324.0	462307	6317208	Inactive[5]
		SP11730_18	Shallow	Kc Fill	328.9	320.7	319.1	462308	6137206	Inactive[5]
		SP11730_19	Intermediate	Kc Fill	328.8	315.1	313.1	462310	6317204	Active
		SP11730_20	Deep	Kc Fill	328.8	260.2	258.7	462315	6317199	Active
G	South Bison Hills Mid-West	SP11730_13	Shallow	Kc Fill	319.5	316.4	314.9	462003	6317106	Active
		SP11730_14	Shallow	Kc Fill	319.5	311.3	309.7	462005	6317106	Active
		SP11730_15	Intermediate	Kc Fill	319.5	305.8	304.3	462008	6317105	Inactive[5]
		SP11730_16	Deep	Kc Fill	319.5	260.0	258.5	462012	6317104	Inactive[3]
H	South Bison Hills East	SP11730_21	Shallow	Kc Fill	316.6	312.0	310.5	461874	6317269	Inactive[5]
		SP11730_22	Shallow	Kc Fill	316.6	308.4	306.8	461875	6317471	Active
		SP11730_23	Intermediate	Kc Fill	316.5	302.8	301.3	461877	6317273	Inactive[5]

[1] Gas concerns
[2] Obstruction in well
[3] Heavy bitumen presence in well
[4] Damaged well
[5] Insufficient water for sample collection
[6] Water level and barometric pressure loggers installed
Ground and screen elevations are in metres above sea level (masl)

Piper diagrams were prepared for the July and November monitoring events and are presented as Figure 7-36 and Figure 7-37, respectively. From the piper diagrams, groundwater from wells in the shallow and intermediate zones would generally be characterized as a sodium and sulphate or bicarbonate type water and the deep wells groundwater (e.g., from the Basal Water Sands and Devonian Limestone) as sodium chloride type water. The ionic characterization did not materially change between summer and fall. These results are consistent with prior years and suggest that shallow and deep groundwater comprise distinct flow paths. There is some variation in the characterization with shallow wells BML11_MW02 (Nest 11), BML12_MW06 (Nest 2), and BML12_MW18 (Nest 4), and intermediate well BML11_MW01 (Nest 11) exhibiting a water chemistry closer to that of the deeper wells; possibly indicating groundwater discharge conditions and vertical connectivity between the different depth intervals. Shallow zone monitoring well SP11730_13 (Nest G) and intermediate well BML12_MW17 (Nest 4) also appear to be characterized by a major ion chemistry that is distinct from that of other shallow and intermediate wells.

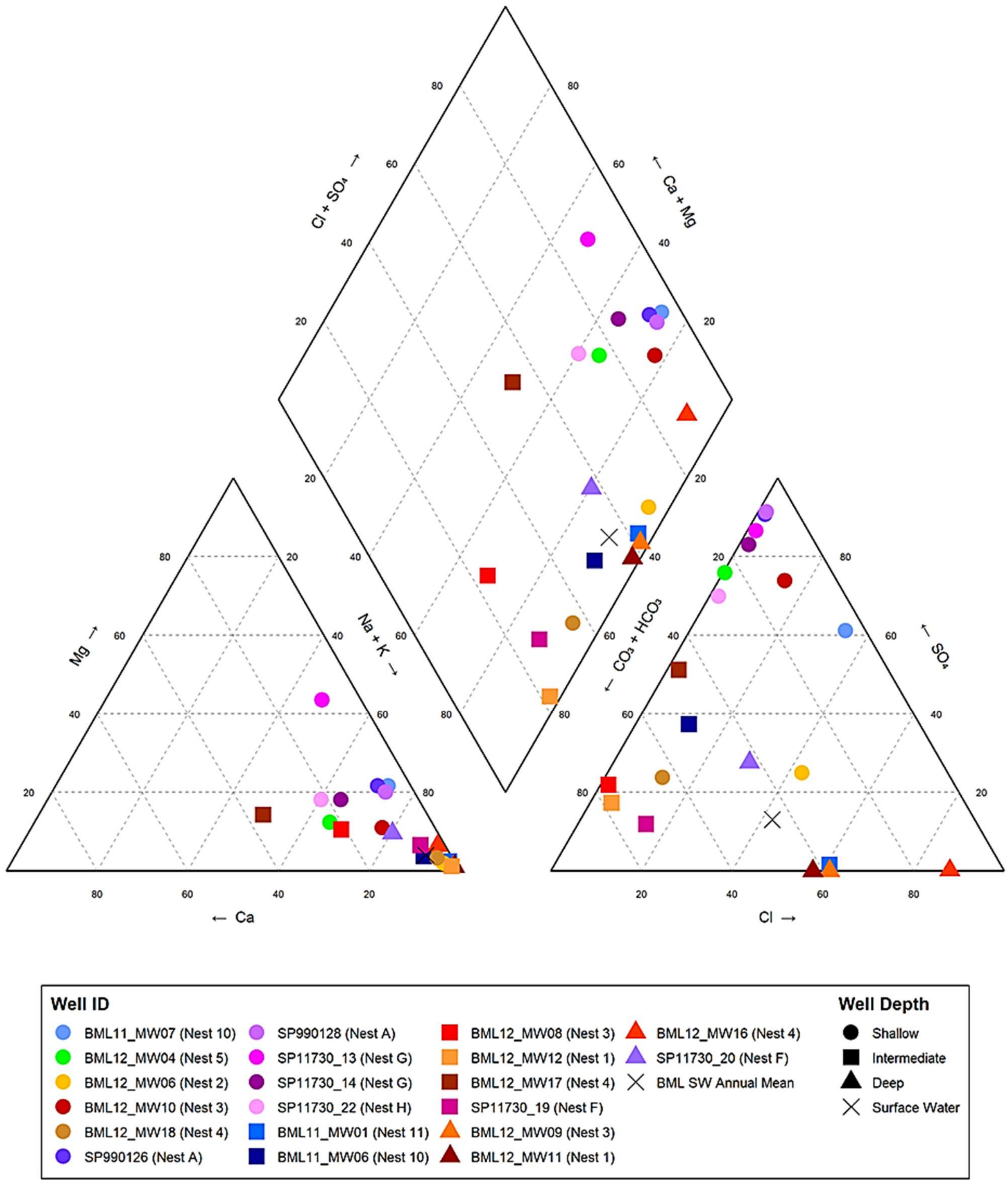


Figure 7-36: Piper plot of ionic composition in BML groundwater zones (Summer 2021).

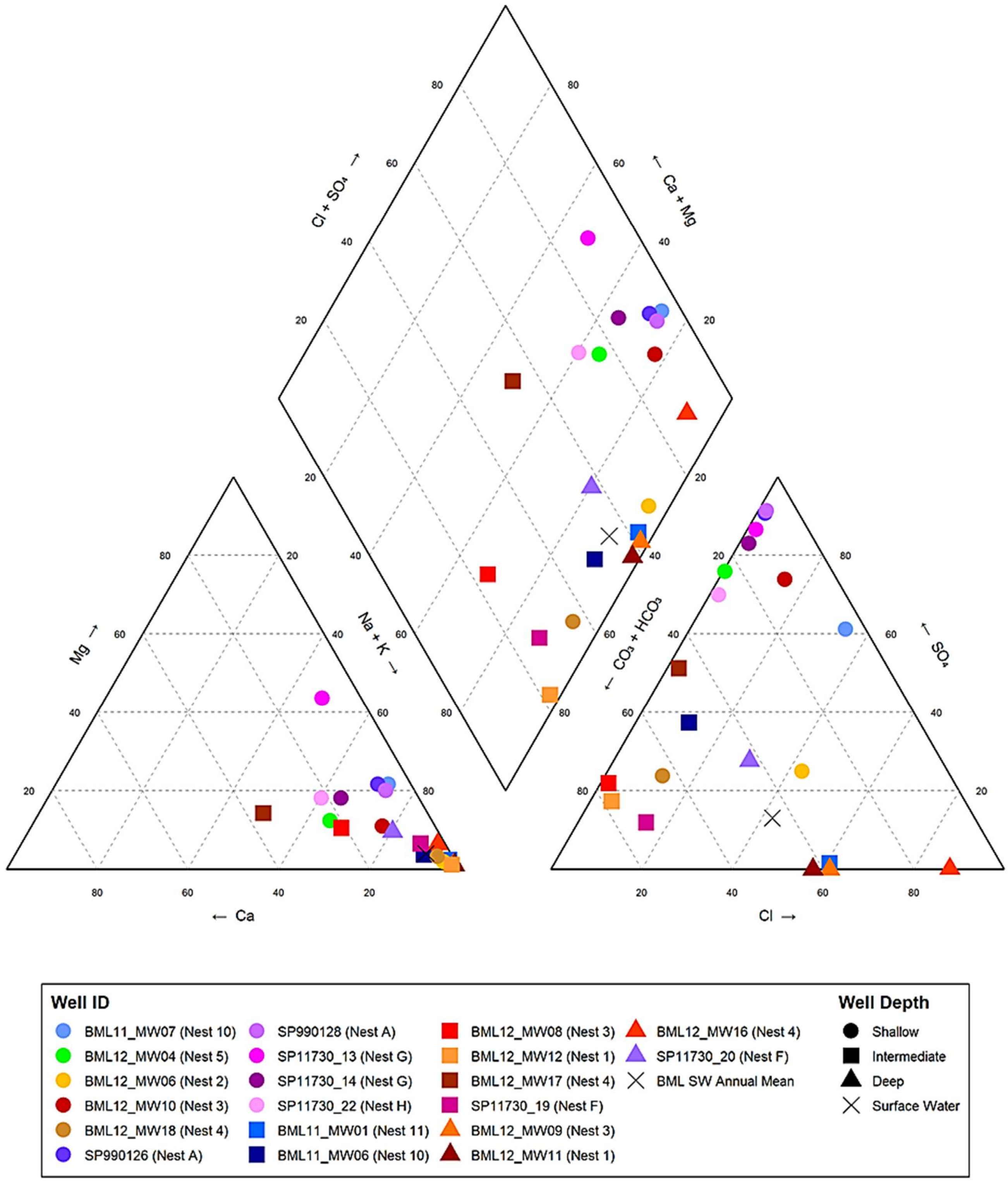


Figure 7-37: Piper plot of ionic composition in BML groundwater zones (Fall 2021).

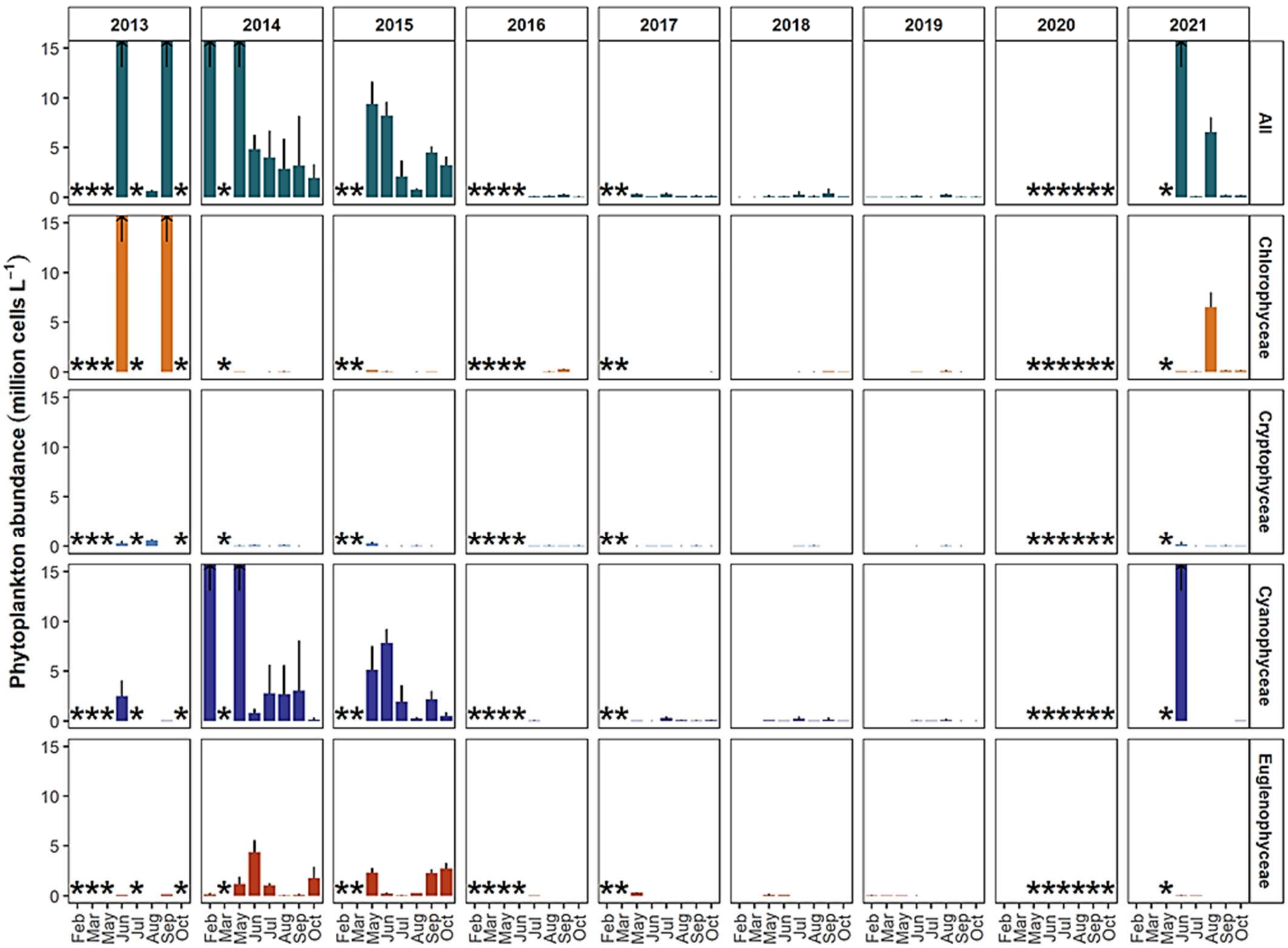
7.3 Biological Components of the Base Mine Lake Monitoring Program

The biological aspects of the Base Mine Lake monitoring program document the important components of the lake's food chain. Monitoring the changes in acute toxicity further validates the shorter-term milestone of water quality improvements with time. Chronic toxicity trends provide an understanding of the longer-term lake trajectory to support end land use expectations (Syncrude, 2016).

7.3.1 Phytoplankton abundance and biomass

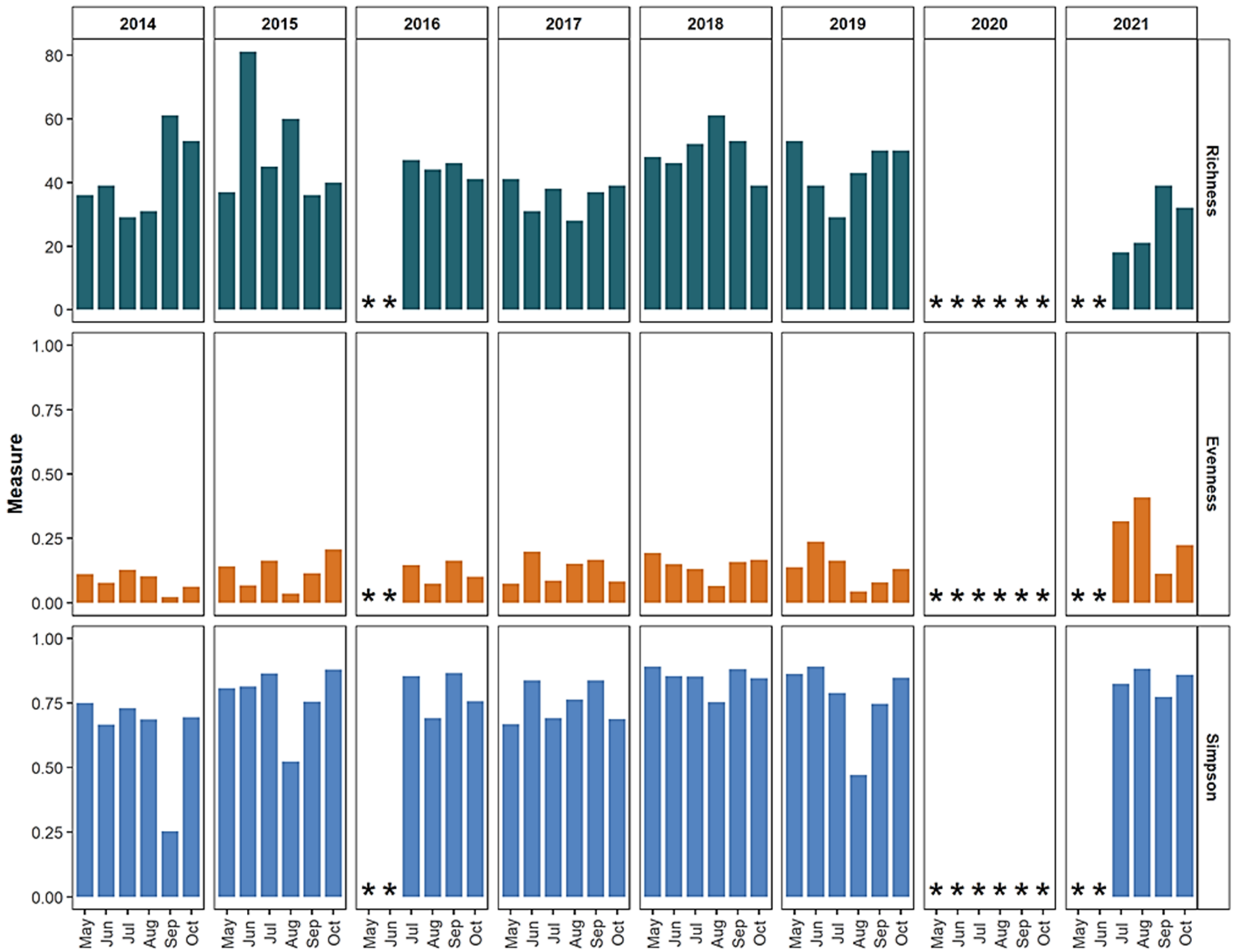
Phytoplankton samples were collected at all three platform stations in February and March 2021. Open-water sampling took place monthly from June to October at the three platform stations, and from July to October at the BCR pump-in station. Conventional microscopic taxonomic analysis and biovolume calculations were completed. A research program using molecular analysis for taxonomic resolution is also underway.

Phytoplankton densities in BML and BCR have generally exhibited high monthly and annual variability since monitoring commenced in 2013 (Figure 7-38). Phytoplankton communities in BML have generally followed seasonal trends typical of temperate lakes, with low densities of winter phytoplankton, high densities in the spring followed by a gradual decrease in density during the summer because of senescence and zooplankton grazing, and an increase in the fall in response to nutrient upwelling from fall turnover (Sommer et al. 1986). In 2021, winter phytoplankton densities were the lowest observed since monitoring began, while summer phytoplankton densities were the highest on record. Phytoplankton abundance has remained low since 2016 because of low numbers of cyanobacteria in the phytoplankton community. The highest annual abundance (6,566,716 cells/L) was recorded in 2021, which is possibly related to an increase in water clarity and light penetration (Hatfield 2022a). In 2021, total phytoplankton abundance in February and March were the lowest documented to-date (14,258 cells/L and 8,300 cells/L, respectively). Phytoplankton abundance in BCR followed similar seasonal trends (Figure 7-39). Historically, abundance in BCR has been higher than BML; however, BCR had unusually low abundances in 2021 (approximately one order of magnitude less than normal).



Mean phytoplankton abundance (total and dominant taxonomic groups) pooled across BML stations, with error bars shown as standard deviations. High abundance of chlorophytes in June (33 million cells per L) and September 2013 (16 million cell per L), and cyanobacteria in February 2014 (33 million cells per L), May 2014 (47 million cells per L), and June 2021 (76 million cells per L) are flagged with arrows. Months without phytoplankton abundance samples are marked with asterisks.

Figure 7-38: Monthly phytoplankton abundance in Base Mine Lake, 2013 to 2021.



Phytoplankton community diversity metrics. Months without phytoplankton samples are marked with asterisks.
Phytoplankton samples are not collected from BCR during ice-covered periods.

Figure 7-39: Monthly phytoplankton richness, evenness, and Simpson's diversity index in Beaver Creek Reservoir, 2014 to 2021.

7.3.2 Zooplankton diversity, abundance and biomass

Triplicate zooplankton samples were collected each month from June to October 2021 at the three platform stations, and from July to October at the BCR pump-in station. Conventional microscopic taxonomic identifications and dry weight biomass using published length-width conversions were completed. Results are presented in Figure 7-40.

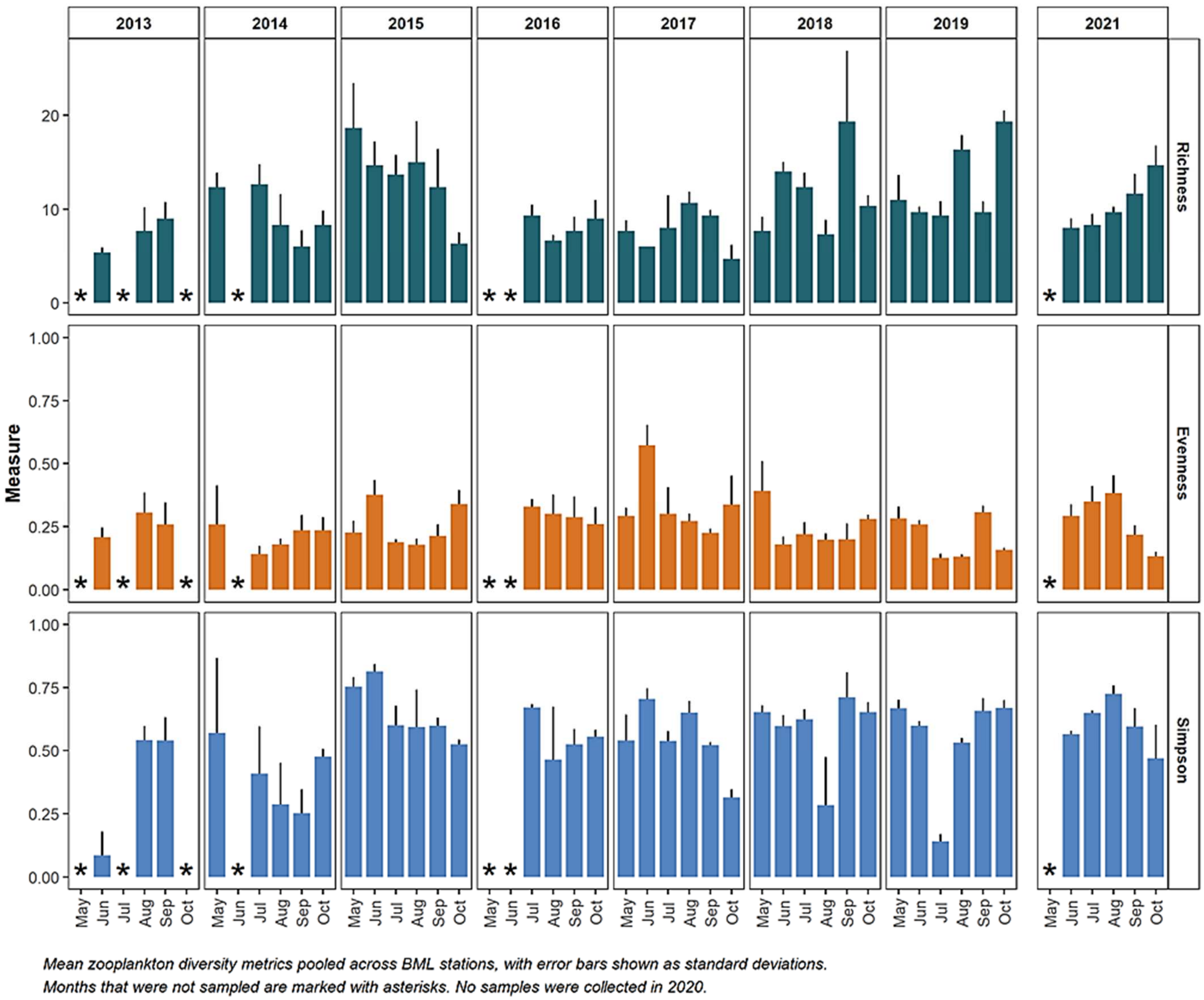


Figure 7-40: Monthly zooplankton richness, evenness, and Simpson's diversity index in Base Mine Lake, 2013 to 2021.

7.3.3 Benthic macroinvertebrate diversity and biomass

Benthic invertebrates were sampled between September 1 and 14, 2021, using petite ponar grabs in littoral areas (0.42-1.0 m depth of water). Benthic invertebrate samples were sorted and identified following standard Canadian Aquatic Biomonitoring Network (CABIN) protocols. Total dry biomass by taxonomic group was determined by drying and weighing specimens. Results are presented in Figure 7-41.

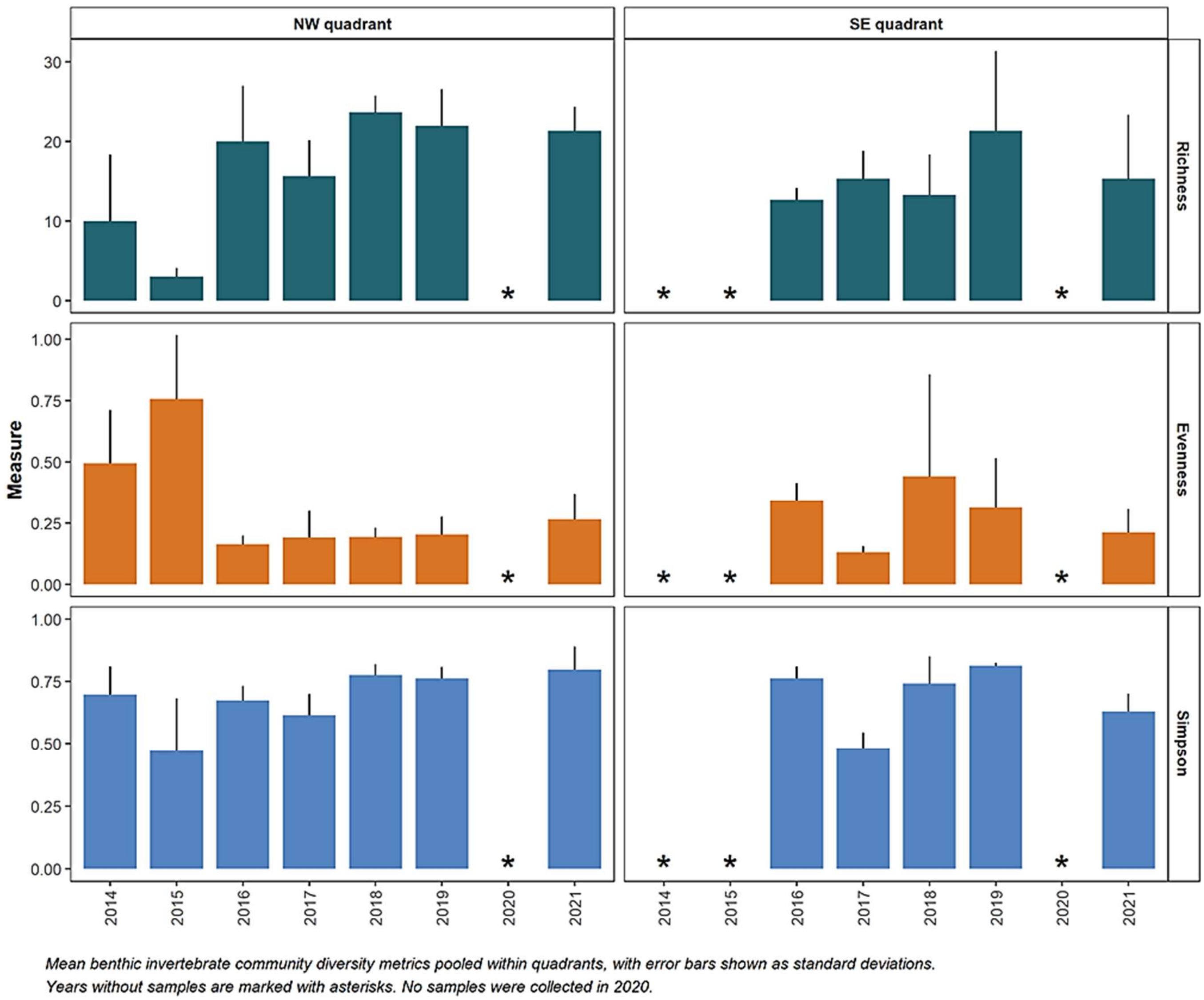


Figure 7-41: Benthic invertebrate taxonomic richness, evenness, and Simpson's diversity index in Base Mine Lake, 2014 to 2021.

7.3.4 Surface water toxicity bioassay

Water toxicity samples were collected in June, July, and September 2021, at all three platform stations. Each sample consisted of a composite of multiple grabs from two discrete depths in the field-estimated euphotic zone (twice the Secchi depth), collected with a 4-L horizontal Van Dorn sampler. The grab samples were composited in clean laboratory-supplied 20-L carboys. At each of the three platform stations, 70 L of water was collected for testing. Samples were shipped immediately, unpreserved, to Nautilus Environmental (Nautilus) in Calgary, Alberta.

Acute and chronic water toxicity tests were performed by Nautilus using the following methods:

- Acute toxicity tests:
  - EPS 1/RM/13: Biological Test Method: Reference Method for Determining Acute Lethality of Effluents to Rainbow Trout (Environment Canada 2000, 2nd Edition); and
  - EPS 1/RM/14: Biological Test Method: Reference Method for Determining Acute Lethality of Effluents to *Daphnia magna* (Environment Canada 2000, 2nd Edition).
- Chronic toxicity tests:
  - EPS 1/RM/21: Biological Test Method: Test of Reproduction and Survival Using the Cladoceran *Ceriodaphnia dubia* (Environment Canada 2007a);
  - EPS 1/RM/22: Biological Test Method: Test of Larval Growth and Survival Using Fathead Minnow *Pimephales promelas* (Environment Canada 2011);
  - EPS 1/RM/25: Biological Test Method: Growth Inhibition Test Using the Freshwater Alga *Raphidocelis subcapitata* (formerly *Selenastrum capricornutum* and *Pseudokirchneriella subcapitata*) (Environment Canada 2007b, 2nd Edition);
  - EPS 1/RM/37: Biological Test Method: Test for Measuring the Inhibition of Growth Using the Freshwater Macrophyte *Lemna minor* (Environment Canada 2007c, 2nd Edition); and
  - EPS 1/RM/24: Biological Test Method: Toxicity Test Using Luminescent Bacteria (*Vibrio fischeri*) (Environment Canada 1992).

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, or fish. Survival endpoints report the proportion of test organisms that survive over a fixed duration at particular dilutions of the water being tested. 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 (in this example, 50%), with increasing concentrations representative of decreasing effects. Since monitoring was initiated in 2013, chronic toxicity has been observed for some test organisms, whereas acute toxicity has not been observed consistently in BML. No clear seasonal trends in chronic toxicity have been evident since the onset of monitoring, with standard deviations between years and months overlapping across most test organisms. In 2021, toxicity of BML water was within the range of historical results.

7.3.4.1 Acute Toxicity

The 96-hour static acute test on rainbow trout (*Oncorhynchus mykiss*) did not show any effect on survival resulting from exposure to BML water in 2021, with all LC50 values >100% v/v BML water (Table 7-8 and Figure 7-42). Historically, rainbow trout exposure to BML water resulted in a mortality response until May 2014, with LC50 values ranging from 69% to 87% v/v; no survival effect has been observed in any subsequent rainbow trout test.

The 48-hour acute *Daphnia magna* test on BML water has shown no survival effect since monitoring began in 2013, with all LC50 values >100% v/v BML (Table 7-8 and Figure 7-42). The 48-h *D. magna* acute test conducted since 2016 has similarly showed no toxicity of BML water on *D. magna* mobility, with EC50 values >100% v/v BML in all three years.

7.3.4.1.1 Bioluminescence Test

The 15-minute bacterial (*Vibrio fischeri*) bioluminescence tests showed a toxic effect in all nine IC20 tests in 2021, with the strongest responses in September (13% v/v BML), followed by July (30% v/v) and June (31% v/v) (Table 7-8 and Figure 7-43). Historically, *V. fischeri* have demonstrated high toxicity of BML water at the IC20 level, with mean values ranging from 14% v/v in May 2017 to 85% v/v in August 2013. In contrast, IC50 tests showed no toxic effect in 2021 (>91% v/v BML for all tests) (Table 7-8 and Figure 7-43). IC50 toxic effects have been observed only three times since testing began in 2013; values indicated moderate toxicity of BML water in June and July 2013 (75% and 70% v/v BML, respectively) and May 2015 (59% v/v BML).

7.3.4.2 Chronic Toxicity

7.3.4.2.1 Survival Tests

The 7-day survival tests on *Ceriodaphnia dubia* did not show any effect on survival resulting from BML water exposure in 2021, with all LC50 values >100% v/v BML (Table 7-8 and Figure 7-44). BML water collected during eight of the 17 sampling events between 2013 and 2018 showed some level of toxicity on *C. dubia*, with LC50 values ranging from 75% v/v in May 2017 to 92% v/v in July 2013 and July 2018. There was no indication of chronic toxicity on *C. dubia* in 2019 or 2021.

The 7-day survival tests on fathead minnow (*Pimephales promelas*) did not show any effect on survival resulting from BML water exposure in 2021, with all LC50 values >100% v/v BML (Table 7-8 and Figure 7-44). The only fathead minnow test that has documented any chronic toxicity was in July 2013, with an LC50 of 69% v/v BML.

7.3.4.2.2 Growth Inhibition Tests

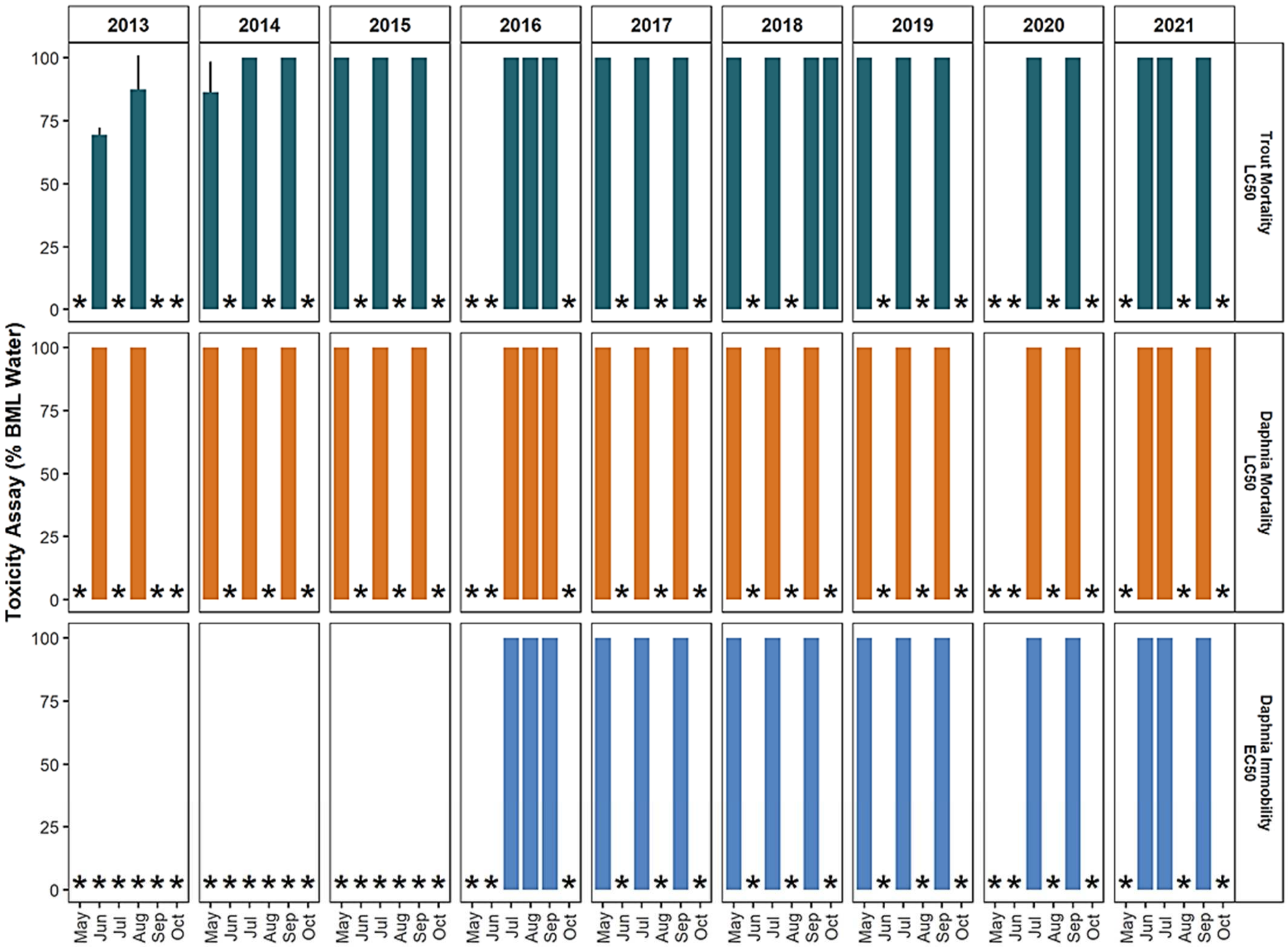
The 7-day growth tests on fathead minnow found no effect of exposure to BML in 2021, with all IC25 values >100% v/v BML (Table 7-8 and Figure 7-44). Between July 2014 and May 2018, the 7-day growth test showed no toxicity; however, IC25 effects were observed at concentrations of 55% v/v BML in July 2013, 88% v/v BML in May 2014, and 80% v/v BML in July 2018.

The 72-hour growth tests on the fresh water alga (*Raphidocelis subcapitata*) indicated toxicity in three of the nine tests conducted during the 2021 open water season, with a mean IC25 value of 51% v/v BML in June and 82% v/v BML in July (Table 7-8; Figure 7-45;); samples collected in September did not demonstrate toxicity of BML water (>95 % v/v BML). Chronic effects of BML water on *R. subcapitata* generally have been minimal, with results typically exceeding 75% v/v BML water except in May and June 2014, July and September 2015, July and August 2016, and June 2021. Mean IC25s ranged from approximately 60% v/v BML in 2014 and 2016 to 84% v/v BML in 2018. No effects on *R. subcapitata* growth were observed in 2017, or September 2021 (>91% v/v BML).

The 7-day macrophyte (*Lemna minor*) growth tests indicated toxic effects on both dry weight and frond numbers in 2021 (Table 7-8 and Figure 7-45). Toxicity was observed in five of nine dry weight tests in 2021, with the greatest IC25 responses in September (40% v/v BML) and July (51% v/v BML); samples collected in June did not exhibit a toxic response (>97% v/v BML) (Table 7-8; Figure 7-45;). Toxic effects also were observed in all nine frond number tests, with the greatest IC25 responses in June (4% v/v BML), followed by July (13% v/v BML) and September (32% v/v BML). The 7-day *L. minor* growth tests exhibited higher toxic responses than all previous years except 2017, which were the highest on record since testing began in 2014.

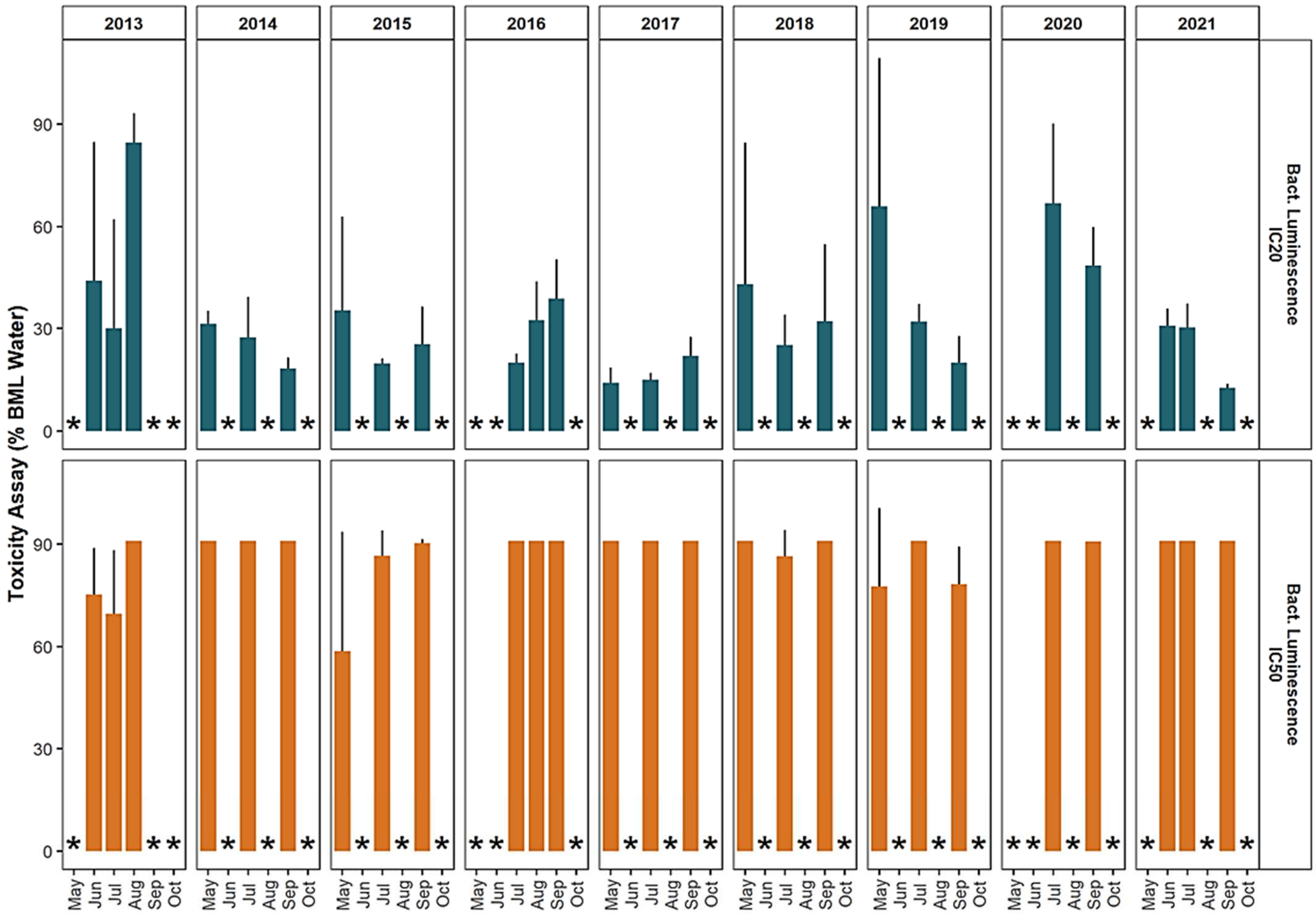
7.3.4.2.3 Reproduction Test

The 7-day reproduction tests on *Ceriodaphnia dubia* indicated toxic effects in seven of the nine tests in 2021. *C. dubia* showed the greatest IC25 response to water samples collected in July (67% v/v BML), followed by September (70% v/v BML) and June (87% v/v BML) (Table 7-8 and Figure 7-44). The effects of BML water on *C. dubia* reproduction have generally decreased from 2013 to 2021. The *C. dubia* IC25 response was similar in 2021 (67.3 to 87.3% v/v BML) and 2019 (42 to 89% v/v BML).



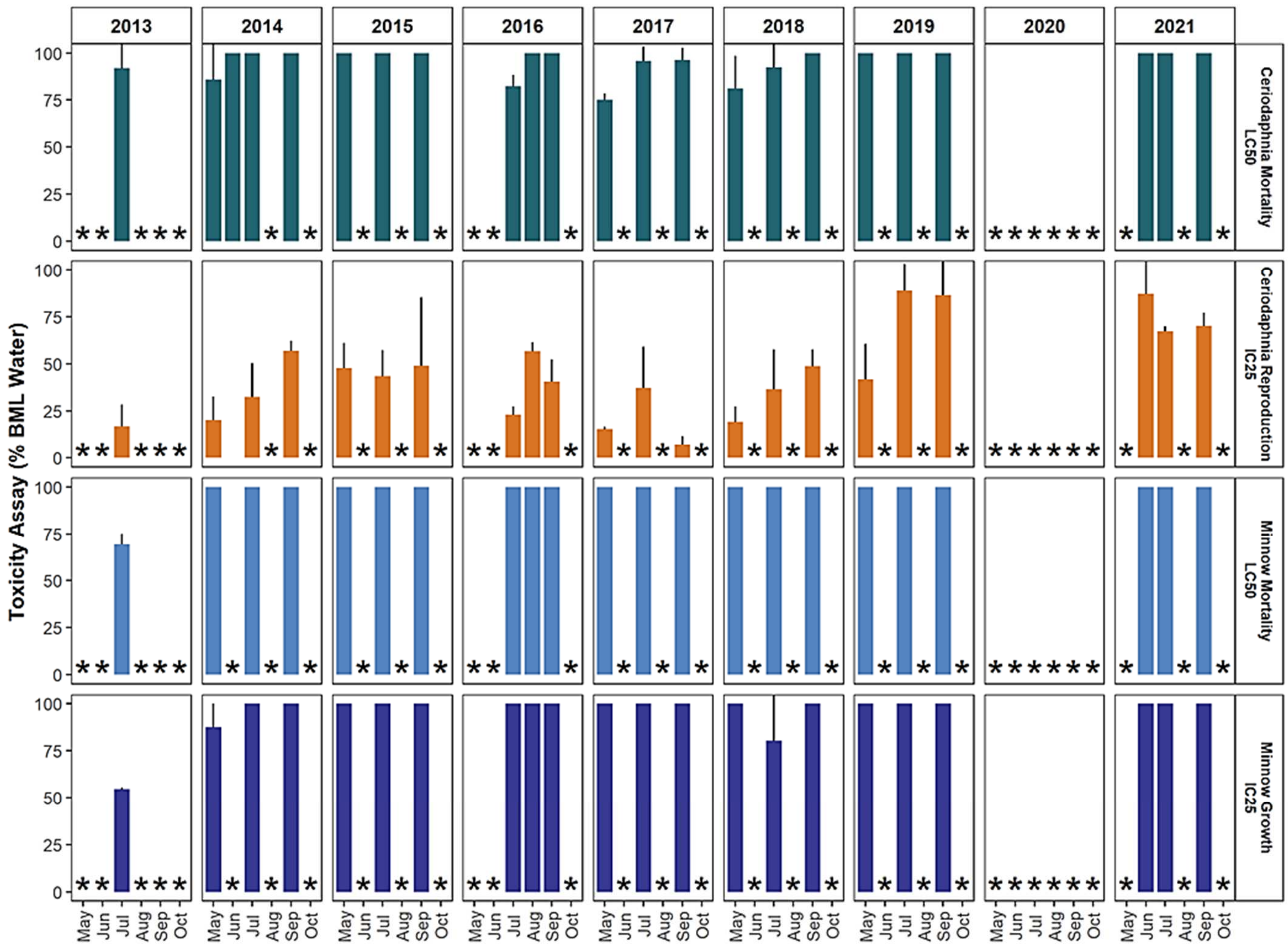
Shown are pooled averages of toxicity assay results across BML platform stations, with standard deviations shown as error bars where applicable.
LC50 is the concentration of BML water, diluted by non-toxic medium, estimated to cause 50% mortality in exposed test organisms.
EC50 is the concentration of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

Figure 7-42: Acute toxicity responses of invertebrates and fish exposed to Base Mine Lake waters, 2013 to 2021.



Shown are pooled averages of toxicity assay results across BML platform stations, with standard deviations shown as error bars where applicable.
IC20 is the concentration of BML water, diluted by non-toxic medium, estimated to impair the physiology and growth of 20% of exposed test organisms.
IC50 is the concentration of BML water, diluted by non-toxic medium, estimated to impair the physiology and growth of 50% of exposed test organisms.
The maximum concentration of BML water for bacteria liminescnece tests was 91% as per lab standard
Seasons without toxicity assay results for these endpoints are marked with asterisks.

Figure 7-43: Acute toxicity response of bacteria exposed to Base Mine Lake waters, 2013 to 2021.



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

Figure 7-44: Chronic toxicity responses of invertebrates and fish exposed to Base Mine Lake waters, 2013 to 2021.

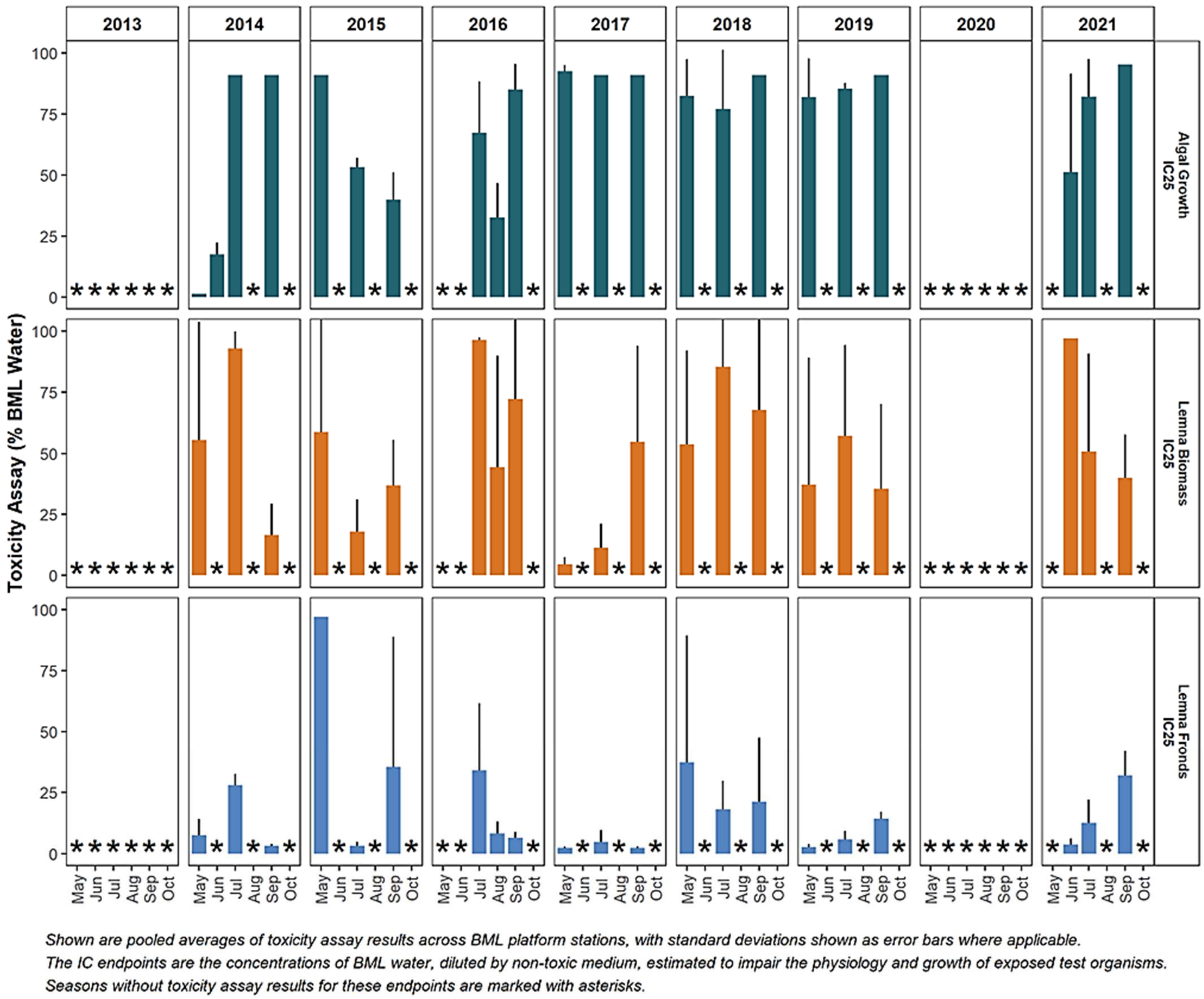
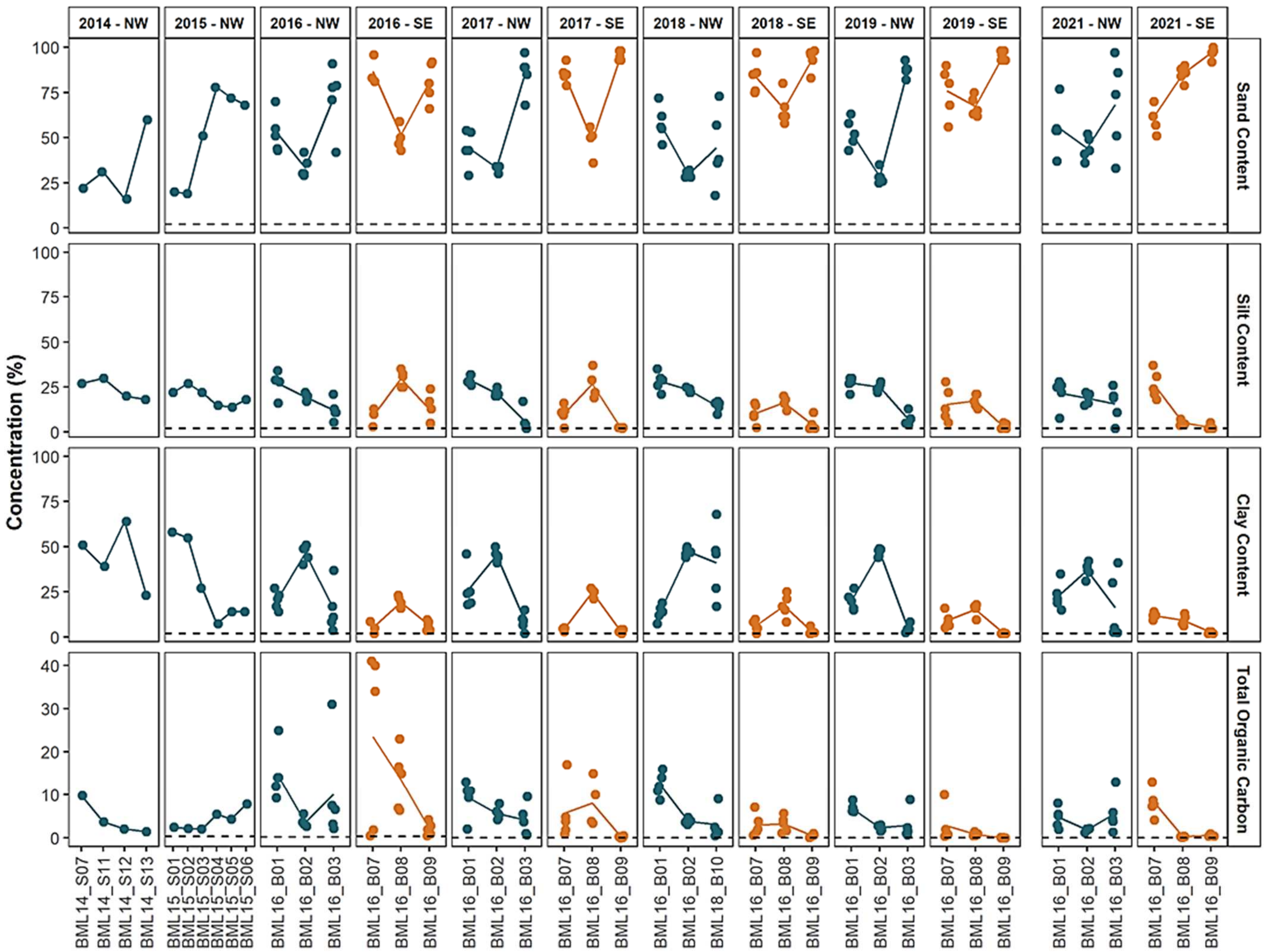


Figure 7-45: Chronic toxicity responses of primary producers exposed to Base Mine Lake waters, 2013 to 2021.

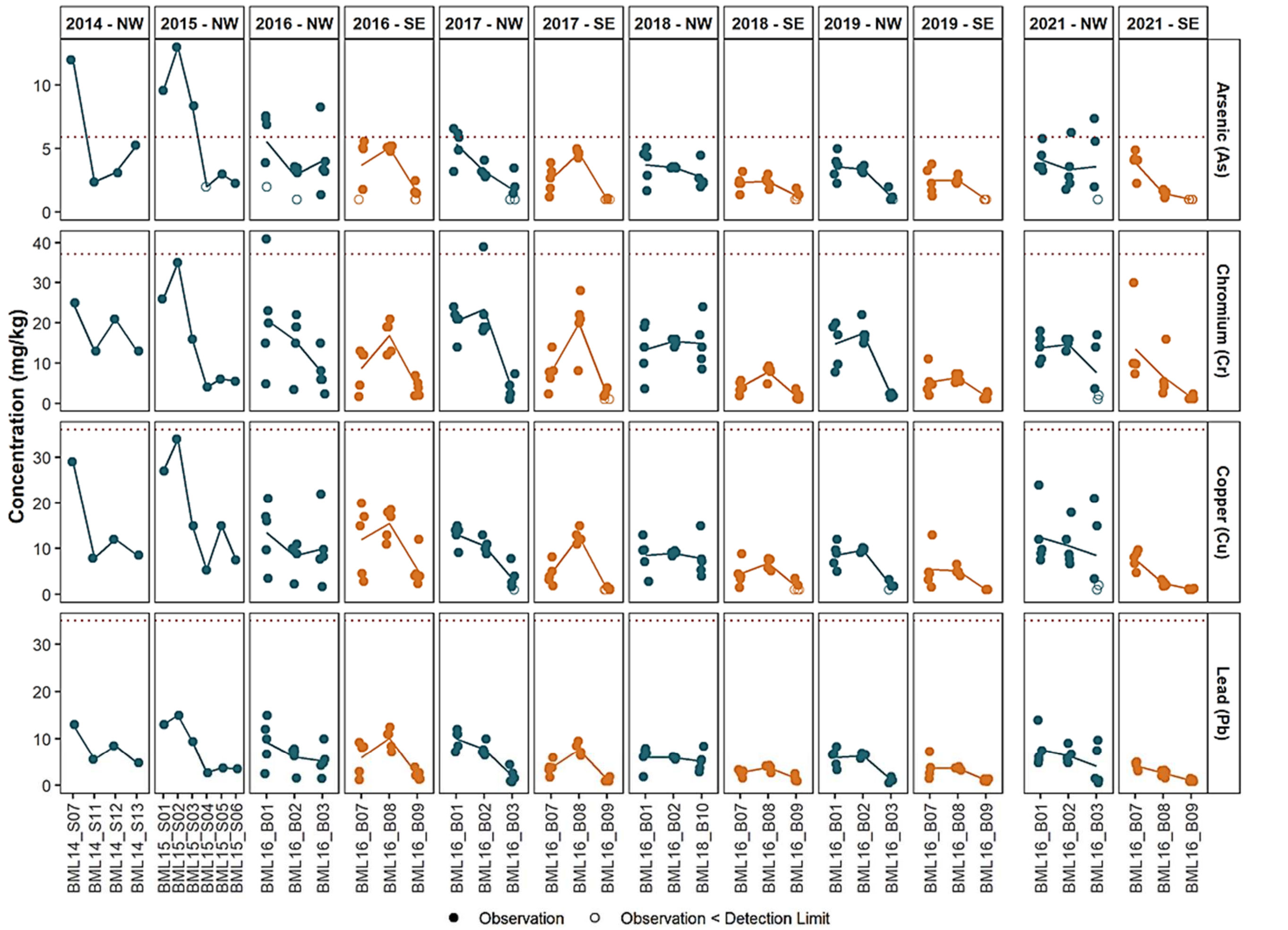
7.3.5 Littoral zone sediment chemistry

Sediment quality samples were collected between September 1 and 14, 2021, in conjunction with the benthic invertebrate program. Five replicate samples were collected at each of the six littoral stations, using a petite ponar with an effective sampling area of 0.023 m^2. Littoral zone sediment is not FFT, but conventional reclamation soils. There are some areas of the littoral where hydrocarbon sheen from the water surface has accumulated on top of the surface soils as a result of lake elevation fluctuations.

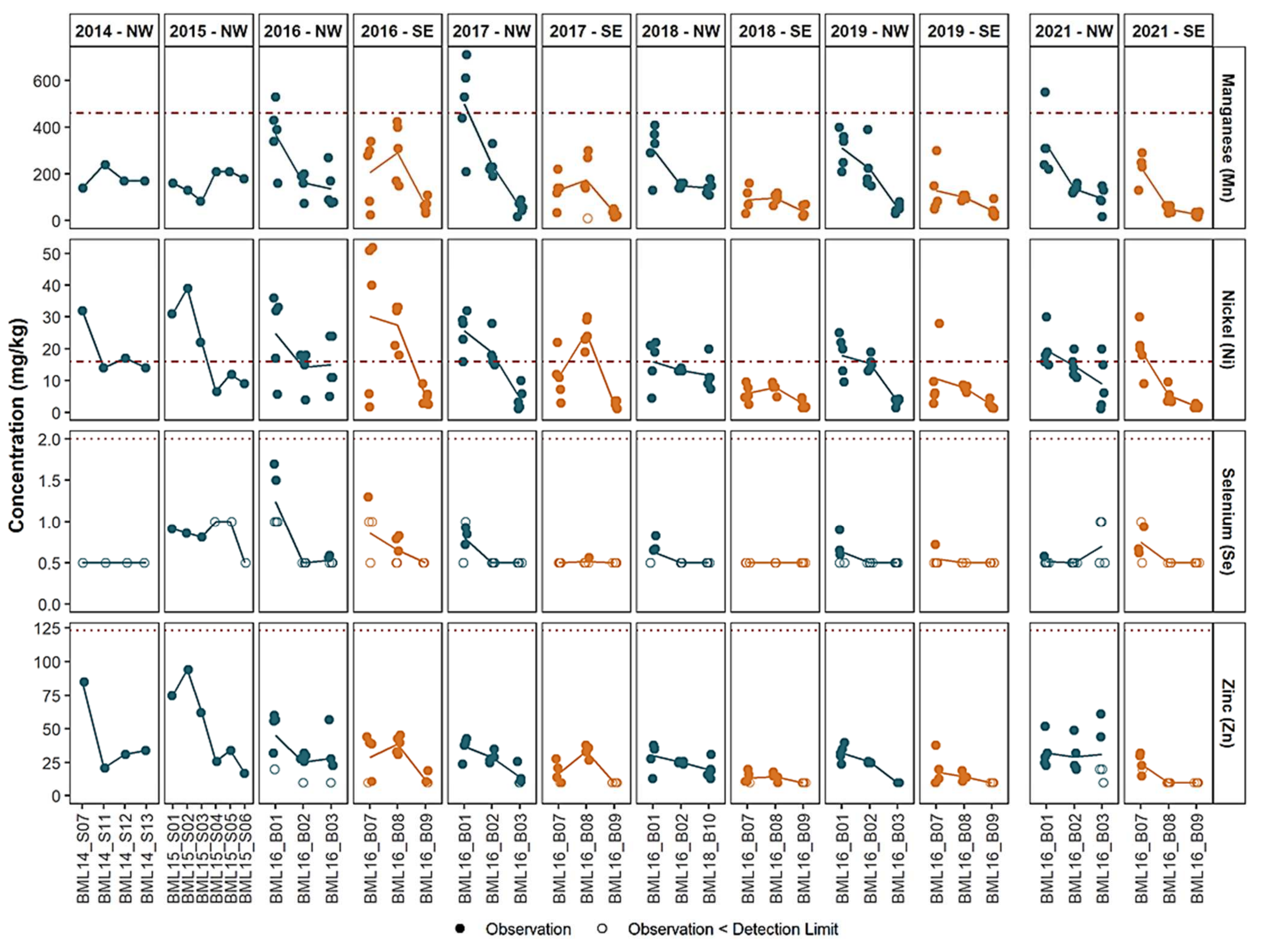


Sediment quality measurements for each replicate at each station.Sampling effort varied between years - 4 stations in the NW quadrant in 2014, 6 stations in the NW quadrant in 2015 and 3 stations in each the NW and SE quadrant from 2016 to 2019 and 2021. No samples were collected in 2020.
Mean sediment concentration for each sampling event shown as the solid-coloured line and median detection limits for each year shown as dashed lines, if available.

Figure 7-46: Physical composition/properties of sediment collected from the NW and SE quadrants of Base Mine Lake, 2014 to 2021.

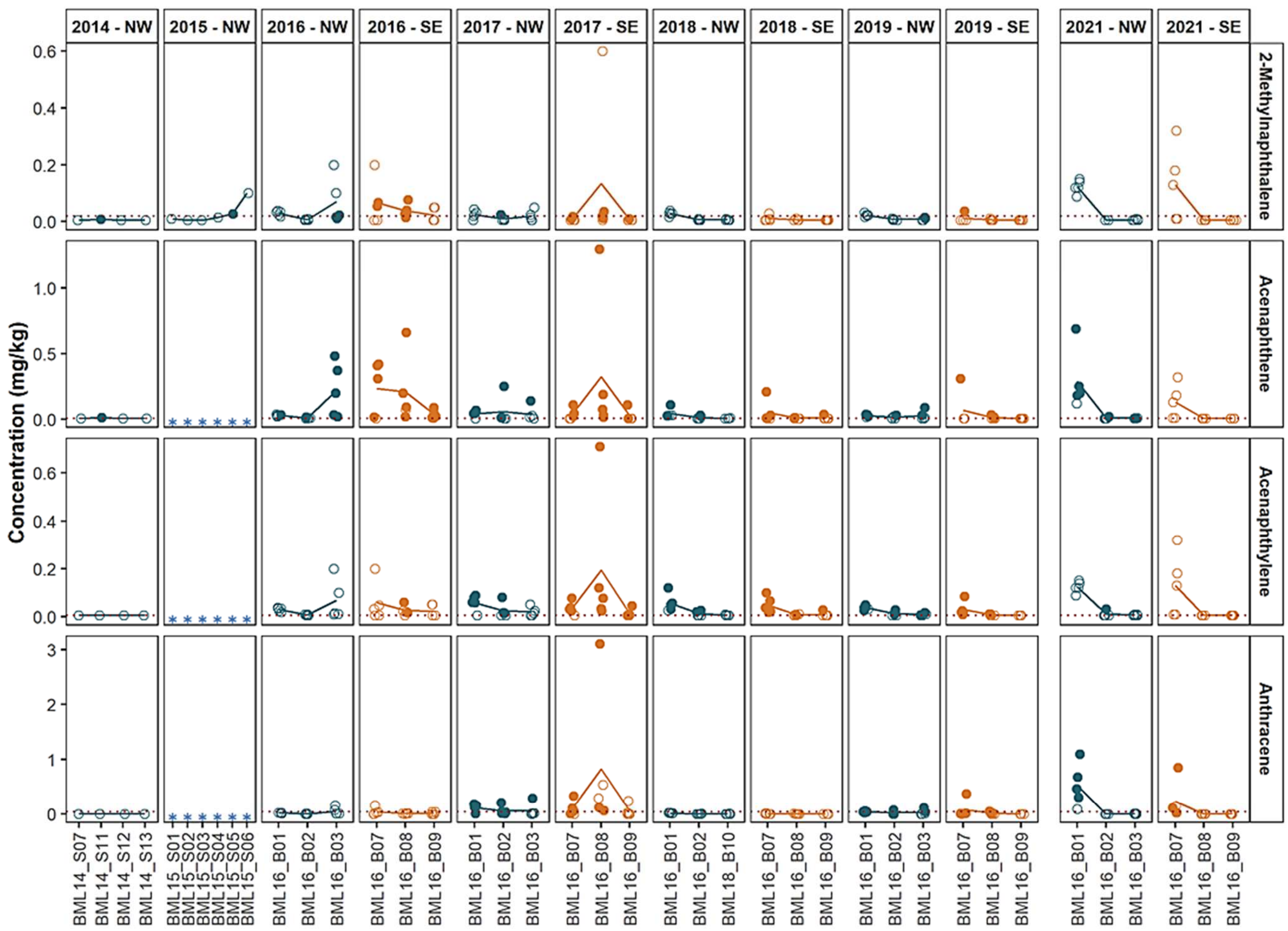


Sediment quality measurements for each replicate at each station. Sampling effort varied between years -- 4 stations in the NW quadrant in 2014, 6 stations in the NW quadrant in 2015 and 3 stations in each the NW and SE quadrant from 2016 to 2019 and 2021. No samples were collected in 2020.
Mean sediment concentration for each sampling event shown as the solid-coloured line and Interim Sediment Quality Guidelines (ISQG) shown as dotted lines, if available.

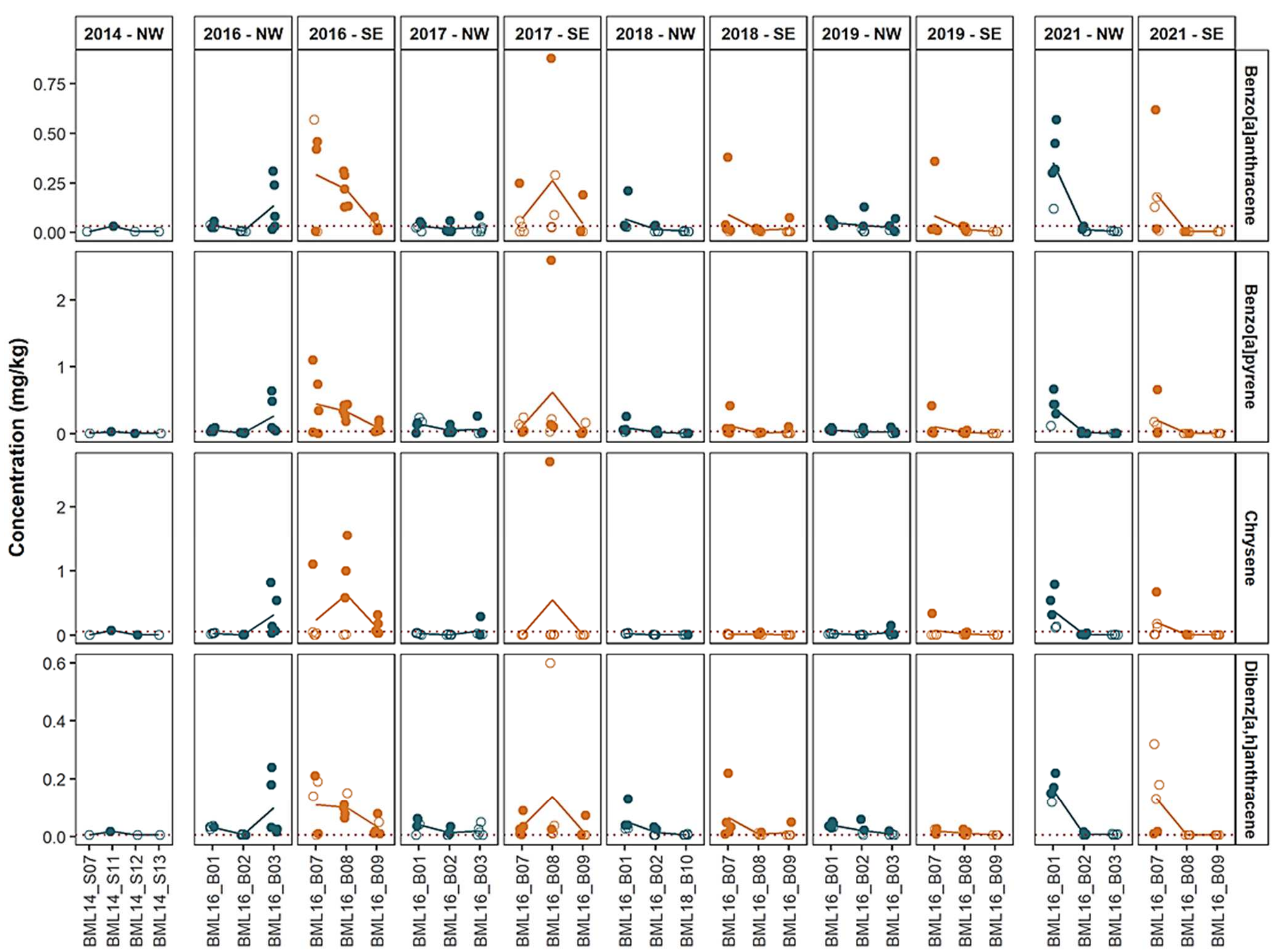


Sediment quality measurements for each replicate at each station. Sampling effort varied between years -- 4 stations in the NW quadrant in 2014, 6 stations in the NW quadrant in 2015 and 3 stations in each the NW and SE quadrant from 2016 to 2019 and 2021. No samples were collected in 2020.
Mean sediment concentration for each sampling event shown as the solid-coloured line, Interim Sediment Quality Guidelines (ISQG) shown as dotted lines, and Lowest Effect Level (LEL) shown as dot-dash, if available.

Figure 7-47: Select metal concentrations in sediment collected from the NW and SE quadrants of Base Mine Lake, 2014 to 2021.

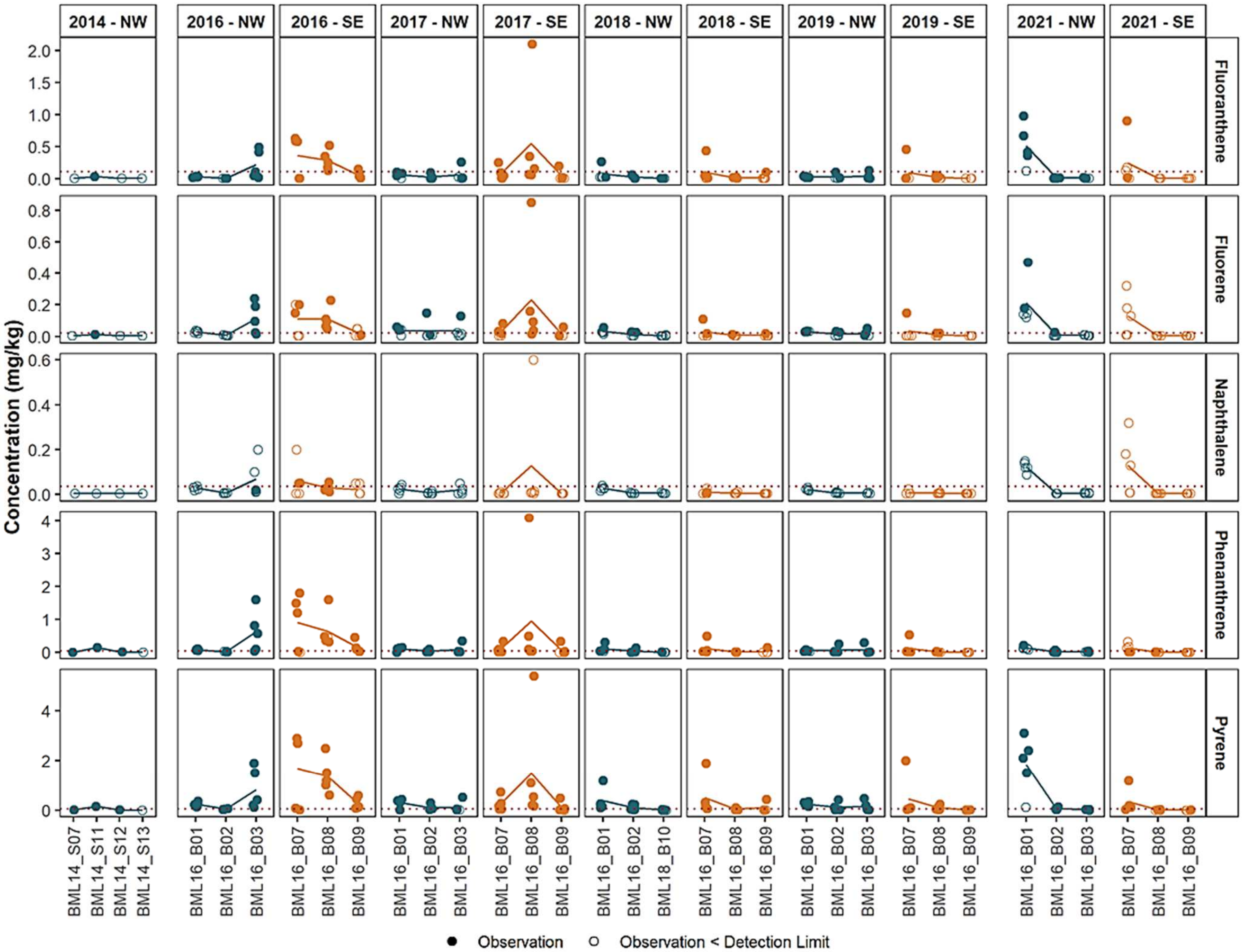


Sediment quality measurements for each replicate at each station. Sampling effort varied between years -- 4 stations in NW quadrant in 2014, and 6 stations in the NW quadrant in 2015, and 3 stations in each area in 2016 to 2019 and in 2021. No samples were collected in 2020.
Mean sediment concentration for each sampling event shown as the solid coloured line and Interim Sediment Quality Guidelines (ISQG) shown as dotted lines, if available.
Only 2-methylnaphthalene was measured in 2015; asterisks mark the un-measured analytes.



Sediment quality measurements for each replicate at each station. The sampling effort varied between years -- 4 stations in NW quadrant in 2014, and 6 stations in the NW quadrant in 2015, and 3 stations in each area in 2016 to 2019 and in 2021. No samples were collected in 2020. Displayed parent PAHs were not measured in 2015.
Mean sediment concentration for each sampling event shown as the solid coloured line and Interim Sediment Quality Guidelines (ISQG) shown as dotted lines.

Figure 7-48: Select PAH concentrations in sediment collected from the NW and SE quadrants of Base Mine Lake, 2014 to 2021.



Sediment quality measurements for each replicate at each station. The sampling effort varied between years -- 4 stations in NW quadrant in 2014, and 6 stations in the NW quadrant in 2015, and 3 stations in each area in 2016 to 2019 and in 2021. No samples were collected in 2020. Displayed parent PAHs were not measured in 2015. Mean sediment concentration for each sampling event shown as the solid coloured line and Interim Sediment Quality Guidelines (ISQG) shown as dotted lines.

Figure 7-48 (continued)

Table 7-8: Exceedances of sediment quality guidelines (as % of samples) in the NW and SE quadrants of Base Mine Lake, 2014 to 2021

Variable	NW Quadrant																				
	2014			2015			2016			2017			2018			2019			2021		
	ISQG	PEL	LEL	ISQG	PEL	LEL	ISQG	PEL	LEL	ISQG	PEL	LEL	ISQG	PEL	LEL	ISQG	PEL	LEL	ISQG	PEL	LEL
Total Metals																					
Arsenic (As)	25	-	0	50	-	0	27	-	0	13	-	0	0	-	0	0	-	0	13	-	0
Chromium (Cr)	0	-	0	0	-	0	7	-	0	7	-	0	0	-	0	0	-	0	0	-	0
Copper (Cu)	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0
Lead (Pb)	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0
Manganese (Mn)	-	0	-	-	0	-	-	0	7	-	0	20	-	0	-	-	0	-	-	0	7
Mercury (Hg)	0	-	0	0	-	0	0	-	0	7	-	0	0	-	0	0	-	0	0	-	0
Nickel (Ni)	-	-	50	0	-	50	0	-	53	0	-	47	0	-	27	0	-	27	0	-	33
Selenium (Se)	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0
Zinc (Zn)	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0
Parent PAHs																					
2-Methylnaphthalene	0	0	-	33	0	-	47	0	-	40	0	-	27	0	-	27	0	-	33	0	-
Acenaphthene	25	0	-	ns	ns	-	87	20	-	67	13	-	53	7	-	73	0	-	60	33	-
Acenaphthylene	0	0	-	ns	ns	-	80	7	-	67	0	-	53	0	-	73	0	-	53	13	-
Anthracene	0	0	-	ns	ns	-	13	0	-	40	7	-	0	0	-	20	0	-	33	27	-
Benzo[a]anthracene	25	0	-	ns	ns	-	47	0	-	27	0	-	27	0	-	53	0	-	40	13	-
Benzo[a]pyrene	25	0	-	ns	ns	-	53	0	-	53	0	-	40	0	-	53	0	-	40	0	-
Chrysene	25	0	-	ns	ns	-	27	0	-	7	0	-	0	0	-	7	0	-	33	0	-
Dibenzo[a,h]anthracene	25	0	-	ns	ns	-	87	13	-	67	0	-	53	0	-	67	0	-	60	27	-
Fluoranthene	0	0	-	ns	ns	-	13	0	-	7	0	-	7	0	-	7	0	-	33	0	-
Fluorene	0	0	-	ns	ns	-	53	13	-	47	7	-	40	0	-	53	0	-	40	20	-
Naphthalene	0	0	-	ns	ns	-	20	0	-	13	0	-	7	0	-	0	0	-	33	0	-
Phenanthrene	25	0	-	ns	ns	-	67	20	-	40	0	-	33	0	-	33	0	-	40	0	-
Pyrene	25	0	-	ns	ns	-	80	13	-	53	0	-	47	7	-	67	0	-	47	27	-

Variable	SE Quadrant														
	2016			2017			2018			2019			2021		
	ISQG	PEL	LEL	ISQG	PEL	LEL	ISQG	PEL	LEL	ISQG	PEL	LEL	ISQG	PEL	LEL
Total Metals															
Arsenic (As)	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0
Chromium (Cr)	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0
Copper (Cu)	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0
Lead (Pb)	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0
Manganese (Mn)	-	0	-	-	0	-	-	0	-	-	0	-	-	0	-
Mercury (Hg)	0	-	0	7	-	0	0	-	0	0	-	0	0	-	0
Nickel (Ni)	0	-	53	0	-	40	0	-	0	0	-	7	0	-	27
Selenium (Se)	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0
Zinc (Zn)	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0
Parent PAHs															
2-Methylnaphthalene	60	0	-	13	7	-	7	0	-	7	0	-	20	7	-
Acenaphthene	93	40	-	67	27	-	40	7	-	20	7	-	33	20	-
Acenaphthylene	60	7	-	73	7	-	53	0	-	47	0	-	33	20	-
Anthracene	7	0	-	60	27	-	0	0	-	13	7	-	20	7	-
Benzo[a]anthracene	67	20	-	40	7	-	20	0	-	7	0	-	20	7	-
Benzo[a]pyrene	80	7	-	60	7	-	27	0	-	20	0	-	27	0	-
Chrysene	47	20	-	7	7	-	0	0	-	7	0	-	20	0	-
Dibenzo[a,h]anthracene	93	27	-	80	7	-	53	7	-	53	0	-	33	13	-
Fluoranthene	60	0	-	33	0	-	7	0	-	7	0	-	20	0	-
Fluorene	67	27	-	47	13	-	7	0	-	13	7	-	20	13	-
Naphthalene	40	0	-	7	7	-	0	0	-	0	0	-	20	0	-
Phenanthrene	73	27	-	53	7	-	20	0	-	7	7	-	20	0	-
Pyrene	93	47	-	67	13	-	53	7	-	40	7	-	27	7	-

7.3.6 Littoral zone sediment toxicity

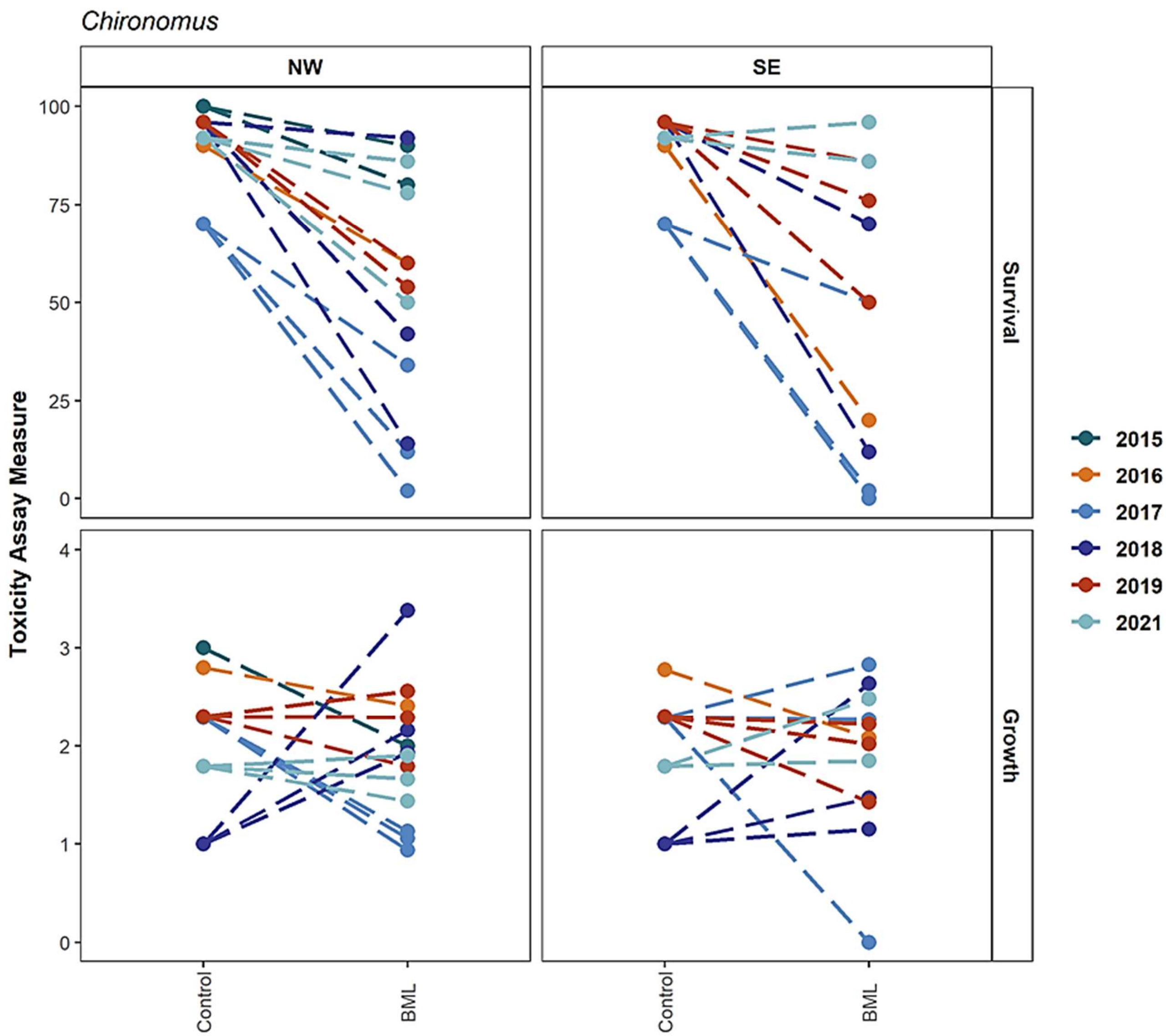
Sediment toxicity samples were collected in September 2021, in conjunction with the sediment quality sampling program. Sediment toxicity samples were collected from each of the six sediment/benthic invertebrate sampling stations. Five replicate samples were collected at each sediment toxicity station, using a petit ponar with an effective sampling area of 0.023 m^2. There are some areas of the littoral where bitumen sheen from the water surface has accumulated on top of the surface soils as a result of lake elevation fluctuations.

Sediment toxicity tests used the following methods:

- EPS 1/RM/33: Biological Test Method: Test for Survival and Growth in Sediment Using the Freshwater Amphipod *Hyalella azteca* (Environment Canada 2013) – 14-day survival; and
- EPS 1/RM/32: Biological Test Method: Test for Survival and Growth in Sediment Using the Larvae of Freshwater Midges (*Chironomus dilutus* or *C. riparius*) (Environment Canada 1997) – 10-day survival.

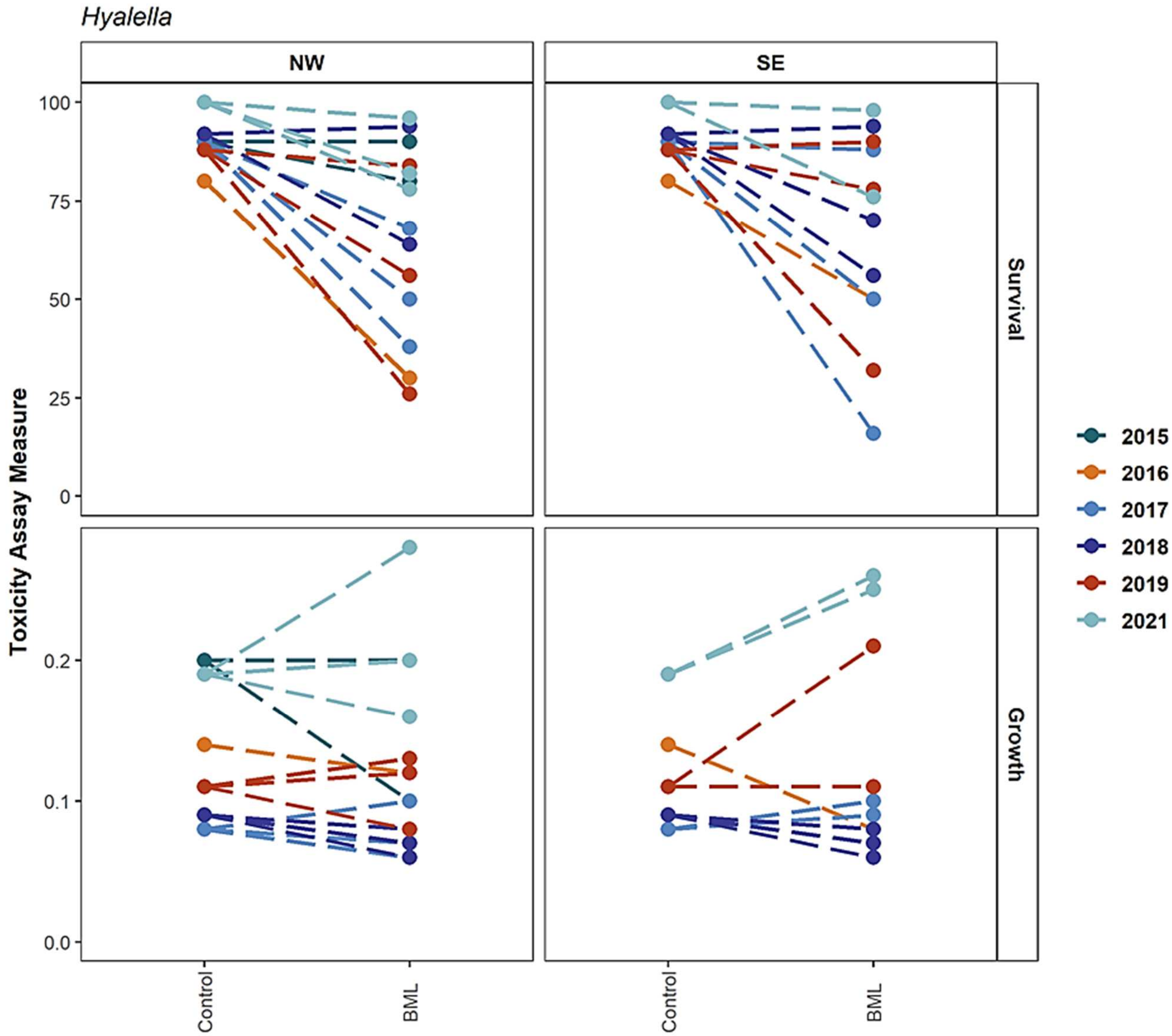
Sediment toxicity is used to determine whether the substrate of BML may be acutely or chronically toxic to benthic invertebrates, and to provide information on the lake's ability to support colonization by benthic organisms. Figure 7-49 and Figure 7-50 summarize toxicity responses of test organisms exposed to sediment samples collected from the NW and SE quadrants each fall from 2015 to 2021. Three stations in each quadrant were tested annually between 2017 and 2021 except in 2020 when no sediment toxicity samples were collected, whereas a single station from the NW quadrant was tested in 2014 and 2015, and single stations from both quadrants were tested in 2016.

The 2021 results are compared with those from 2015 through 2019; no comparisons can be made with 2014 data because a laboratory issue invalidated these tests. Toxicity responses are presented as percent survival and growth for both test and control groups using *Chironomus dilutus* and *Hyalella azteca*, to facilitate comparisons among years.



Toxicity assay results for control sediment and BML sediments, identified by year, and linked by lines for comparison.
The survival assay measures % survival of test organisms. The growth assay measures the change in biomass of organisms (mg).
Equal survival results for two stations in the SE quadrant in 2019 are presented as a single point at 60% survival.
Equal survival results for two stations in the SE quadrant in 2021 are presented as a single point at 86% survival.
Sediment toxicity samples were not collected for 2020.

Figure 7-49: Toxicity responses of freshwater midge exposed to sediment from NW and SE quadrants of Base Mine Lake, 2015 to 2021.



Toxicity assay results for control sediment and BML sediments, identified by year, and linked by lines for comparison.
The survival assay measures % survival of test organisms. The growth assay measures the change in biomass of organisms (mg).
Equal growth results for two stations in the SE quadrant in 2019 are presented as a single point at 0.11 mg/organism.
Equal survival results for two stations in the SE quadrant in 2021 are presented as a single point at 98%.
Sediment toxicity samples were not collected for 2020.

Figure 7-50: Toxicity responses of amphipods exposed to sediment from NW and SE quadrants of Base Mine Lake, 2015 to 2021.

8 Summary of Key Performance Results from the Base Mine Lake Research Program

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

As mentioned previously, 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 Base Mine Lake towards becoming a functional component of the reclaimed closure landscape. The current research programs are focused on key parameters influencing early Base Mine Lake development. Recently, research and technology development has been underway to build tools for detection of bitumen mats, and to monitor gas bubble driven bitumen liberation from the bitumen mats to the water surface.

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 until the work is complete and published. The Base Mine Lake monitoring and research program has a good record of publication to date, and many scientific papers are in preparation. The next five years of research will continue to focus on similar activities that have been addressed previously, 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 Base Mine Lake when necessary.

In 2020 and 2021, all research program activities were adapted in response to the COVID-19 pandemic and resulting safety measures. Due to site access restrictions, inter-provincial travel restrictions, and university work restrictions, all research programs were limited by sample procurement, as well as lab and office access to progress work.

8.1 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.

Seasonal turbidity continues a gradual decline with the exception of near the summer minimum, which has remained similar over the last four years. Ebullition (bubbling) is modulated by pressure throughout the year. Imagery of the mudline has revealed small pock marks presumably left from bubble ebulltion (Figure 5.5). Images of BML ice cover has also revealing information about the lake bathymetry. These and other observations and information are supporting a complete qualitative, and in some cases quantitative, description of bathymetric/mudline features (e.g., what is the distribution of pock marks in space and size?).

The majority of the moored dissolved oxygen instruments continued to function well through the gap in maintenance caused by COVID-19. Like turbidity, the seasonal epilimnetic dissolved oxygen concentrations at the moored depths are generally increasing. Note, as the FFT settles and the water cap deepens the stability of the lake is expected to increase and the hypolimnetic dissolved oxygen near the FFT interface may decrease.

Profiles collected during the winters of 2017, 2018, 2019, 2020 and 2021 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. Although preliminary, 2021 summer data has indications of evaporation driven increases in salinity. The period from 2019 to 2021 had the most steady salinity concentrations yet observed in BML. While the salinity of BML has either decreased or remained constant the flux from settling FFT has resulted in an increase in the volume of the water cap and the total mass of salt in the water cap. While during most summers fresh water inflows have been the dominant source of salinity variation, during the summer of 2021, evaporation may have dominated. During the winter the dominant source of salinity variation is the exclusion of salt from the ice. Ice melt results in a relatively large decrease in salinity in the water cap during spring turnover.

Although the energy balance has not yet been completed, the water temperature record indicates heat from the mud is warming the lower portion of the water-cap during the ice-covered period. Conversely, the water cap is warming the upper portion of the mud in the ice-free period.

Commercial modelling packages have limited ability to capture several processes that are of importance in BML. This research program has been attempting to understand these processes (20 or so potential mixing mechanisms identified in Tedford *et al.* 2019), particularly waves, under ice processes, and heat transport across the water-FFT interface. This work includes using and developing numerical models.

In 2021, numerical and laboratory modelling of the transport of heat and salt under ice was undertaken, and laboratory modelling of ebullition and its impact on suspended solids is currently underway. Modelling of the seasonal cycle of suspended solids is also in progress.

Future modelling will investigate the impact heat and salt flux on turbidity.

8.2 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. Most of the work in this program is completed and published.

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 2020/2021 were the development, testing and refinement of gas pressure sensors to understand gas pressure in the FFT. The gas pressure sensors were deployed in spring 2022 and will collect data over the open water season. Results will be shared when that work is complete.

A key paper (Francis *et al.* 2022) was published from this research that demonstrates a positive relationship between $CH_{4(aq)}$ saturation and enhanced mixing, showing that ebullition enhances internal mass loading.

8.3 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 used an experimental approach to quantify physical and biogeochemical processes in a laboratory system simulating an end pit lake. 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. This work was completed and has been summarized in previous reports and theses and scientific journal articles.

8.4 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. Focus more recently has been on sulfur biogeochemistry in BML. The program has provided evidence of sulfur cycling (both reduction and oxidation) occurring in BML which then influences water cap oxygen concentrations. Results indicate that rates of sulfur reduction (SRR) and oxidation (SOR) are seasonally and spatially variable in BML resulting in differential impacts on linked oxygen consumption rates (OCR).

In 2021, the goals of the project were focused on: establishing the occurrence of sulfur reducing and sulfur oxidizing processes and the sulfate reducing (SRB) and sulfur oxidizing (SOB) involved; initiating quantification of the impact of these S cycling processes on BML oxygen concentrations; and identifying the possible controls, outcomes, and rates. Research has combined a field sample collection to establish BML seasonal water cap physico-chemistry and geochemistry, using a hybrid strategy of Syncrude and the University of Toronto (UoT) (August sampling trip) with laboratory experimentation to delineate mechanisms involved. Using this strategy, UoT is in the process of finishing geochemical and microbiological analyses on the 132 samples collected variably from P1, P2, E16 and D17 sites at multiple depths from February , March, July, August and October 2021. In addition, for the first time in 2021, UoT deployed a set of sensors to collect depth dependent DO, pH, light, and pressure values at 1 hr intervals at P1 (pre and post bottom water anoxia) and P2 (post bottom water anoxia) in BML, along with specialized samplers to collect water from the anoxic bottom water zone for geochemical analyses. These data will better identify the geochemical changes occurring during the transition to an anoxic lower water cap in BML.

Geochemical and microbial (DNA, RNA) analyses from these samples are on-going but support three manuscripts in preparation, targeting submission in 2022: (1) BML water cap sulfur mass balance and implications for oxygen consumption, (2) The interplay of sulfate reducing (SRB) and sulfur oxidizing (SOB) bacteria, organic carbon and oxygen in BML, and (3) Physical and biogeochemical determinants of oxygen concentrations in BML during the first 10 years of development.

In addition, laboratory-based experiments were set-up using shipped BML samples throughout the year, and when site access was possible in August 2021, field experiments were executed. These experiments were designed to assess: (1) rates of oxygen consumption (OCR) and identify the important oxygen consuming constituents (OCC) post alum addition in BML for late summer (to compare to OCR determined in 2016 prior to alum addition); (2) rates of sulfate reduction and sulfur oxidation for both winter and summer and identify the SRB and SOB involved; and (3) initiate investigation into the roles of autochthonous carbon (i.e., algal biomass), sulfur intermediate compounds (e.g., thiosulfate, elemental sulfur) identified to occur in BML water samples, and methane in observed OCR. As per field samples, analyses are underway but are making good progress.

Preliminary results generated in 2021 for OCR (um O_2 / L/ hr) show similar values to those determined for 2016 BML water cap prior to the alum addition in the lower waters, i.e., oxygen consumption associated with biogeochemical consumption has not reduced in this zone; determination of geochemical analytes (ongoing) will identify whether any changes in important OCC driving OCR have occurred. It also appears that OCR rates have increased in the upper water cap in 2021 compared to 2016 values. This may be due to the greater productivity occurring in BML post-alum; i.e., greater respiration, in addition to possible sulfur oxidation processes. Ongoing BML sulfur mass balance, SOB identification and sulfur oxidation rates (SOR) analyses will help to identify if and to what extent possible sulfur intermediate compound oxidation by SOB is impacting oxygen levels in the upper water cap.

Microbial census results (16S on BML field collected samples and SOB enrichment experiments) have identified the widespread and ubiquitous occurrence of SOB throughout the BML water cap, indicating sulfur oxidation is a contributor to oxygen consumption. A water cap sulfur mass balance assessing the concentrations of sulfur compounds (total S as well as intermediate compounds: thiosulfate, elemental sulfur, sulfite, and tetrathionate) in addition to sulfate and sulfide for 2015 -2021 is nearing analytical completion. These results will establish how much sulfur occurs in possible oxygen consumption species (i.e., intermediate S compounds, as well as sulfide) at various depths over seasonal and BML developmental scales, providing some of the first quantification of the possible S risks to BML water cap oxygen.

Emerging results assessing 2021 SRBs and seasonal rates of sulfate reduction, and thus sulfide production indicates that the same SRB (*Desulfovibrio* and *Desulfomicrobium*) seem to dominate both winter and summer enrichments from a variety of sites through BML; i.e., these seem to be ubiquitous and important SRB in BML, but winter rates of sulfate reduction (SRR) are lower (~ ½ those observed for summer samples). On-going analyses will quantify the impacts of algal biomass and FFT amendments on SRR. Further, experiments assessing sulfide generation in SRB experiments fed differing sulfur compounds such as thiosulfate and elemental sulfur, (both commonly detected within the BML water cap), as well as sulfate, identified differential sulfide generation (and therefore subsequent oxygen consumption), dependent on which sulfur species was added. These results add to the growing evidence identifying a complex sulfur cycle occurring in BML that involves multiple possible sulfur compounds. Ongoing and future experiments are focused on quantifying rates of sulfur reduction (SRR) and oxidation (SOR) and associated oxygen consumption (OCR). These experiments will identify important controls on these processes and how sulfur-reducing and sulfur-oxidizing pathways interact and quantify how they collectively influence oxygen concentrations.

Results developed in 2021 have finalized the overall 16S survey of BML water cap microbial communities for every sample (year, month, depth) collected since 2015. Thus, we have a developmental trajectory of the microbial community structure and functional repertoires from 2015-

2021. Preliminary analyses indicates that the communities are changing rapidly, in line with the observed rapid changes in geochemistry occurring in BML over this time, identifying 3 discrete microbial community phases: 1) 2015-2016 pre alum community; 2) 2017-2020 post alum community; and 3) 2021 discretely different community from the previous three years. These results suggest BML is a system still in development with rapidly adapting microbial communities responding to physico-chemical and geochemical changes. All BML samples are divergent from Beaver Creek Reservoir microbial communities, indicating that while BCR may be a source of some microbes to BML, the physico-chemical and geochemical characteristics of BML is uniquely shaping its endemic microbial communities. BML microbial communities across all years and depths sampled, contain comprehensive metabolic functionalities including photoautotrophs, fermenters, methano/methyl-trophs, heterotrophs, sulfur oxidizers, sulfur reducers and a variety of unknown, unclassified organisms. However, the relative abundances of these functional groups change, suggesting interactive and dynamic alternations in linked carbon, sulfur, nitrogen, and oxygen cycling. Ongoing bioinformatics analyses on metagenome samples collected post alum will be combined with these 16S microbial survey results, geochemical field characterization and biogeochemical changes in OCR, SRR and SOR experiments to more fully identify the biogeochemical processes involved, associated controls and collective dynamic impact on BML oxygen levels.

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

This project has been ongoing for a number of years and has provided much insight into the development of the microbial (bacterial and microbial eukaryotes) community. The project has three main objectives:

1) To monitor the development of the microbial community (bacteria and microbial eukaryotes) in BML over time, and compare it to adjacent natural habitats (e.g., Beaver Creek Reservoir, BCR) and active tailings ponds (e.g., Mildred Lake Settling Basin, MLSB).
2) To understand the role of algae in the carbon cycle of BML. The lake may be transitioning from a primarily organotrophic system based on hydrocarbon degradation to a primarily phototrophic system based on algal primary productivity. This may change parameters such as oxygen status and nutrient cycling.
3) To understand the roles of some abundant microbial groups (methanotrophic bacteria and phototrophic algae) in bioremediation of organic pollutants. This may inform adaptive management strategies to maximize biodegradation activity.

DNA sequencing of 2021 samples is still ongoing and will be completed in, 2022, followed by analysis and interpretation. Results from this program are similar to previous years, but the data are more comprehensive. Although BML communities are highly variable in time, they are unique compared to communities in a tailings pond (MLSB) and communities in a more natural water body (BCR). Statistical analysis has identified some species (bacterial and eukaryotic) that are similarly abundant between BML and BCR, and others that are similarly abundant in BML vs MLSB. Certain “indicator” species that are typical of BCR but not MLSB appear to be increasing in BML over time, particularly some diatoms. Species diversity of eukaryotes, methanotrophic bacteria, and algae in BML are increasing slightly over time. Total algal cell counts are increasing over time since 2016. Major algal species cycle in repeatable seasonal patterns, a pattern typical of many natural boreal lakes. Methanotrophic bacteria show regular seasonal and spatial patterns, becoming abundant in winter and spring and less abundant in summer. Methanotroph populations in surface sediment are 2 to 4 orders of magnitude greater than in the water column, supporting other evidence that this is the main site of methane oxidation, especially during summer stratification. Methane oxidation in the water column is most important in fall and winter.

8.6 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.

8.7 Characterization of organic compounds and naphthenic acids in Base Mine Lake: Implications to methane production, transport, oxygen consumption and naphthenic acid persistence (Slater, Mumford: McMaster)

This laboratory based study focuses on an experimental approach to characterize the impacts of methane ebullition from sediment on gas exchange and potential for organic transport within the overlying water column in laboratory analogues relevant to Base Mine Lake (BML). Results of experiments in large-scale columns (bubble towers), will be used to understand fundamental processes related to bubble size and release frequency during ebullition, and to provide detailed datasets of water column gas exchange.

These laboratory experiments have three main objectives: 1) to investigate the relationship between sediment depth and gas release characteristics, including gas bubble size, bubble release frequency and gas pressure, 2) to measure the mass exchange between rising bubbles and dissolved gases in the water column, and 3) assess the potential for gas bubbles to facilitate the transport of other organic compounds out of the sediment. This work will be linked to other research and monitoring programs on the full-scale lake.

Progress in 2021 was significantly impacted by the COVID-19 pandemic both from the standpoint of decreased laboratory and field access, but also due to shutdown related performance issues for the GCxGC system, the core of much of the analytical work. Despite being repaired twice the GCxGC system still requires one turbo-pump be replaced. This repair has been initiated and should be completed in the first month of 2022.

Previously completed bulk and chromatographic characterization of organic compounds in the upper FFT were compiled to assess patterns in distribution and fingerprints as a starting point for the spatial and temporal comparison planned for this work. Preliminary evidence indicates losses of low molecular weight organic compounds in the upper FFT (~1 m below the mudline) at two sites, despite increases in overall total organic carbon presence. This contrast indicates loss of organics in the upper FFT that are likely due to microbial biodegradation. It is also possible that these losses may contributed to by stripping during ebullition of biologically produced methane. The latter process would be expected to result in transport of these compounds to the water column.

In contrast to this observation a high-resolution comparison of chromatographically well resolved PAHs across the upper FFT showed no evidence of trends with depth at P1, P2 and P3. This indicates that losses are not occurring for these compounds, which may be due to their lower biodegradability.

Continued analysis of NA distributions in the water column and comparison of these fingerprints with potential sources of NA to BML is underway. This analysis has shown that the BML NA are stable over a period of 4 years. Comparison with FFT has confirmed that there are distinct fingerprints and higher concentrations of NA in the FFT pore water as compared to the water column. This implies that inputs of NA are occurring from the FFT during pore water advection, diffusion or ebullition. The stability of water column NA profiles, despite these inputs, indicates biodegradation is occurring in the water column.

Further comparison of NA fingerprints to OSPW and raw bitumen samples was undertaken. Comparability in concentration ranges and distinct fingerprints between OSPW and BML water column indicated that the OSPW was not the source of NA in the water cap. Initial OSPW was diluted with fresh water when BML was commissioned, and thus would have been diluted. Notably, OSPW samples had lower concentrations of NA relative to FFT. This could be due to temporal variability but may also be due to biodegradation of PH producing NA in the FFT.

To further understand potential biodegradation, high resolution MS analysis of BML FFT and water column samples was used to search for hydroxyl compounds, hydroxylated NAs and NAs indicative of production during biodegradation. This investigation yielded no resolvable evidence for hydroxylated compounds or aldehydes or ketones. It was possible to identify succinates within the FFT, indicative of biodegradation of petroleum hydrocarbons occurring within the FFT. Within the water cap, observation of C12 and C13 adamantane diacids was consistent with aerobic degradation of related NA.

These are preliminary results and work is expected to continue through 2022 to continue the laboratory experiments to refine results and interpretation. Plans are underway to use Fourier Transform Ion

Cyclotron Resonance Mass Spectrometry (FTICRMS) one of the highest resolution mass spectrometry techniques, to characterize the NA in the BML water column and representative FFT samples. The processing of the initial dataset is underway to determine what information concerning the distribution of polar organics could be gleaned from this perspective. Microcosm incubation experiments have also been initiated to attempt to directly assess methane production from upper FFT, using FFT samples collected from BML in 2021.

8.8 Base Mine Lake Process Dynamics (Bara, Syncrude)

This research is focused on understanding the mechanisms and mitigation of bitumen liberation from mats on the FFT surface. A significant effort has been underway to delineate and understand the extent of bitumen mats on the FFT surface. Residual naphtha in these mats are consumed by methanogenic microbes, producing methane gas. The gas bubbles can be coated in bitumen and when released, carry bitumen to the water surface resulting in a hydrocarbon sheen. This sheen can drift into the shoreline where it coats plants and sediments.

Observations from the Base Mine Lake research and monitoring program have indicated that ice cores from BML can show both gas bubbles and bitumen (see section 4.3.3.2) and could be a useful method for tracking changes in bitumen liberation resulting from removal of the bitumen mats through dredging. The challenge was making these qualitative assessments quantitative. This program was developed using a CT scanning method for the ice cores which allows quantification of gas voids and bitumen (see Figure 4-5 for images of ice cores). A method for reliable analysis of the Oil-Water-Solids content of the cores was also developed. This ice core method has become a key component of monitoring effects of bitumen mat dredging activities on gas and bitumen liberation to the water column.

8.9 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: Hurley, D., Lawrence, G., and Tedford, E. (2020). Effects of Hydrocarbons on Wind Waves in a Mine Pit Lake. Mine Water and the Environment. 39. 10.1007/s10230-020-00686-7. 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

Zhao, K., Tedford, E., and Lawrence, G. (2022). Ebullition Regulated by Pressure Variations in a Boreal Pit Lake. Frontiers in Earth Science. 10. 0.3389/feart.2022.850652.

Zhao, K., Tedford, E.W., Zare, M., Frigaard, I.A., and Lawrence, Greg. (2021). Bubbles rising through a layer of Carbopol capped with water. Journal of Non-Newtonian Fluid Mechanics. 300. 104700. 10.1016/j.jnnfm.2021.104700.

Theses:

Chang, Sarah. 2020. Heat budget for an oil sands pit lake. M.Sc. Thesis, University of British Columbia. http://hdl.handle.net/2429/75704

Hurley, David Lee. 2017. Wind waves and Internal Waves in Base Mine Lake. M.Sc. Thesis, University of British Columbia. 91 pp. http://hdl.handle.net/2429/62524

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.

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Theses:

Dompierre, Kathryn. 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.

Francis, Daniel, J. 2020. Examining controls on chemical mass transport across the tailings-water interface of an oil sands end pit lake. M. Sc. Thesis, University of Saskatchewan, Saskatoon, Canada, 177 pp. https://harvest.usask.ca/handle/10388/12776

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.

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

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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:

Arriaga D, Nelson TC, Risacher FF, Morris PK, Goad C, Slater GF, Warren LA. 2019. The co-importance of physical mixing and biogeochemical consumption in controlling water cap oxygen levels in Base Mine Lake. *Appl Geochem* 111:104442.

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El-Waraky, M., D. Bowman, R. Nelson, C. Reddy, L.A. Warren and G.F. Slater, 2022. Initial characterization of the identity and biodegradation potential of the hydrocarbons in fluid fine tailings underlying an end pit lake (submitted)

Jessen, G.L., Chen, L-X., Mori, J.F., Colenbrander Nelson, T., Slater, G. F., Lindsay M.B.J., Banfield, J. F., and Warren, L. A. 2022. Alum addition triggers hypoxia in an engineered pit lake. Microorganisms 10(3) 510. https://doi.org/10.3390/microorganisms10030510

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Understanding Air-Water Exchanges and the long-term hydrological sustainability of Base Mine Lake: McMaster University, Carleton University

Publications:

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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.

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