B.C. Works'
Sulphur Dioxide Environmental Effects Monitoring Program

2023 Annual Report, Draft V.2

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Version Tracking Table

No.	Date	Summary of content /changes
V.1	April 19, 2024	Draft for review by Rio Tinto
V.2	May 31, 2024	Draft for review by B.C. Ministry of Environment and Climate Change Strategy (B.C. ENV)
V.3		Draft for review by Rio Tinto with edits per ENV comments
V.4		Final for B.C. ENV

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Executive Summary

ATMOSPHERIC PATHWAYS

The atmospheric pathways activities implemented in 2023 were:

- continuous SO_2 monitoring and analysis
- passive SO_2 sampling and analysis, and
- sulphur deposition monitoring and analysis.

All **continuous SO_2 analyzers** passed B.C. ENV's audits and had greater than 90% data capture for SO_2 in 2023. However, the 2023 datasets have not yet been validated by B.C. ENV. Therefore all 2023 relevant datasets are considered preliminarily valid for comparisons to the 1-hour and annual average SO_2 Canadian Ambient Air Quality Standards (CAAQS).

Generally, Haul Road concentrations trend closely with SO_2 emissions from the smelter, while stations farther from the smelter change more noticeably due to seasonal weather patterns than to changes in SO_2 emissions.

As in prior years, ambient concentrations of SO_2 remain low (below 4 ppb) most of the time, and higher concentrations occur infrequently.

Annual average and 99th percentile of 1-hour daily maximum monitored concentrations aligned closely with model results in 2023, with slight to moderate overprediction at all sites except Kitamaat Village for 1-hour 99th percentile regional-scale. Overall, these comparisons are consistent with the discussion in the 2019 Comprehensive Review (ESSA et al., 2020a) that predicted modelled concentrations in most areas are higher than measured concentrations, resulting in cautious risk assessments. Model underpredictions at Haul Road in 2022 differed from the patterns observed in 2023 and historic years (when model predictions were greater or equal to monitored values). The return to typical patterns (general overprediction) in 2023 supports the previous report's hypothesis that the underprediction in 2022 was likely an artifact of the model scaling method with several months at very low SO_2 emission levels rather than the possibility that the model's relationship to monitored data changed meaningfully.

The network of **passive samplers** was redeployed in the Kitimat Valley during 2023 following the same procedures as in 2016-2022. Deployment started in May 2023 at 22 sites within the Kitimat Valley, primarily focused along the Wedeene and Bish roads to capture the plume path. Over 200 sample exposures were collected and analysed. The 2023 results are similar to the 2021 and 2022 observations, although concentrations in 2022 were lower as expected during the low emission levels from the smelter in 2022. The spatial pattern is consistent with previous years.

Continued deployments are recommended during 2024 to further define the plume path.

Preliminary data **sulphur wet deposition** monitoring in 2023 show that average annual precipitation volume was consistently higher at Haul Road compared to levels at Lakelse Lake during 2014–2023. During 2023, precipitation volume at Haul Road (2007 mm) and at Lakelse Lake (1366 mm) were slightly lower than the ten-year average, and the relationship between the two stations was consistent with past years. Higher weekly sulphate concentration (mg/L) and lower pH was observed at Haul Road compared with Lakelse Lake. The higher SO_4 and lower pH in rainfall at Haul Road are caused by the higher atmospheric concentration of SO_2 and corresponding higher S deposition at Haul Road. Higher rainfall volume and higher sulphate concentration observed at Haul Road combines to result in a more pronounced wet S deposition difference compared with Lakelse Lake on an annual and weekly basis.

Total mass of **SO_2 dry deposition** was calculated based on modelled dry deposition velocity and measured ambient SO_2 concentrations. The 'big-leaf' model was used to estimate hourly species-specific dry deposition velocity at four stations in the Kitimat Valley (Haul Road, Whitesail, Lakelse Lake, and Terrace Airport [YXT]) using 2023 meteorological data. Total mass of SO_2 dry deposition tended to be more heavily influenced by monitored SO_2 concentration at each site versus changes in SO_2 deposition velocity. This difference in SO_2 concentrations is clearly the reason for elevated dry deposition mass at Haul Road compared to other sites. Similarly, dry deposition rates at all sites increased in 2023 compared to 2022 due to the higher SO_2 concentrations and higher SO_2 emission rates from the smelter in 2023. Similar ratios of wet versus dry S deposition occur during each year from 2016 – 2023 at Haul Road.

There is no **KPI** for atmospheric pathways. The results from analyses of the atmospheric pathways line of evidence are inputs to the KPIs for the human health, terrestrial ecosystems, and aquatic ecosystems lines of evidence.

HUMAN HEALTH

Starting January 1, 2020, the SO_2 health KPI implemented the SO_2 Canadian Ambient Air Quality Standards (CAAQS). In 2023 the CAAQS value was 70 ppb, and in 2025 the CAAQS value changes to 65 ppb. The SO_2 health KPI is used to assess residential SO_2 ambient air quality. The SO_2 Health KPI for 2023 is a threshold for residential SO_2 ambient air concentration of 70 ppb and is evaluated as defined in the B.C. Air Quality Objectives.

For 2023 the **KPI** is calculated as the 3-year average of the annual 99th percentile of the D1HM (maximum daily 1-hour concentrations of SO_2) using validated data for years 2021 and preliminary data from 2022 and 2023. The 2023 KPI calculation results for Kitamaat Village, Riverlodge, Whitesail, and Industrial Ave were all well below the KPI (CAAQS value of 70 ppb) and, as such, demonstrate attainment of the KPI.

TERRESTRIAL ECOSYSTEMS

Most of the terrestrial ecosystems work done in 2023 was under the **Vascular Plant and Cyanolichen Biodiversity Monitoring Program (PCMP)**.

Activities for the vegetation component of the SO_2 EEM Program in 2023 included the first assessment of eleven field plots (i.e., the completion of final third of the full set of 33 PCMP sites), and analysis and presentation of results in the March 2024 submission of the third annual report and first end-of-cycle report for the PCMP. As part of the regular PCMP activities, an assessment of vegetation and cyanolichen health was undertaken at all eleven assessed plots in the Kitimat-Terrace valley. Reconnaissance for ten new alternate sites (for a current total of twelve) in the Kitimat Valley was also completed in 2023. As 2023 represented the first complete end-of-cycle, additional efforts were made to examine potential risks and explore recommendations for improving sampling design and subsequent analysis.

Vegetation health inspections were undertaken as part of regular PCMP assessments at the eleven 2023 sites in the Kitimat Valley. Cyanolichen health inspections are part of the cyanolichen assessment portion of the PCMP, and these inspections were also made at the 11 plots assessed in 2023. Overall, no patterns related to plant or cyanolichen health and deposition category were noted based on these inspections for 2023, or for the PCMP sites to-date.

The major components of biodiversity are species richness and abundance (or evenness), which were both assessed in 2023, as in the preceding two years, for plants in the low shrub and herb layers. As expected, no trends between deposition zones are noted in initial plant biodiversity results. These data generally show that cyanolichen diversity is inversely proportional to increasing deposition zone (largely as an historical artifact of fluoride emissions); however, the data also demonstrate the stochastic nature of this metric (e.g., if a host tree is lost from a plot, a dramatic shift in recorded cyanolichen diversity may occur).

The Program is designed to detect potential *differential trends* across deposition zones in the biodiversity of vascular plants in the low shrub and forb layers, and of arboreal cyanolichens, in forest ecosystems of the Kitimat Valley. As only one assessment of each site has been made at this first end-of-cycle juncture, it is not yet possible to analyse those trends for species and sites. Instead, we have taken advantage of the moment to examine the balance of the sites in relation to deposition zones, and determine if there are any initial trends to be aware of. Results from this exercise have shown that the design of the project appears to be robust to individual site differences, and that many species overlap sites across the deposition zones, which will aid future trend analysis comparisons. This deeper dive into the data has resulted in a number of recommendations, and also assurance that the Program is on a good footing going forward: After the collection of three years of data, we find that the results support the goals and objectives of the monitoring program.

Soil samples were collected and analysed for pH, exchangeable cations and exchangeable acidity at all established sites where collection was possible in 2022, and thus no soil sampling was undertaken in 2023: Each site that is actively in the program (i.e. has been fully assessed) has now also had a baseline soils assessment (with the exception of one site where organic depth precluded mineral soil sampling). From the results of the analyses, sensitivity to acidification can be ranked.

Plant and cyanolichen health and diversity are informative indicators for effects of SO_2 emissions from the smelter. With respect to the Evidentiary Framework, no Vegetation Health indicators have achieved the threshold for increased monitoring or mitigation and, as we have only completed the first complete cycle of measurements, there cannot yet be analysis of trend lines for vegetation, therefore there can be no triggers at this point in the Program.

The **KPI** of Critical Load Exceedance from modelled atmospheric S deposition will not be assessed for attainment during Phase III of the EEM Program (as noted in the Phase III Plan). The Phase III Comprehensive Review will assess if a KPI can be established for the plant biodiversity component of the terrestrial ecosystems line of evidence.

In 2023 the **permanent long term soil sample plots** were re-sampled according to the 5-year resampling schedule. Analysis of the soils will be completed in 2024 and the assessment of the long-term soil acidification KPI will be presented in the 2024 SO_2 EEM Annual Report.

Field sampling in 2023 also occurred for projects on **wetland geochemistry and aluminum solubility in soils**, as recommended in the 2019 Comprehensive Review. Organic soil and pore water were collected from nine wetland locations within the study domain of the SO_2 EEM program. Wetland soils were sampled following established procedures and wetland classification was based on the average pH of their organic soil. There were three sites for each wetland type (bog, poor fen, intermediate fen). The aluminium solubility study focuses on mineral soils, defined as soils with an organic matter content below 40%. Selection of the sampling sites focused on soils previously sampled under several monitoring programs in the Kitimat Valley. All samples for both projects were shipped to Trent University for chemical analysis, and results will be reported in the 2024 SO_2 EEM Annual report.

AQUATIC ECOSYSTEMS

The sampling in 2023 was conducted in the regional context of exceptionally dry hydrologic conditions and a substantial increase in emissions from the very low levels following the labour dispute in 2021. By August 2023, emissions had returned to 32.1 tpd, similar to the annual average of 30.2 tpd observed in 2019. Either of these regional drivers could potentially have a notable influence on lake chemistry; however, overall, the observed patterns do not clearly indicate greater influence of hydrology or emissions on the 2023 lake chemistry for the sensitive lakes. For some metrics and some lakes, the observed changes may reflect the combined influence of both of these regional factors or even that neither of these factors had a dominant effect this year. Considering the multi-year context, the potential strength of influence of both these factors could plausibly be less than otherwise expected – i.e., the 2023 dry conditions follow dry conditions in 2022, so the relative difference is less; the average emissions levels in the year preceding lake sampling in September 2023 are much higher than for 2022 but similar to 2021.

Most of the seven sensitive lakes showed increases in CBANC, Gran ANC, BCS and pH between the pre-KMP baseline (2012) and the last three years (2021-2023, used to represent current post-KMP conditions). LAK012 and LAK028 are the only two lakes that show a long-term decline in CBANC (Table 3-9). For LAK012, the decline since 2012 (-12.5 µeq/L) is still above the lake-specific *change limit* threshold (-16.3 µeq/L) and the current mean CBANC (102 µeq/L) is well above the *level of protection* threshold (20 µeq/L)[1]. For LAK028, the decline since 2012 (-0.7 µeq/L) is still above the lake-specific *change limit* threshold (-13.4 µeq/L) and the current mean CBANC (15.3 µeq/L) is below the *level of protection* threshold (20 µeq/L), and similar to the 2012 baseline (16.0 µeq/L). LAK012 and LAK028 also continue to be the only two sensitive lakes with a long-term decline in BCS, but neither lake exceeds both thresholds for BCS. None of the seven sensitive EEM lakes show a long-term decline in Gran ANC or pH.

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[1] The SO_2 EEM Program Phase III Plan uses a two-threshold structure, including both a *level of protection* threshold (to prevent acidification of lakes not at risk of aquatic impacts) and a *change limit* threshold (which prevents further acidification of lakes already below the level of protection due to natural organic acids or past acidic deposition). A lake must exceed both thresholds for CBANC to exceed the KPI. See Table 3-11.

Using the established statistical analysis methods, we evaluated the KPI and the informative indicators using the two-threshold structure (Table 3-10). None of the 11 EEM lakes have a high % belief in exceedance of the KPI or any of the informative indicators. None of the 11 EEM lakes have even a moderate % belief in exceedance of the KPI – **all lakes show a low % belief in exceedance of the CBANC KPI**. However, two sensitive EEM lakes and one control lakes show moderate % belief of one or two of the informative indicators:

- LAK022 shows moderate % belief in exceedance for pH
- LAK028 shows moderate % belief in exceedance for BCS
- NC184 (a control lake) shows moderate % belief in exceedance of Gran ANC and pH (unrelated to sulphur from the smelter, since [SO_4] has not increased)

The mean values of CBANC for the 2021-2023 indicate **KPI** attainment, meaning that **there have been no exceedances of the KPI thresholds.**

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1 Introduction

The purpose of the SO_2 Environmental Effects Monitoring (EEM) Program is to monitor effects of SO_2 on human health, terrestrial ecosystems, and aquatic ecosystems. Results from the SO_2 EEM Program will inform decisions regarding the need for changes to the scale or intensity of monitoring, as well as decisions regarding the need for mitigation. The SO_2 EEM Program includes impact threshold criteria either for emission reduction or other mitigations that, when exceeded, would trigger emission reduction and/or other mitigation.

The SO_2 EEM Program is structured around the conceptual model shown in Figure 1-1.

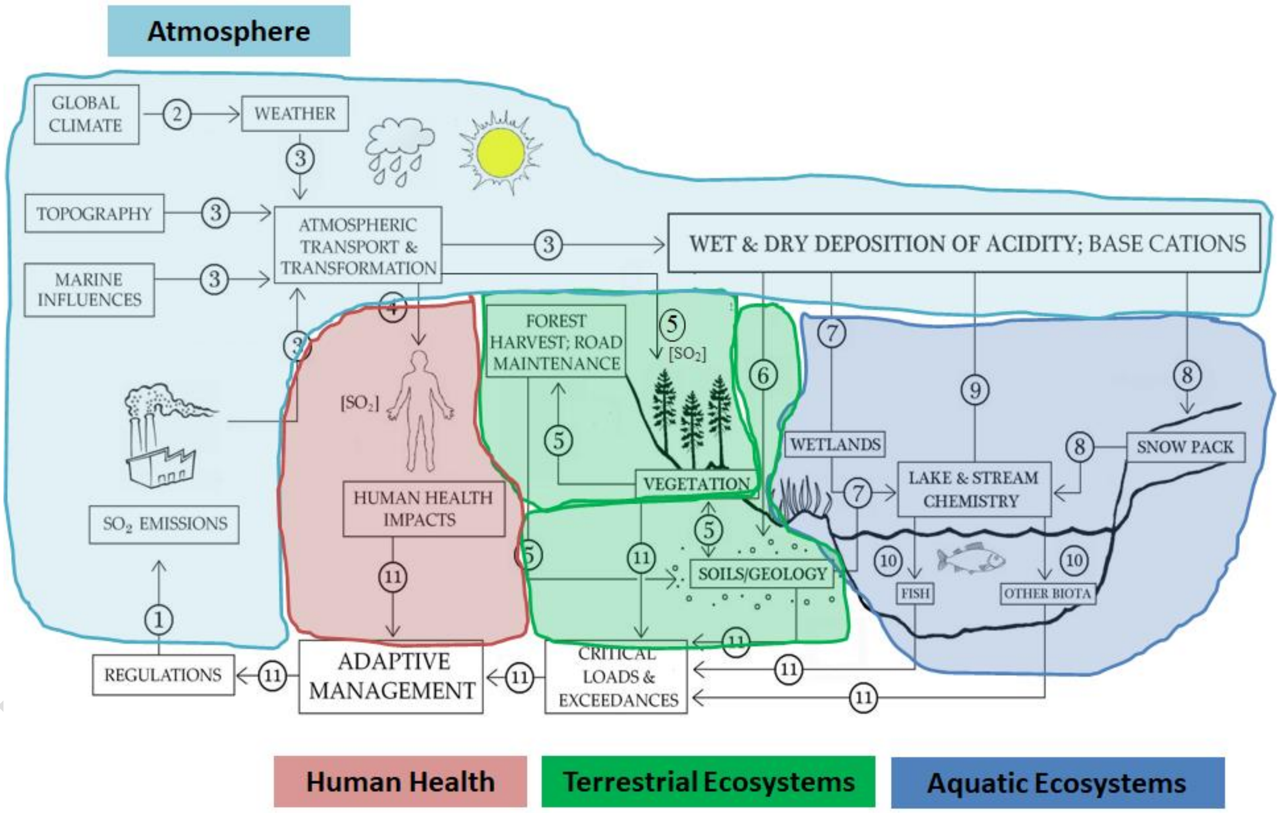

Figure 1-1. Conceptual (source-pathway-receptor) model of SO_2 emissions in the environment, showing linkages between sources and receptors. Source: Figure 1-1 from ESSA et al., 2020a.

This document comprises the SO_2 EEM Program 2023 Annual Report. It is organized into sections according to the pathway and receptor lines of evidence depicted Figure 1-2. The SO_2 EEM Program Annual Report for 2024 will be prepared in the spring of 2025.

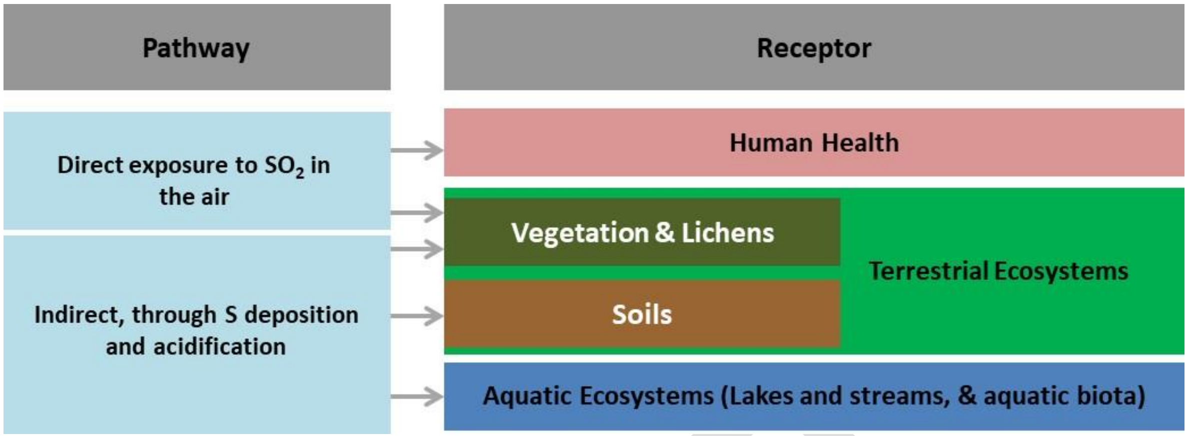

Figure 1-2. Organization of the five lines of evidence in the SO_2 EEM Program.

2 Facility Emissions

Average annual emissions of SO_2 from the Kitimat smelter increased from the 7.4 t/d average rate in 2022 to an average rate of 25.8 t/d in 2023 (Figure 2-1). SO_2 emissions in 2023 remained below the 42 t/d permit limit. SO_2 emissions were below the normal emission range due to the continuation of the smelter restart, which saw the coke calciner restarted at the end of March and last pot restarted in August. SO_2 emissions started to ramp-up with the restart of the anode baking furnace and the restarts of the aluminium smelting pots (an average of 0.75 pot start per day). As pots were being brought online, SO_2 emissions increased proportionally with the increased consumption of anode carbon (Figure 2-2).

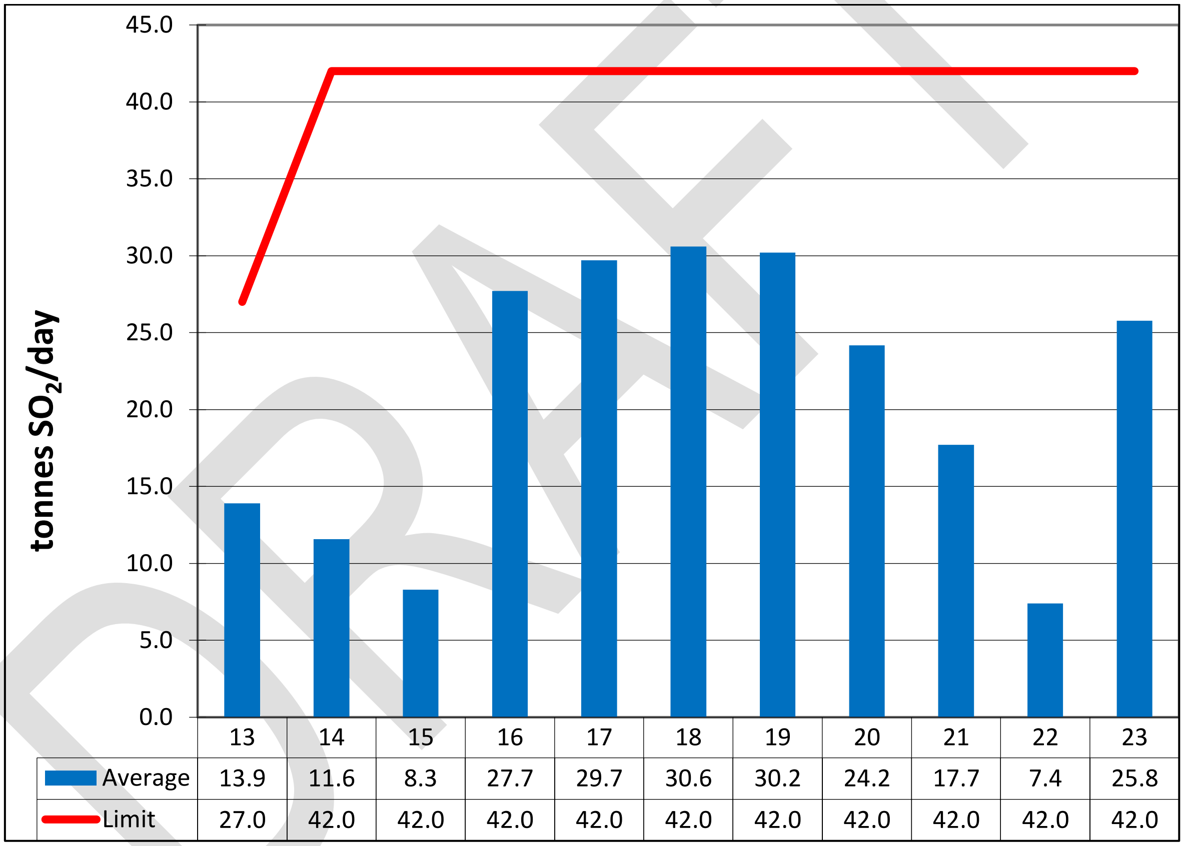

Figure 2-1. Annual SO_2 emissions from the Kitimat smelter from 2013 to 2023. (Source: Rio Tinto)

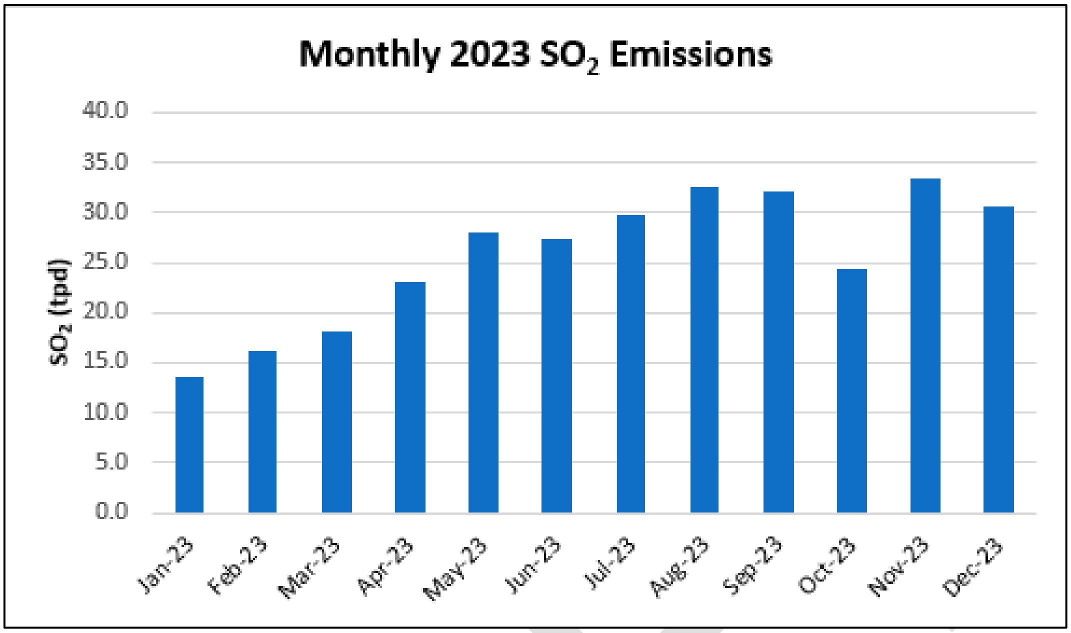

Figure 2-2. Average monthly SO_2 emissions from the Kitimat smelter throughout 2023. (Source: Rio Tinto)

3 EEM Activities

3.1 Atmospheric Pathways

3.1.1 SO_2 Concentrations – Continuous Monitoring

Continuous SO_2 monitoring data were collected from six existing continuous analysers: Haul Road (fenceline), Riverlodge (lower Kitimat), Whitesail (upper Kitimat), Kitamaat Village, Lakelse Lake[2], and Industrial Avenue (Figure 3-1). A seventh station (not pictured) was established in 2015 by the B.C. Ministry of Environment and Climate Change Strategy (B.C. ENV) in Terrace that can also be used to help assess SO_2 emissions from the smelter. The newest continuous SO_2 monitoring station was established in Service Centre (Industrial Avenue) in May 2020. The continuous air quality monitoring stations record hourly observations of SO_2. They provide information on air quality in the area on an ongoing basis and will provide important data for many EEM activities over the next several years.

All SO_2 analyzers passed B.C. ENV's[3] audits and had greater than 90% data capture for SO_2 in 2023. However, validated continuous SO_2 data are not available from the B.C. ENV until late in the following year or sometimes later. Validated datasets have not yet been completed and posted for 2022 or 2023. Therefore, all 2022 and 2023 relevant datasets are considered preliminarily valid for comparisons to the 1-hour and annual average SO_2 Canadian Ambient Air Quality Standards (CAAQS). The continuous SO_2 data summarized in this report include final, post-validated data for 2021 and prior years and preliminary data for 2022 and 2023.

Figure 3-2 shows the pattern of the monthly average SO_2 concentrations at the seven continuous monitoring stations from 2013 through 2023, along with monthly SO_2 emissions over the same period. Figure 3-3 presents the same data without the Haul Road and Industrial Avenue stations in order to show the detailed changes at the lower concentrations. Figure 3-2 shows that the Haul Road concentrations generally trend closely with SO_2 emissions from the smelter. Figure 3-3 (without Haul Road) shows that stations farther from the smelter change more noticeably due to seasonal weather patterns than due to changes related to SO_2 emission levels. Even when smelter SO_2 emissions decreased drastically in August 2021, concentrations at Riverlodge, Whitesail, Kitamaat Village, Lakelse Lake, and Terrace were not substantially lower than concentrations during previous years' fall and winter months. While less noticeable, the spring-summer concentrations were lower in 2022 and returned to typical levels in 2023 at these stations.

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[2] The sole purpose of the Lakelse SO_2 analyzer is for estimating dry deposition and is not included in air quality monitoring network for British Columbia.

[3] B.C. Ministry of Environment and Climate Change Strategy (ENV) conducts audits on all monitoring stations within the network; however, since the Lakelse Lake monitor's purpose is for estimating dry deposition, it is not within the network and not audited by ENV.

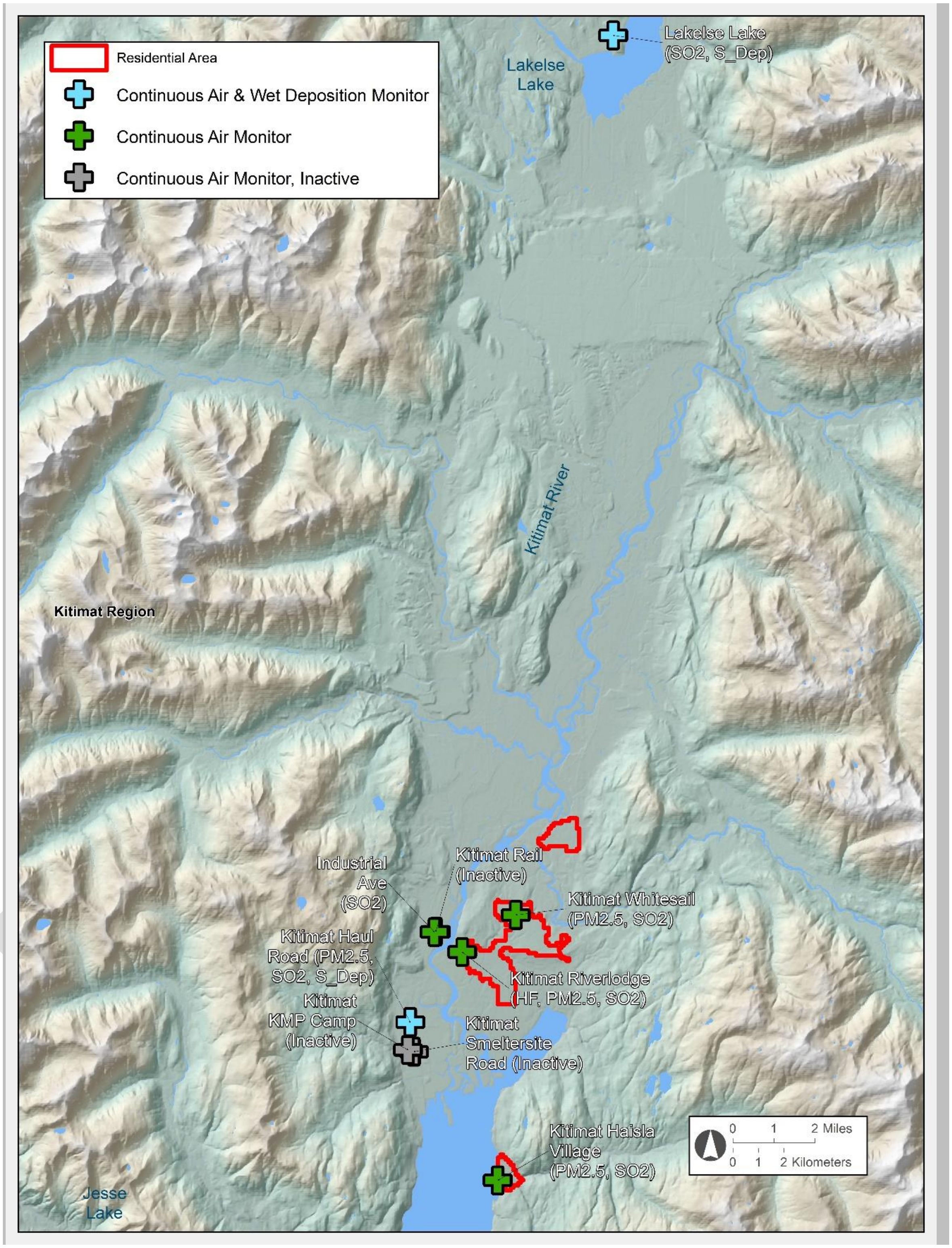

Figure 3-1. Locations of the six Rio Tinto continuous SO_2 analysers (Haul Road, Whitesail, Riverlodge, Kitamaat Village, Industrial Ave, Lakelse Lake).

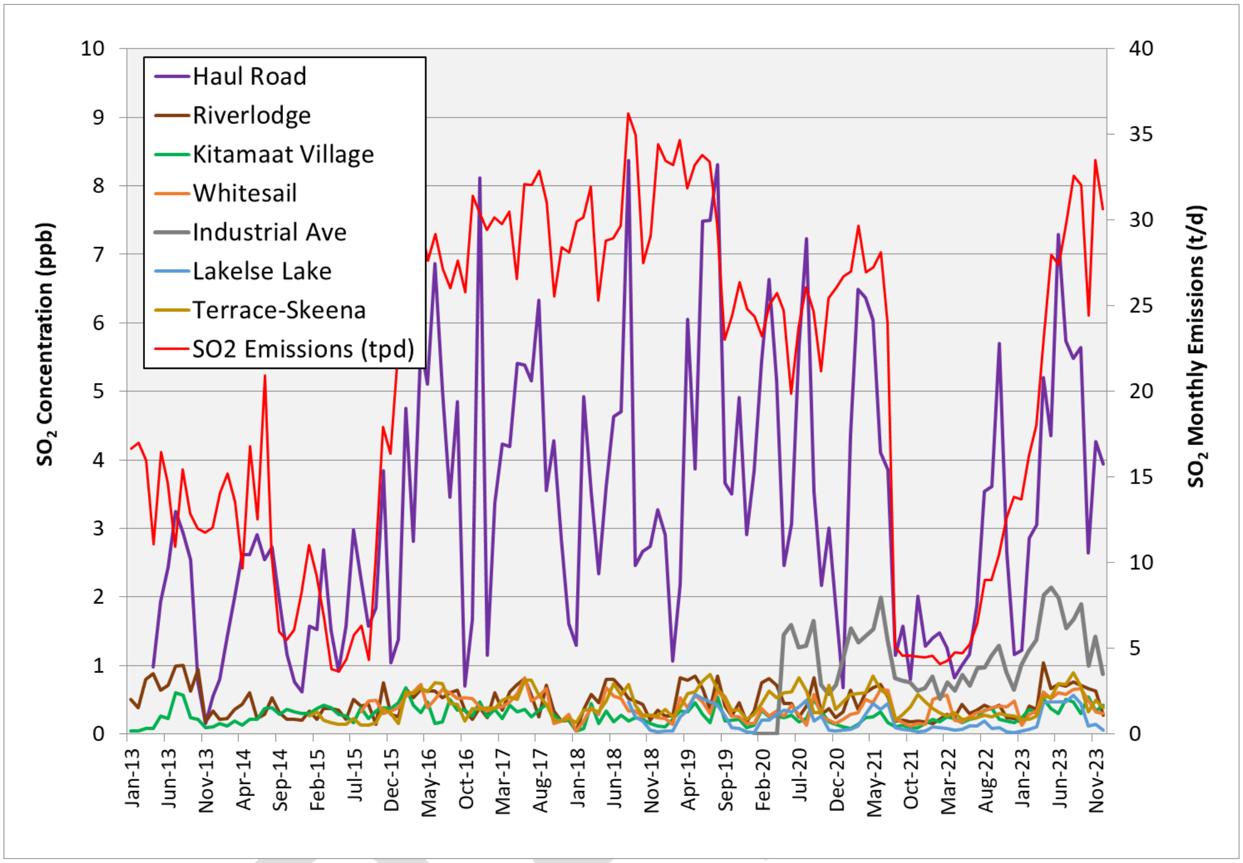

Figure 3-2. Monthly SO₂ emissions (red line) and monthly average ambient SO₂ concentrations at the seven continuous monitoring stations (purple, brown, green. orange, grey, blue and gold lines) for 2013 to 2023. (Source: Rio Tinto and Envista database)

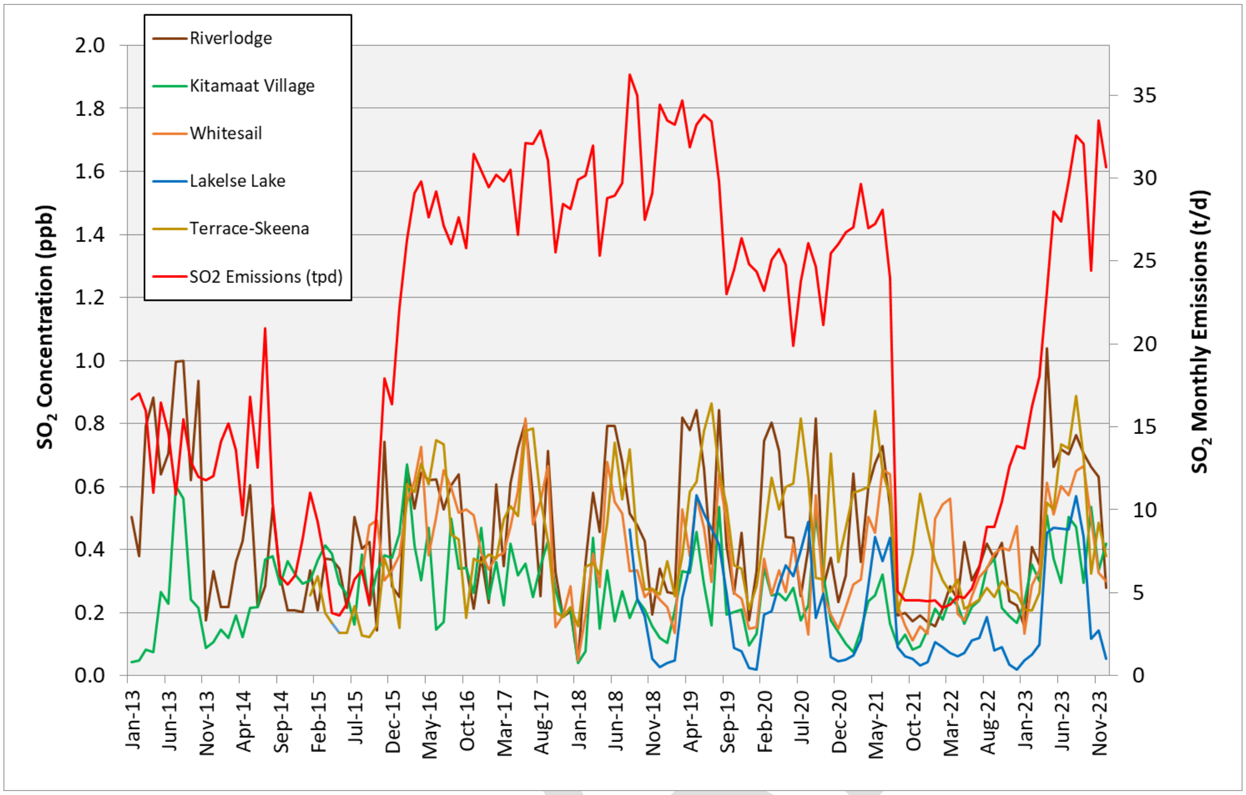

Figure 3-3. The same monthly SO_2 emissions (red line) and monthly average ambient SO_2 concentrations data as in Figure 3-2 but excluding the Haul Road and Industrial Avenue stations in order to show the detailed changes at the lower concentrations. (Source: Rio Tinto and Envista database)

Figure 3-4 shows a histogram depicting the relative frequency of hourly averaged concentrations of SO_2 at Haul Road (fenceline), Riverlodge (lower Kitimat), Whitesail (upper Kitimat), Kitamaat Village, and Industrial Avenue (Service Centre).[4] Low concentrations (below 4 ppb) occur most of the time (high frequency), and higher concentrations occur infrequently.

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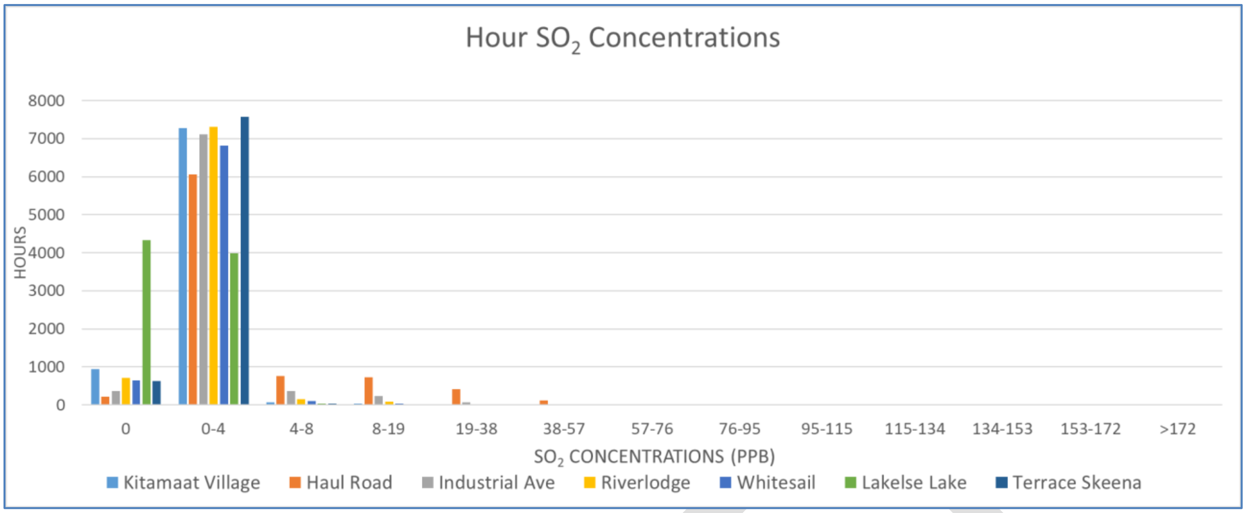
[4] The sole purpose of the Lakelse SO_2 analyzer is for estimating dry deposition and is not included in air quality monitoring network for British Columbia nor in Figure 3-4.



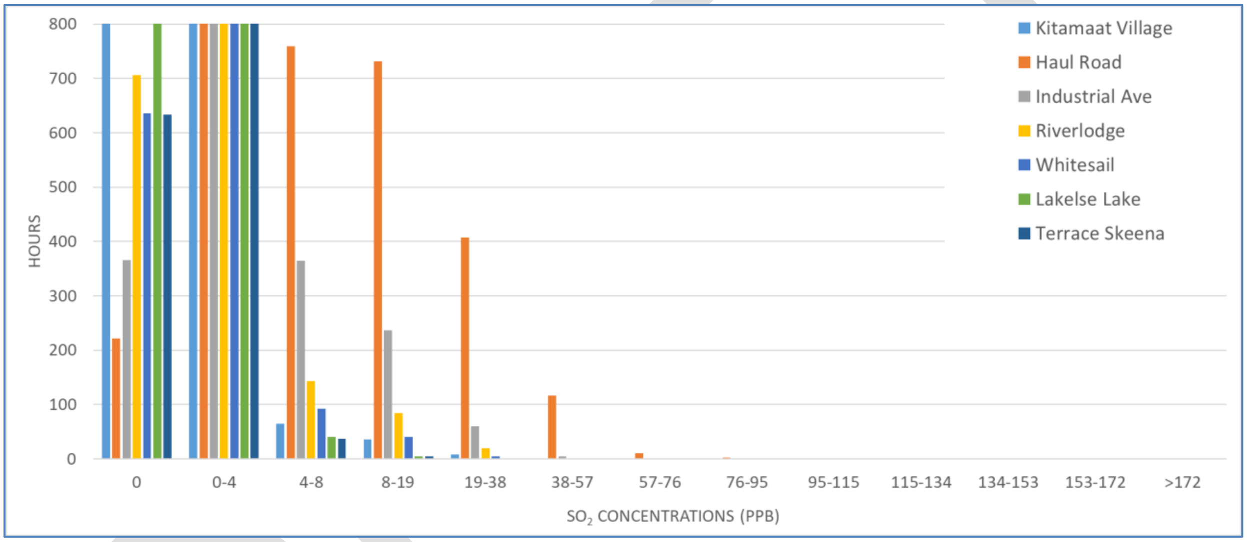


Figure 3-4. SO_2 hourly concentrations in 2023 at the Kitamaat Village, Haul Road, Industrial Avenue, Riverlodge, Whitesail, Lakelse Lake, and Terrace Skeena continuous monitoring stations (top graph). The bottom graph zooms in on the subset of the data showing lower frequencies (800 hours and less) of higher concentrations. (Source: Rio Tinto)

Comparison to the Model Output

Monitoring data collected at the four[5] monitor stations are compared to the air dispersion modelling results prepared for the EEM 2019 Comprehensive Review (ESSA et al., 2020a). The model comparisons in this section reflect the updated CALPUFF model results using corrected CALMET wind data.[6] Table 3-1, Figure 3-5, and Figure 3-6 show the comparison between monitored concentrations in 2023 and the predicted SO_2 concentrations from the air dispersion modelling analysis for 99th% 1-hour daily max and annual averaging periods. All results are in the form of the Canadian Ambient Air Quality Standards (CAAQS), which are used as the BC Air Quality Objectives for SO_2. Note that the predicted concentrations from the air dispersion modelling analysis include the more realistic background concentrations (the same background concentrations that were applied in the 2019 Comprehensive Review for the model evaluation).

As shown in Table 3-1, annual average monitored concentrations align closely with model results in 2023, ranging from approximately half of the modelled concentrations (32% at Riverlodge for both scales) to 80% (Kitamaat Village for regional-scale). The 1-hour monitored concentrations also align with model results for all stations other than Kitamaat Village regional-scale (monitored is 142% of the regional scale model). The remaining 1-hour monitor to model comparisons range from 51% (Whitesail local scale) to 80% (Haul Road regional scale). These model results represent actual emissions applying a more realistic background used for model performance evaluation. The Industrial Ave (Service Centre) station is not included in the comparison as the station was added after the modelling was completed.

Overall, these comparisons are consistent with the discussion in the 2019 Comprehensive Review that predicted modelled concentrations in most areas are higher than measured concentrations, resulting in cautious risk assessments. However, while the comparison in 2021 and 2022 continued to support the 2019 Comprehensive Review conclusions related to model performance and general overprediction, comparisons for 2021 and 2022 show lower magnitude and fewer instances of overprediction and larger magnitude and more instances of underprediction than the same comparisons for historic years. The levels of overprediction in 2023 monitoring data are more similar to historic years (2016-2020). The measured concentrations at Haul Road compared to scaled model results shows an inverse relationship in 2022 compared to most years (when monitored concentrations are slightly lower than

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[5] The four stations with complete data used for model evaluation in the 2019 Comprehensive Review are used for model comparison in this section. Other stations either have incomplete data or are too distant for comparison.

[6] CALPUFF results revised for wind corrections for all years. ENV and Trinity reviewed wind direction data in 2021 and determined that the Whitesail station was aligned to magnetic north rather than true north prior to August 2018 and that the Yacht Club station wind direction was also misaligned historically and realigned to true north in early 2019. Therefore, the wind directions recorded at these two stations needed correcting for most or all of the Comprehensive Review CALPUFF model period. In addition, Yacht Club wind speed data was be invalidated by ENV for most of 2018. Trinity conducted a study for the full CALPUFF period (2016 through 2018) using the corrected wind data. An addendum to the Comprehensive Review report (ESSA et. al., 2022) evaluated the corrected CALPUFF results for each line of evidence in order to determine if the post-correction CALPUFF results are meaningfully different than the results from the original Comprehensive Review report and whether use of the post-corrected results would lead to different conclusions in the Comprehensive Review.

scaled model results) and returned to typical in 2023. The change in comparison in 2022 was likely an artifact of the model scaling method during these two years with several months at very low SO_2 emission levels rather than the possibility that the model's relationship to monitored data has changed meaningfully. This explanation is further supported by the 2023 comparison aligning with historic comparisons.

Table 3-1. 2023 Monitored Data Compared to Modelled Concentrations.

Site[a]	Averaging Period[b] / Model	Monitored Concentration (ppb)	Modelled Concentration[c] (ppb)	Monitored Concentration (ppb)	Modelled Concentration[c] (ppb)
		2023		3-Year Average	
Haul Road	Annual/Local	4.3	6.7	3.25	4.48
Kitamaat Village	Annual/Local	0.4	0.6	0.26	0.50
Riverlodge	Annual/Local	0.6	1.9	0.43	1.33
Whitesail	Annual/Local	0.4	1.0	0.37	0.74
Haul Road	Annual/Regional	4.3	5.8	3.25	3.87
Kitamaat Village	Annual/Regional	0.4	0.5	0.26	0.42
Riverlodge	Annual/Regional	0.6	1.9	0.43	1.31
Whitesail	Annual/Regional	0.4	1.1	0.37	0.81
Haul Road	99% 1HDM/Local	69.9	103	65.4	68
Kitamaat Village	99% 1HDM/Local	21.2	31	13.4	21
Riverlodge	99% 1HDM/Local	27.3	39	22.1	26
Whitesail	99% 1HDM/Local	20.8	41	14.0	28
Haul Road	99% 1HDM/Rgnl	69.9	87	65.4	58
Kitamaat Village	99% 1HDM/Rgnl	21.2	15	13.4	10
Riverlodge	99% 1HDM/Rgnl	27.3	35	22.1	24
Whitesail	99% 1HDM/Rgnl	20.8	28	14.0	19

[a] Industrial Ave station was not in operation in 2016-2018; therefore, the site is not included in this model comparison. The site is included in the comparison to the human health KPI in Section 3.2.

[b] Averaging periods and forms of results correspond to the CAAQS. 1HDM = 1-hour averaging period, daily maximum

[c] Modelled concentrations are based on results from the actual scenario using actual emissions for 2016, 2017, 2018, based on updated model from wind correction performed in 2021. For 2019 forward, the 3-year average actual model results are scaled from 2016-2018 average emissions to current year emission.

The following background value from Williams Lake is added to account for non-modelled sources of SO_2 (for 2019 forward, note the background is added after scaling model results).

Annual Average	0.26	ppb
99th% 1-hour Daily Max	1.80	ppb

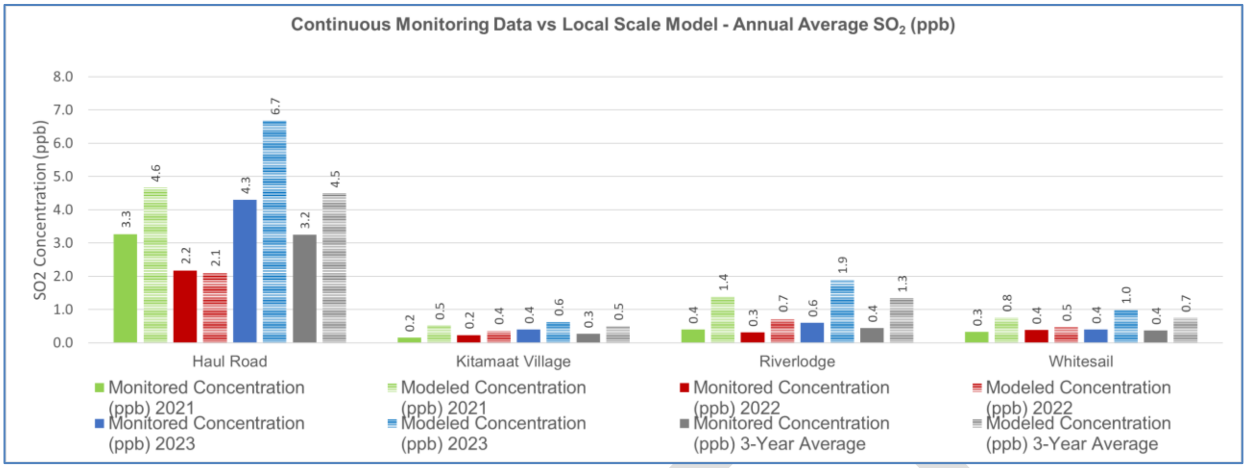

Figure 3-5. 2023 Monitored annual average data compared to modelled concentrations.

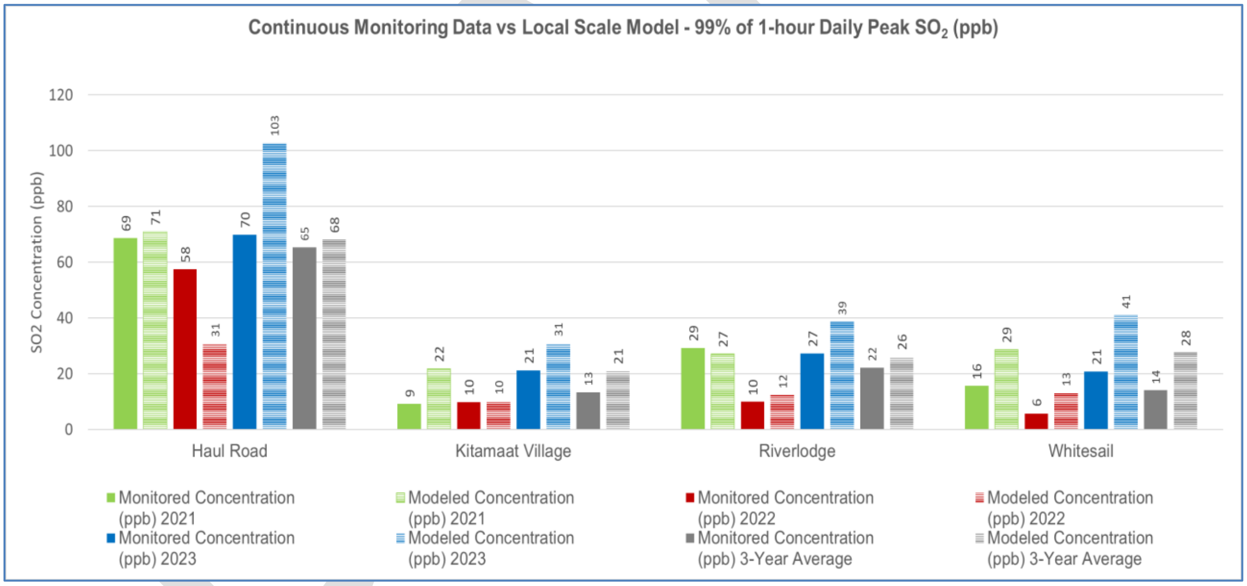

Figure 3-6. 2023 Monitored 1-hour data compared to modelled concentrations.

Network Optimization

Rio Tinto revised Phase 2 of the network optimization to incorporate the updated CALPUFF model results[6] and it is currently under review by B.C. ENV. The Terms of Reference (TOR) for the SO_2 network optimization incorporating the latest monitoring data and the 2019 Comprehensive Review (ESSA et al., 2020a) model results was approved by B.C. ENV in December of 2020. The draft Phase 2 network optimization report was submitted to B.C. ENV in December 2021 and the revised version for corrected CALPUFF model results was submitted to B.C. ENV in December 2022.

3.1.2 SO_2 Concentrations – Passive Sampling

The network of passive samplers was redeployed in the Kitimat Valley during 2022 following the same procedures as in 2016-2021 (ESSA et al., 2020a). The network was deployed starting April 27, 2022[7], at 22 sites within the Kitimat Valley (Figure 3-7), primarily focused along the Wedeene and Bish roads to capture the plume path. This network is referred to as the plume path network and historically referred to as the valley network.[8]

Based on the 2020 passive sampling plan (Trinity 2020), a detailed site evaluation was conducted and documented during the 2020 deployment. The original 15 sites deployed in 2020 were deployed in 2022. In addition, the six sites added in 2021 based on reconnaissance performed in early 2021 were also deployed in 2022.[9] Location A05 (Kitamaat Village) was added in 2022 to understand the extent of the plume to the southeast and for another site to compare with continuous ambient SO_2 monitoring.

As detailed in the Phase III EEM work plan's 2021-Specific Work Plan for Passive Sampling (ESSA et. al., 2021), the network changed from employing IVL SO_2 passive samplers to Bureau Veritas (BV) All-Season Passive Air Sampling System (PASS) and laboratory. All 2022 sample analysis was performed using the BV PASS system.

Six deployments, with an approximate exposure time of one-month (27–34 days), were carried out under the plume path network between April and November 2022. Lake 28 sampling had five deployments from June – November 2022.

In 2023, there were 155 sample exposures across the plume path network collected and analysed during the six deployments. These included replicate samplers deployed approximately 18% of the time (28 duplicate exposures) and 23 blank samples (approximately four per sampling period).

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[7] The Lake 28 sampler was deployed later than the other sites, on May 16, 2023.

[8] A second network of passive samplers deployed in the urban and residential areas of Kitimat was in continuous operation from June 2018 through December 2019. The urban network study concluded in 2019 (before the time period of this report).

[9] Three of the six new 2021 sites (V17, V18/V18b, and V20) were added east and west of V01 to create an east-west transect to better understand the eastern and western boundaries of the plume path. The remaining three new 2021 sites (V21, V22, and V23) were added farther north near Terrace to better understand the northern boundary of the plume path (and to verify where the plume is not).

The observed data show elevated atmospheric SO$_2$ along the plume path (Figure 3-7). Results shown in Figure 3-7 and listed in Table 3-2 are uncalibrated because the BV PASS results need to undergo a new calibration analysis (different from the historic calibration based on IVL sampler data). The BV PASS calibration analysis will be performed after sufficient data have been collected from BV PASS samplers co-located at continuous monitoring stations. The 2023 results within the plume path network are similar to historic observations, although higher concentrations were monitored in 2023 compared to 2022 due to the low 2022 concentrations during the restart. The spatial pattern is consistent with previous years.

Additional information can be found in Technical Memo P07, provided in Appendix A.

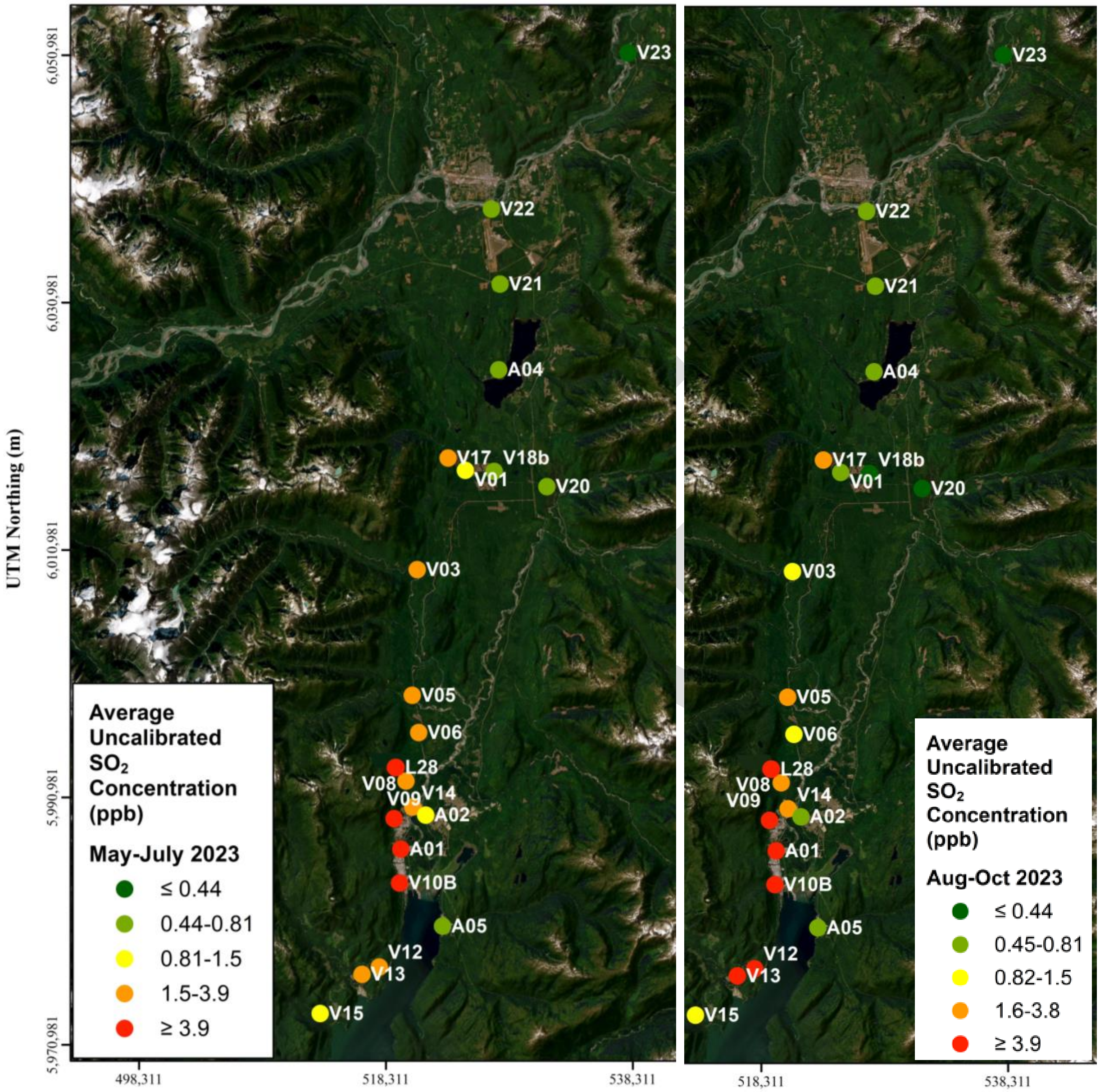

Figure 3-7. Average atmospheric sulphur dioxide (SO₂) concentration during May to July 2023 (left) and during August to October (right) in the Kitimat Valley passive diffusive monitoring networks (uncalibrated).

Table 3-2. Monthly concentration of SO_2 (ppb) from passive samplers in the SO_2 network during the 2023 sampling season.

ID	Site Name	UTM E	UTM N	May-23	Jun-23	Jul-23	Aug-23	Sep-23	Oct-23
A01	Haul Road Station	519527	5986823	7.8*	10.9	7.7*	5.3*	8.8	3.3*
A02	Riverlodge Station	521538	5989580	1.2	0.8*	0.7	0.9*	0.8	0.7
A04	Lakelse Lake NADP Station	527457	6025573	0.7*	0.6	0.5	0.7	0.5	0.2
A05	Kitamaat Village Station	522907	5980600	0.4*	0.4	1.0*	0.7*	0.6*	0.7*
V01	Onion Lake Ski Trail North	524757	6017435	1.8	1.2	1.4	1.0*	0.9	0.4*
V03	Mound TKTP92	520853	6009407	1.8	1.9	2.0	2.5	1.3	0.6
V05	LNG Muster Station	520457	5999250	1.9	2.7	3.1*	3.2	2.6*	0.7
V06	Sand Pit	520970	5996240	2.8	2.1	2.5*	1.5*	1.7	0.5*
V08	Claque Mountain Trail at Powerline	519938	5992329	3.9	3.9	3.9	2.2	2.9	1.1*
V09	Sand Hill at Powerline	518985	5989292	7.8*	9.2	10.7*	6.5	5.9	2.8*
V10B	Pullout before Bish FSR	519425	5984090	7.1*	7.4*	4.8*	2.2*	3.2*	8.7*
V12	Bish Road Pullout 4	517790	5977294	5.1	3.2	3.1	4.6	5.3	16.9
V13	Bish Road at Chevron LNG	516389	5976708	3.4	1.6	2.0	1.3	2.9	8.0
V14	Industrial Area Kitimat Hotel	520490	5990236	2.9	2.0*	1.4	1.6*	2.2	1.0
V15	Bish Mainline	512994	5973534	1.2	0.9	1.1	0.9	0.8	1.1
V17	West Lake	523359	6018434	N/C	2.0*	3.0	1.6*	2.8*	0.2*
V18B	Wedeene mainline	527088	6017351	0.7	0.8	0.7	0.7*	0.4	0.2
V20	Pipeline laydown	531354	6016121	0.6	0.5	0.4	0.5	0.3	0.2
V21	South of airport	527566	6032493	0.8	0.6*	0.7	0.9*	0.6	0.3
V22	Kitselas Development	526862	6038551	0.5	0.5*	0.8*	0.7*	0.6	0.2
V23	Gitaus water tower	537941	6051192	0.4	0.4*	0.4	0.4*	0.2	<0.1
L28	Lake 28	519139	5993425	5.1	9.2	6.1	8.1	5.7	1.2

1. Data are uncalibrated because the passive sampling technology changed to BV PASS in 2021 and have not collected sufficient co-located data to determine a reliable calibration coefficient.
2. Dates are the start month of each sampling period because deployments started near the start of the month. L28 started closer to mid-month and also list the month-beginning.
3. N/C means not collected; * means sample had seeds, insect eggs, or webs in the PASS assembly during the sampling period.

3.1.3 Sulphur Wet and Dry Deposition

3.1.3.1 Wet Deposition (Precipitation Chemistry)

Validated annual wet deposition data values are not available from the National Atmospheric Deposition Program (NADP) until late in the following year. Therefore, annual deposition values are estimated for the reporting year using *preliminary* weekly datasets. The data summarized below include final, post-validated data for 2021 and prior years, and preliminary data for 2022 and 2023.[10,11]

Figure 3-8 compares the amount of annual precipitation (mm) Haul Road and Lakelse Lake precipitation chemistry monitoring stations during 2013 to 2023. Note that because the Lakelse Lake station was only in operation for part of 2013, data from that location are only shown for 2014 to 2022. Average annual precipitation volume was consistently higher at Haul Road compared to levels at Lakelse Lake during 2014–2023 (47% to 80% higher), averaging 2398 mm and 1493 mm, respectively. During 2023, precipitation volume at Haul Road (2007 mm) and at Lakelse Lake (1366 mm) were slightly lower than the ten-year average, and the relationship between the two stations was consistent with past years (47% higher at Haul Road compared to Lakelse Lake).

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[10] January through September 20, 2022 data from NADP are weekly validated. September 20 through December 31, 2022 data are preliminary not yet validated. January 2023 through October 17, 2023 data are preliminary and not yet validated. Data is not yet available for remainder of 2023. The full year 2023 wet deposition was estimated by computing the annual average pollutant concentrations for all available data in 2023 (weighted average based on weekly precipitation rate) and then applying these weighted averages to the total recorded precipitation at each site. Precipitation data was available for all of 2023.

[11] Similarly, the 2021 report showed final data for 2020 and prior and preliminary data for 2021. As a comparison point, the weekly 2021 data at Haul Road yielded an estimated annual SO_4 deposition rate of 40.6 kg SO_4^{2-}/ha/yr compared to the post-validated annual NADP value of 39.8 kg SO_4^{2-}/ha/yr (both marine-adjusted).

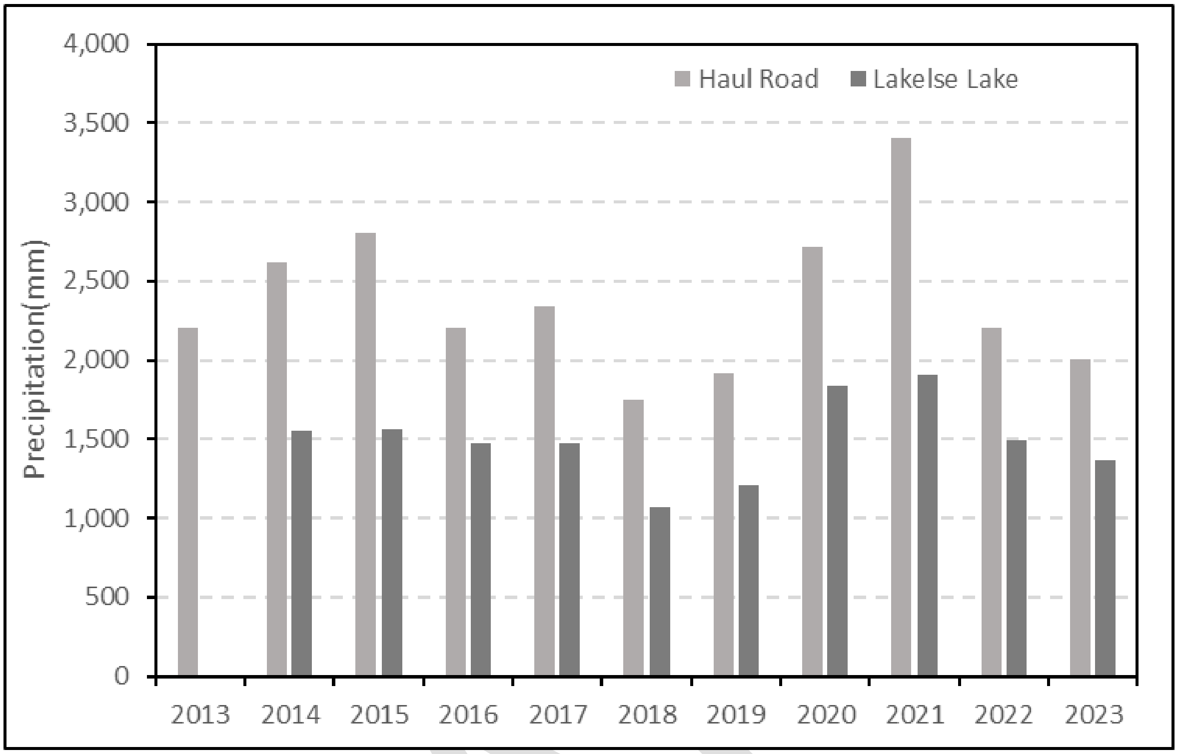

Figure 3-8. Annual precipitation volume (mm) from 2013 to 2023 at the Haul Road and Lakelse Lake precipitation chemistry monitoring stations. (Source: NADP [URL: https://nadp.slh.wisc.edu/precipitation/])

Weekly precipitation volume (mm) at the two stations (operated by the NADP) during the same ten-year period showed a highly synchronous pattern but with generally higher volume at Haul Road (Figure 3-9). Higher volume was recorded at Lakelse Lake for only approximately 7% of the observation on average and 7% of observations in 2023. In addition, higher weekly sulphate concentration (mg/L) and lower pH was observed at Haul Road compared with Lakelse Lake (Figure 3-9). The higher SO_4 and lower pH in rainfall at Haul Road are caused by the higher atmospheric concentration of SO_2 and corresponding higher S deposition at Haul Road.

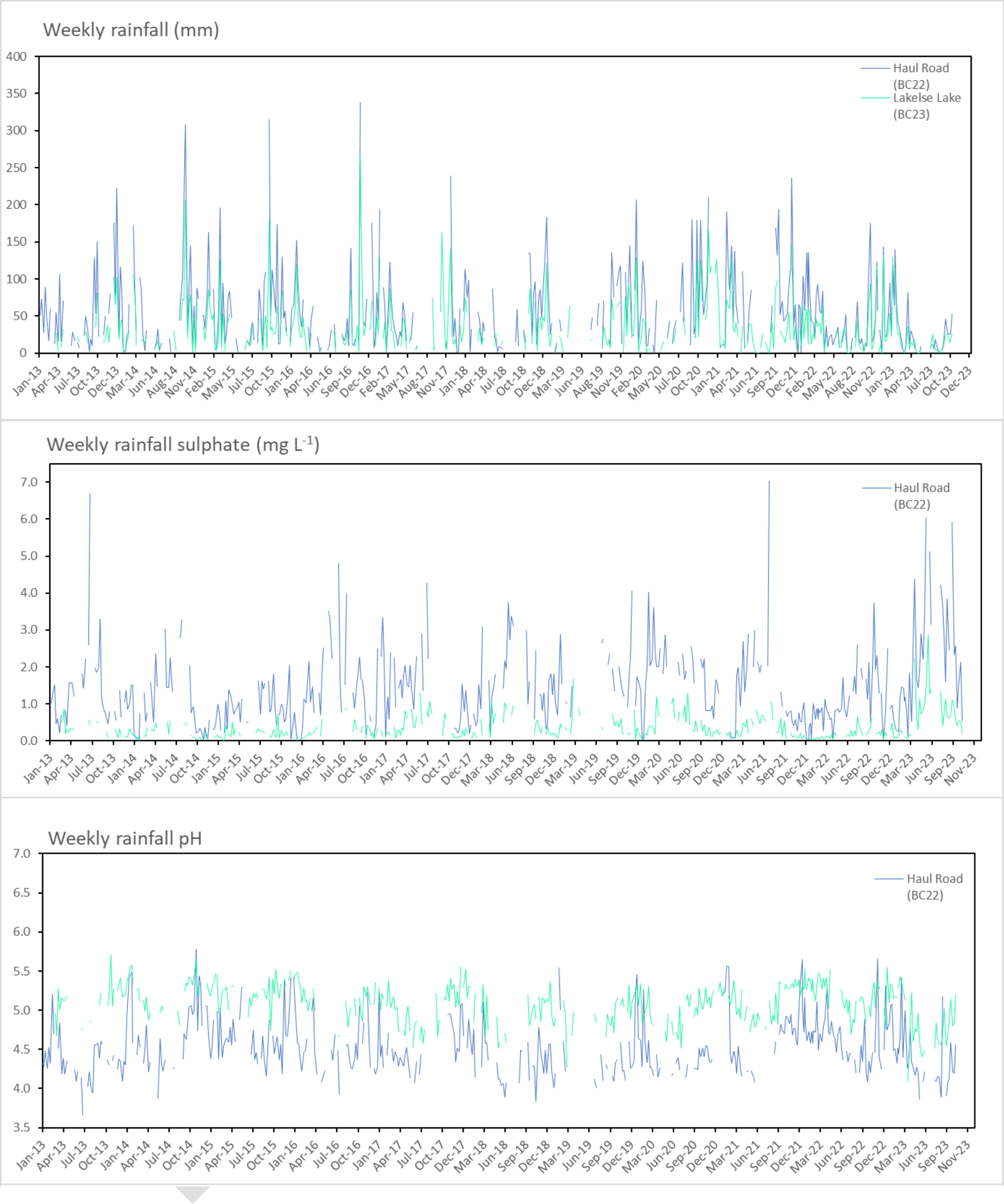

Figure 3-9. Weekly precipitation volume (mm) and chemistry (mg/L) at Haul Road (January 2013 to October 2023) and Lakelse Lake (April 2013–October 2023) showing inter-annual variation in precipitation volume (upper graph), sulphate concentration (middle graph) and precipitation pH (lower graph).[12]

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[12] January 2023 through October 17, 2023 data are preliminary and not yet validated. Data are not yet available for remainder of 2023.

Higher rainfall volume and higher sulphate concentration observed at Haul Road combines to result in a more pronounced wet S deposition difference compared with Lakelse Lake on an annual (Figure 3-10) and weekly basis (Figure 3-11).

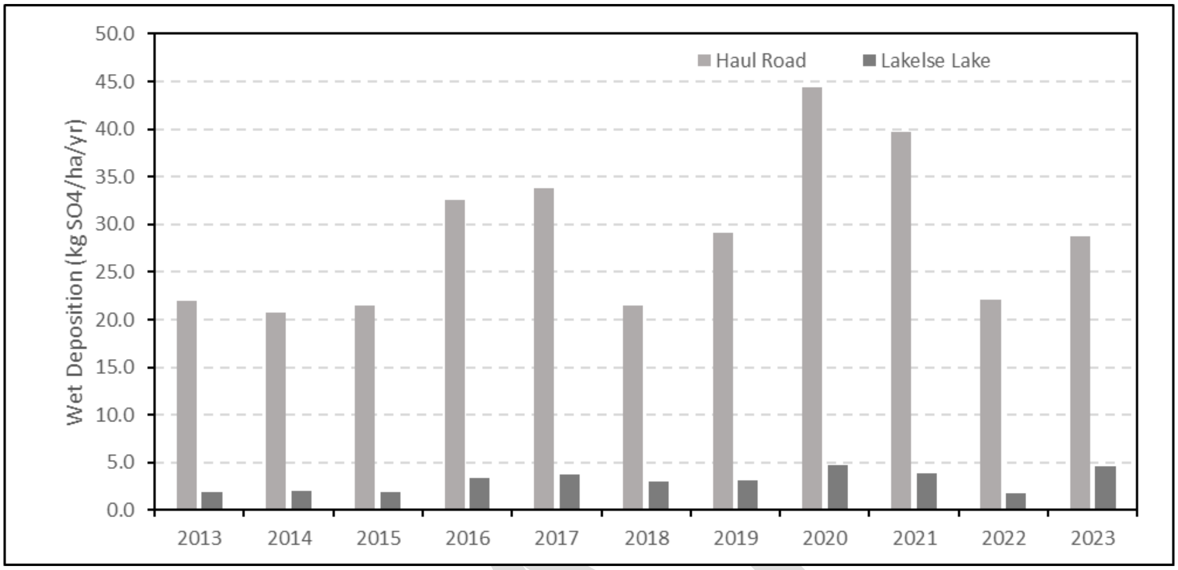

Figure 3-10. Annual wet deposition (kg SO_4/ha/yr) from 2013 to 2023 at the Haul Road and Lakelse Lake precipitation chemistry monitoring stations. (Source: NADP [URL: https://nadp.slh.wisc.edu/precipitation/])

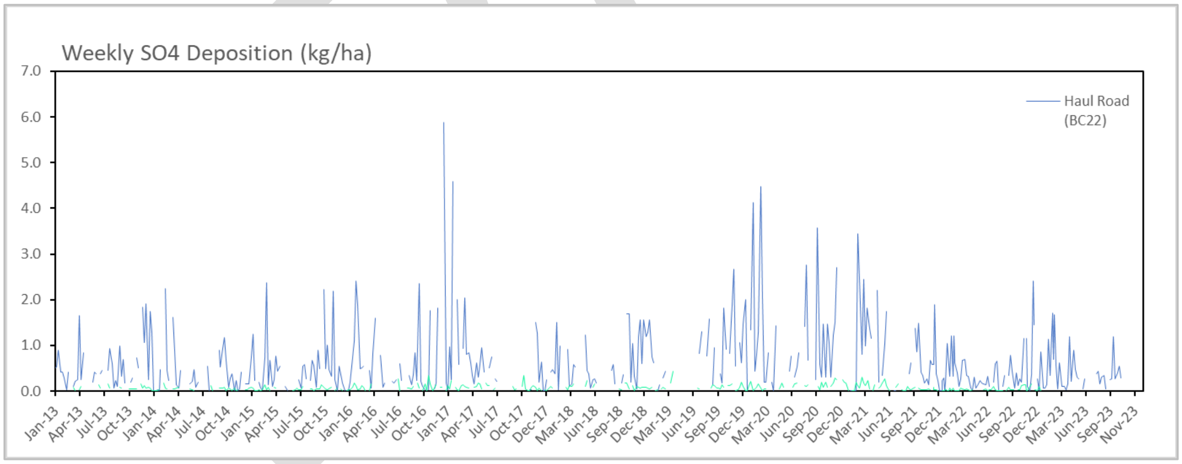

Figure 3-11. Weekly wet deposition (kg SO_4/ha/yr) from 2013 to 2023 at the Haul Road and Lakelse Lake precipitation chemistry monitoring stations. (Source: NADP [URL: https://nadp.slh.wisc.edu/precipitation/])

3.1.3.2 Dry deposition modelling methods

Dry deposition measurements are difficult and rarely conducted because of the requirements for highly sophisticated methods and instrumentation (Wesely and Hicks 2000). In general, dry deposition is modelled from air concentrations of gaseous and particulate species (e.g., SO_2 and p SO_4^{2-}) multiplied by a species-specific dry deposition velocity estimated using modelling techniques, i.e., 'inferential' models (Vet et al., 2014).

$$F = C \times V_d$$

Where:
F is the dry deposition flux,
C is the measured ambient air concentration, and
V_d is the deposition velocity, which is influenced by factors such as wind speed, height of observation, heat flux, moisture availability, vegetation, and surface roughness (Wesely and Hicks 2000).

The 'big-leaf' model developed by Environment and Climate Change Canada (Zhang et al., 2001, 2003a, 2003b; Zhang and He 2014) was used to estimate hourly species-specific V_d at four stations in the Kitimat Valley (Haul Road, Whitesail, Lakelse Lake, and Terrace Airport [YXT]). The V_d model required meteorological forcing variables on an hourly resolution for the period of interest (calendar year 2022). The data sources for the big-leaf dry deposition velocity model at four stations are shown in Table 3-3. The model also requires site-specific variables, such as latitude and land cover; deposition velocities were estimated for coniferous land cover only. For further details on the big-leaf model see Technical Memo D01 (2016) and Technical Memo D02 (2018).

Additional data sources became available beginning in May 2023 from the installation of solar irradiance instrumentation at Whitesail and temperature, relative humidity, solar irradiance, and surface pressure at Lakelse Lake. These data were incorporated into the report as available. Prior to May 2023 installation, the data used for dry deposition modelling was identical to the methods for prior years, as detailed in Table 3-3.

Table 3-3. Data sources for meteorological variables required to model deposition velocity at Haul Road, Whitesail, Lakelse Lake and Terrace Airport.

Variable	Kitimat: Haul Road	Kitimat: Whitesail	Lakelse Lake	Terrace Airport
Temperature	Haul Road hourly	Whitesail hourly	Lakelse Lake hourly Prior to May 13, 2023: Terrace Airport hourly	Terrace Airport hourly
Wind speed	Haul Road hourly	Whitesail hourly	Terrace Airport hourly	Terrace Airport hourly
Relative humidity	Whitesail hourly	Whitesail hourly	Lakelse Lake hourly	Terrace Airport hourly

Variable	Kitimat: Haul Road	Kitimat: Whitesail	Lakelse Lake	Terrace Airport
			Prior to May 13, 2023: Terrace Airport hourly	
Solar irradiance	Whitesail hourly Prior to May 13, 2023: Modelled from maximum and minimum daily temperature using Hargreaves method	Whitesail hourly Prior to May 13, 2023: Modelled from maximum and minimum daily temperature using Hargreaves method	Lakelse Lake hourly Prior to May 13, 2023: Modelled from maximum and minimum daily temperature using Hargreaves method	Modelled from maximum and minimum daily temperature using Hargreaves method
Precipitation rate	NADP Haul Road, obtained from University of Wisconsin	Haul Road	NADP Lakelse Lake, obtained from University of Wisconsin	Terrace Airport daily data, disaggregated by NADP Lakelse Lake hourly data
Surface pressure	Haul Road hourly[13]	Whitesail hourly[14]	Lakelse Lake hourly Prior to May 13, 2023: Terrace Airport hourly	Terrace Airport hourly
Snow depth	Environment Canada, Kitimat Hatchery, daily data applied to all hours	Environment Canada, Kitimat Hatchery, daily data applied to all hours	Terrace A / Terrace PCC daily snow depth, applied to all hours	Terrace A / Terrace PCC daily snow depth, applied to all hours
Cloud fraction	Environment Canada, Terrace Airport hourly	Environment Canada, Terrace Airport hourly	Environment Canada, Terrace Airport hourly	Environment Canada, Terrace Airport hourly

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[13] In 2023 at Haul Road and Whitesail the surface pressure was not available for much of the year. Available data was used and missing hours were substituted with data from nearby Riverlodge.

[14] The Vd for Lakelse Lake was first modelled for reporting year 2022 and was also modelled using data back to 2020. Dry sulphur deposition calculations based on SO_2 measured at Lakelse Lake for periods prior to 2020 (starting August 2018 when the Lakelse Lake SO_2 monitor was established) have applied modelled Vd from the Terrace Airport.

3.1.3.3 Dry deposition modelling results

Annual modelled dry deposition velocity (V_d) for SO_2 ranged between 0.05 – 4.68 cm/s for Haul Road, 0.06 – 4.47 cm/s for Whitesail, 0.03 – 4.80 cm/s for Lakelse Lake, and <0.01 – 4.36 cm/s for Terrace Airport. Figure 3-12 shows the annual distribution of modelled V_d for SO_2 at each location.

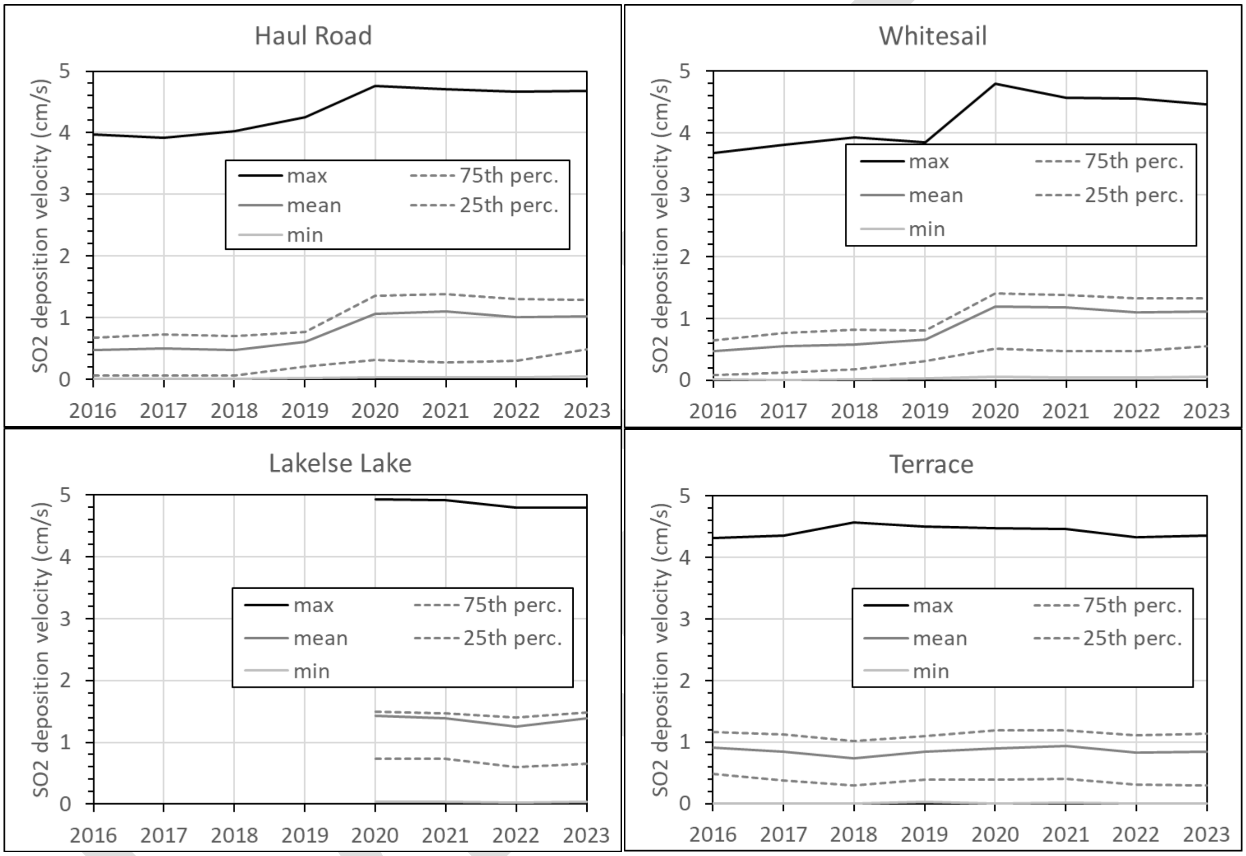
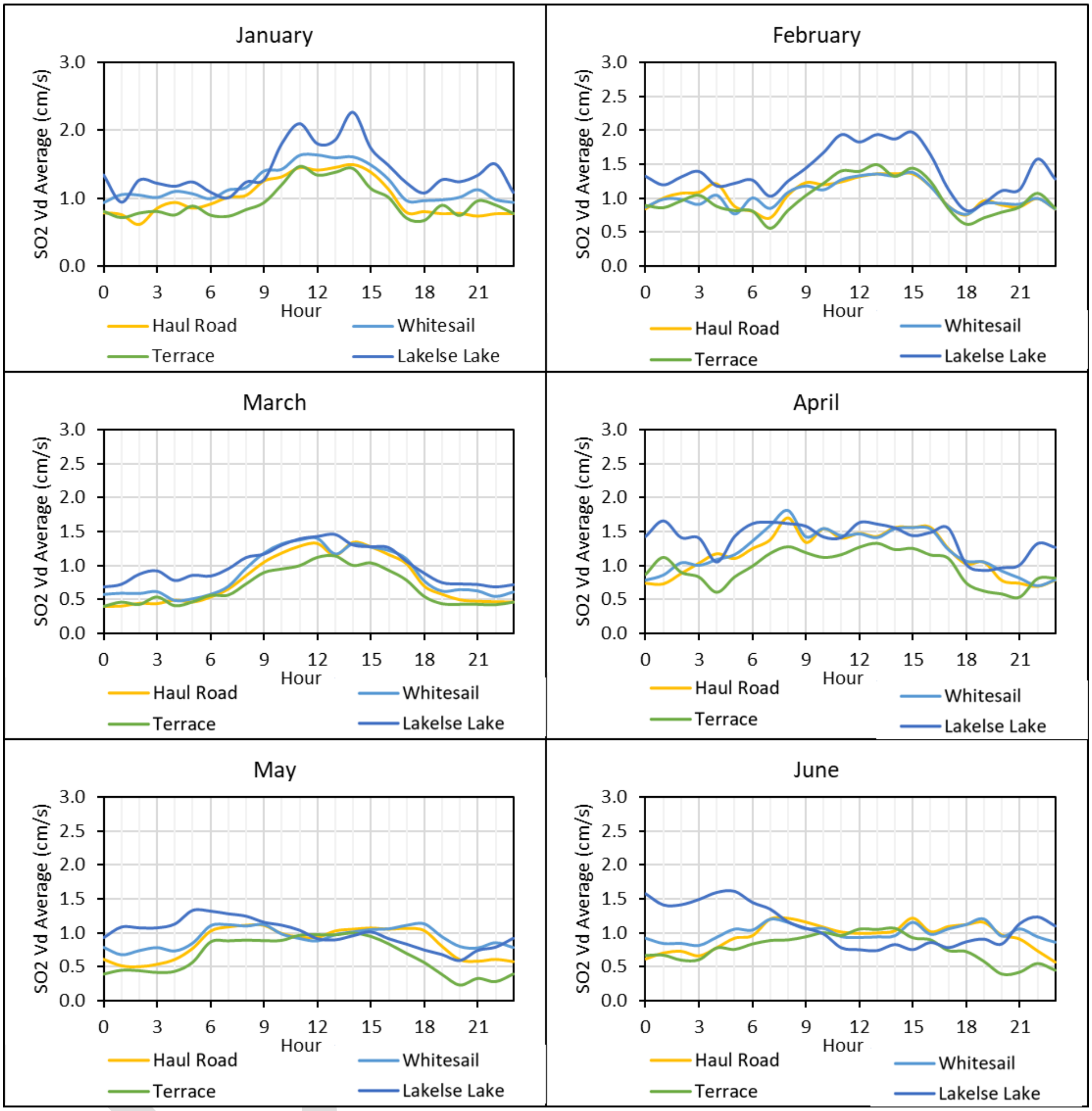


Figure 3-12. Annual distribution of SO_2 V_d for 2016 – 2023.

The annual distribution of SO_2 V_d was similar among all years 2016-2023, with a slight increase in overall magnitude during 2020 for Haul Road and Whitesail. This analysis also investigated trends in variable SO_2 V_d on a daily and seasonal basis. Figure 3-13 demonstrates the 2023 diurnal behavior of SO_2 V_d showing that SO_2 V_d is higher during daytime hours aligning similarly with trends in daily temperature and solar irradiance.


January
February
March
April
May
June
SO2 Vd Average (cm/s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Hour
0
3
6
9
12
15
18
21
Haul Road
Whitesail
Terrace
Lakelse Lake

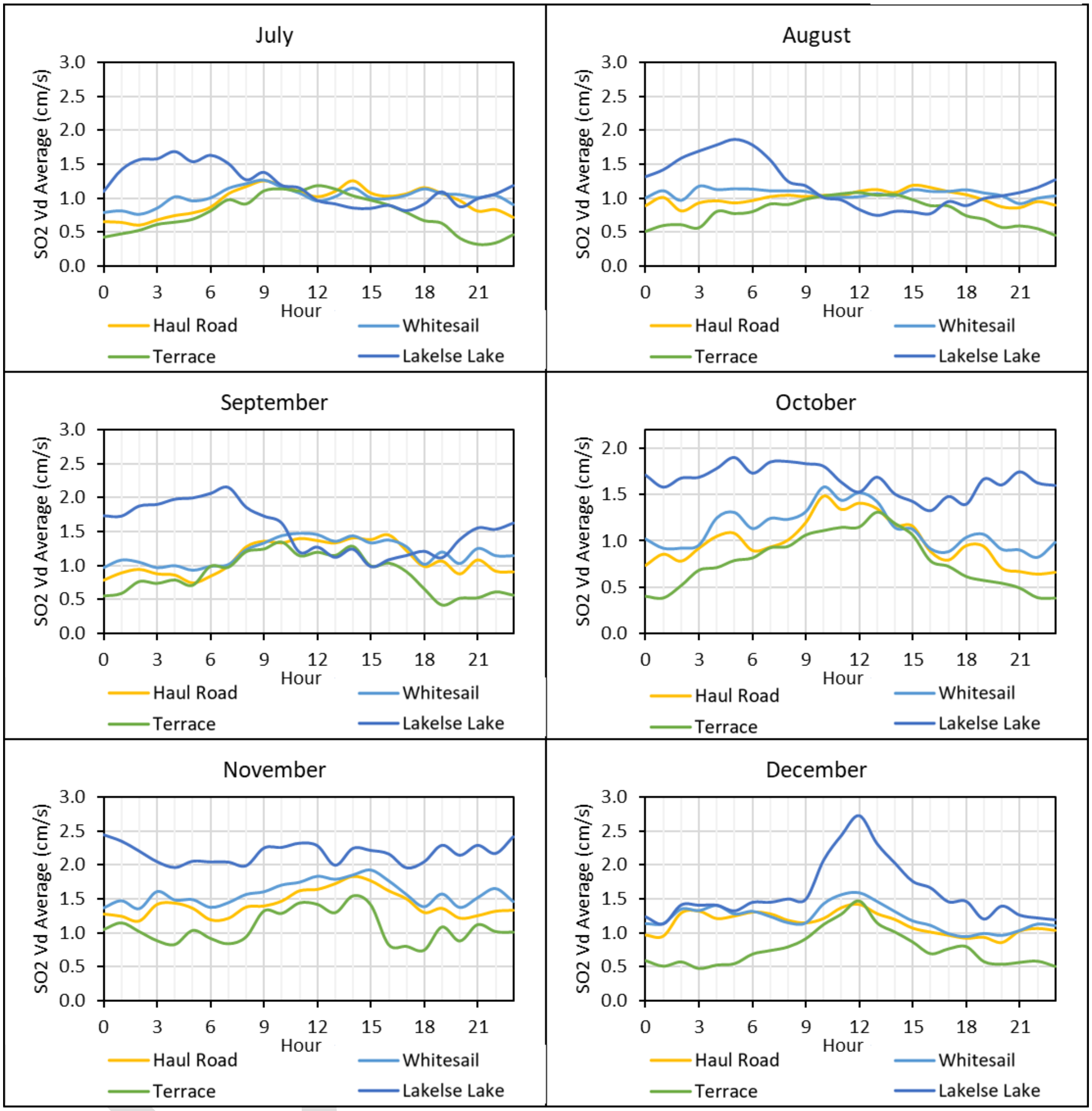


Figure 3-13. Diurnal behavior of SO_2 V_d in 2023.

Hourly SO_2 V_d was multiplied by the preliminary hourly monitored SO_2 concentrations to determine the total mass of SO_2 dry deposition in 2023. Dry deposition velocities were modelled at the Haul Road, Whitesail, and Lakelse Lake monitoring stations, using co-located SO_2 monitoring data and meteorological data (when available). The modelled dry deposition velocities for the Terrace airport were applied to the SO_2 monitoring data from the Terrace-Skeena Middle School. The total SO_2 dry deposition mass in 2023 was 50.5 kg/ha/yr for Haul Road, 4.9 kg/ha/yr for Whitesail, 2.7 kg/ha/yr for Lakelse Lake, and 3.6 kg/ha/yr for Terrace-Skeena Middle School. Figure 3-14 shows 2023 and prior years' SO_2 dry deposition mass.

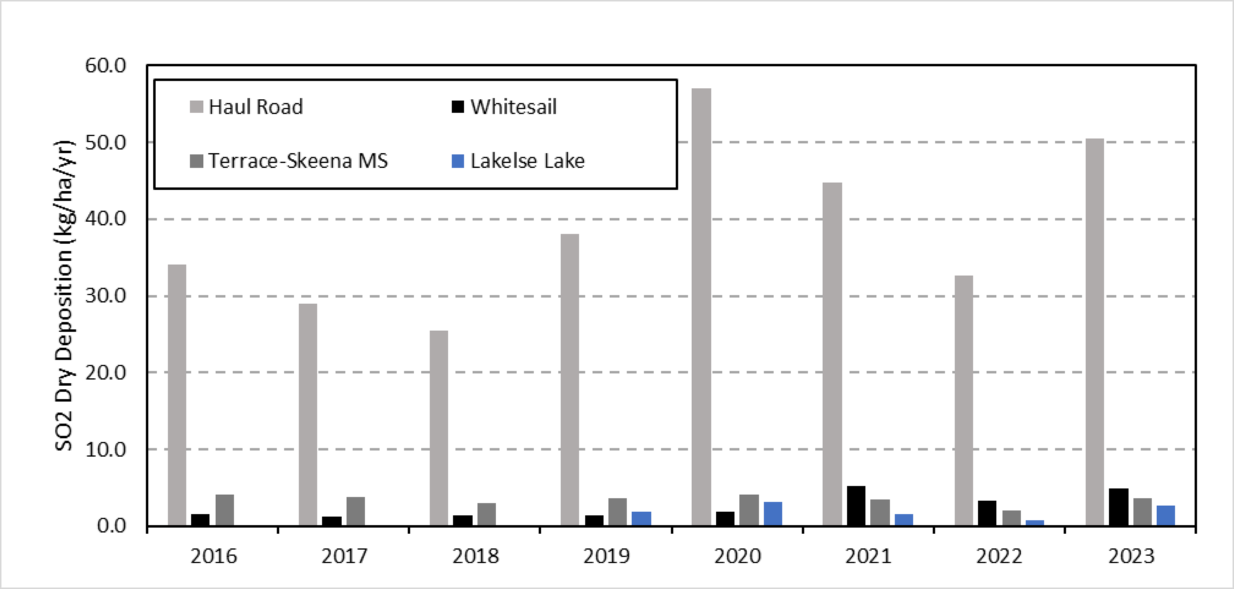


Figure 3-14. Annual SO_2 dry deposition mass 2016 – 2023.

Total mass of SO_2 dry deposition tended to be more heavily influenced by monitored SO_2 concentration at each site versus changes in SO_2 V_d. This difference in SO_2 concentrations is clearly the reason for elevated dry deposition mass at Haul Road compared to other sites. Similarly, dry deposition rates at all sites are higher in 2023 compared to 2022 due to the higher SO_2 concentrations and higher SO_2 emission rates from the smelter in 2023 compared to 2022.

3.1.3.4 Total Sulphur Deposition

Figure 3-15 illustrates total mass of annual monitored wet deposition combined with modelled dry deposition at the Kitimat Haul Road location. Similar ratios of wet versus dry S deposition occur during each year from 2016 – 2023 at Haul Road.

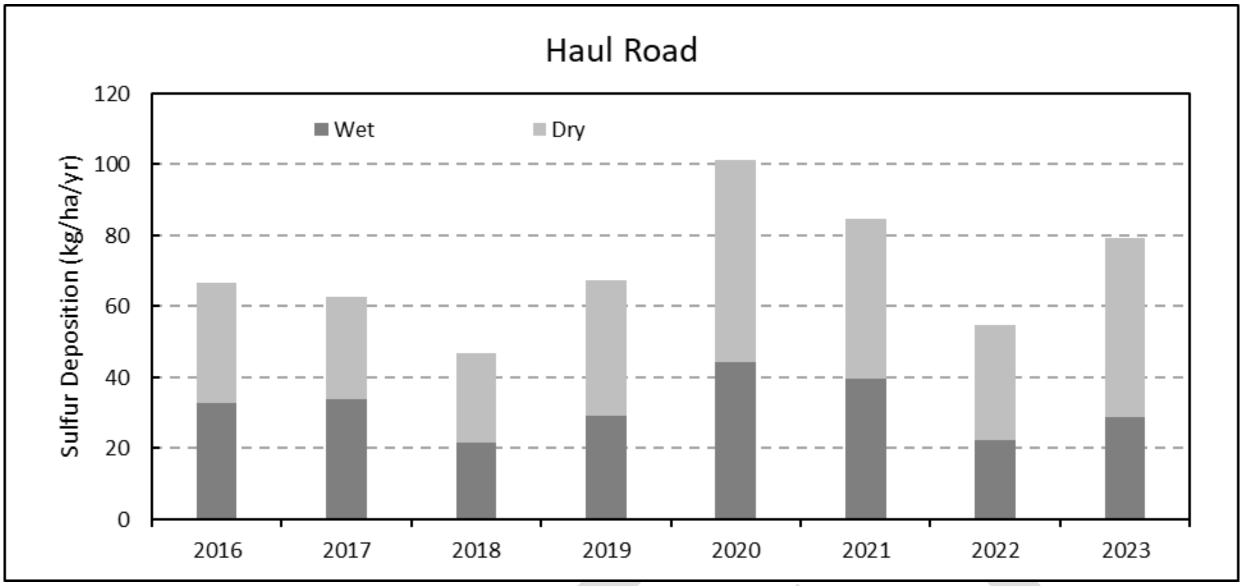


Figure 3-15. Haul Road wet and dry sulphur deposition annual total mass.

3.2 Human Health

B.C. ENV updated the province-wide interim SO_2 ambient air quality objective (IAAQO) in 2016, which became the SO_2 health KPI of the SO_2 EEM Program starting 2017. Starting January 1, 2020, the SO_2 health KPI implemented the SO_2 Canadian Ambient Air Quality Standards (CAAQS). In 2022, the CAAQS value was 70 ppb. In 2025 the CAAQS value changes to 65 ppb. The SO_2 health KPI is used to assess residential SO_2 ambient air quality. The SO_2 Health KPI for 2023 is a threshold for residential SO_2 ambient air concentration of 70 ppb and is evaluated through the following method as defined in the B.C. Air Quality Objectives:[15]

- *Achievement based on annual 99th percentile of daily 1-hour maximum (D1HM),*
- *averaged over three consecutive years,*
- *effective January 1, 2020;*
- *used to inform new air management decisions beginning January 1, 2017 and all air management decisions beginning January 1, 2020.*

Table 3-4 provides the KPI results for 2023, using the 3-year average of the 99th percentile of the D1HM for 2021 – 2023. The "Human Health KPI Calculations for 2023" memorandum is provided in Appendix B. The 2023 KPI calculation results for Kitamaat Village, Riverlodge, Whitesail, and Industrial Ave were all well below the KPI (CAAQS value of 70 ppb) and, as such, demonstrate attainment of the KPI.

Table 3-4. Calculation method and results for the SO_2 Health KPI in 2023.[a]

Station	99th percentile D1HM [b] SO_2 (ppb)			SO_2 Health KPI (ppb) (3-year average of 99th percentile D1HM[b])	KPI Attainment / Non-Attainment
	2021	2022	2023		
Kitamaat Village	9.1	9.8	21.2	13.4	Attainment
Riverlodge	29.2	9.9	27.3	22.1	Attainment
Whitesail	15.6	5.7	20.8	14.0	Attainment
Industrial Ave	33.4	18.6	40.0	30.7	Attainment

[a] Data for this table were extracted from the Envista database of B.C. ENV in March 2024. Verification of 2022 and 2023 data by B.C. ENV was not confirmed as of the date of the download. Therefore, the 2022 and 2023 datasets are *preliminary*.
[b] D1HM = Daily 1-hour average maximum.

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[15] BC air quality objectives (https://www2.gov.bc.ca/assets/gov/environment/air-land-water/air/reports-pub/aqotable.pdf), footnote 18.

3.3 Terrestrial Ecosystems

This section contains a condensed summary of the major actions and knowledge gained in 2023 with respect to Terrestrial Ecosystems, including the Informative Indicators of soils, biodiversity and plant health.

For 2023, most Terrestrial Ecosystems subsections fall under the umbrella of the Vascular Plant and Cyanolichen Biodiversity Monitoring Program ("PCMP"). The PCMP plan was agreed to and finalized in November 2020 (Laurence et al., 2020), and the field manual to support its implementation finalized and agreed to in June 2021 (Coosemans and Laurence 2021), prior to commencing field activities. As described in the April 2023 update to the Annual Work Plan (ESSA Technologies et al. 2023) for Terrestrial Ecosystems, field activities scheduled for 2023 as part of the EEM Phase III included the following tasks:

- complete assessment of the final 11 of the total 33 Kitimat Valley sites, including
  - site characterization/assessment;
  - detailed vegetation assessments (low shrub and herb layers, as well as cyanolichens); and,
  - visual assessments of plant & cyanolichen health; and,
- additional reconnaissance to ensure a minimum of nine "alternate" sites (three in each deposition zone) are available in the Kitimat Valley.

Monitoring for the 33 Kitimat Valley sites is conducted using a 3-year rotating panel method, thus all 33 total Kitimat Valley sites have now been monitored for the first time. Further detail on the 2023 assessments is provided in the following subsections, and in the *Vascular Plant and Cyanolichen Biodiversity Monitoring Program Third Annual Report* (Coosemans and Grossmann 2024) and in the *Vascular Plant and Cyanolichen Biodiversity Monitoring Program First End-of-Cycle Report* (Coosemans, Grossmann and Schwarz 2024).

No notable deviations from the schedule of activities for 2023 were made, with the notable exception that the reporting was expanded to include an Annual Report in addition to an End-of-Cycle Report (referenced above), in order to better align year-to-year reporting.

2023 saw the completion of the restart of the smelter following the labour dispute in 2021, and with it an amendment to the P2-00001 Multimedia Waste Discharge Permit (the "P2 Permit"). The P2 Permit included the conditions that a Monthly Program (MP) and Vegetation Monitoring Program (VMP) be resumed during the restart (2022 and 2023 growing seasons), wherein monthly vegetation health inspections were required to be conducted at 20 pre-established and agreed-upon sites, and western hemlock sampling for F and paired vegetation health inspections were required at 11 pre-established and agreed-upon sites, respectively (and among which were 7 sites that overlapped both programs). VMP activities and results for 2023 are detailed in Coosemans, Grossmann and Laurence (2024). Note that these activities were directly related to the P2 Permit, as they are no longer part of the SO_2 environmental effects monitoring program (SO_2 EEM Program), and thus are not part of the Work Plan and Schedule for Terrestrial Ecosystems (ESSA et al., 2023), and are not reported on further here.

3.3.1 Plant and Cyanolichen Biodiversity and Plant Health

Activities in 2023 centered around the continued implementation of the PCMP (begun in 2021), which replaces the vegetation component of the SO_2 EEM Program from previous years. In the 2019 Comprehensive Review (ESSA et al., 2020a), recommendations were made to transition vegetation sampling and analysis of western hemlock needles for S and assessment of visible injury to a more ecologically-based program designed to detect subtle changes in the occurrence and abundance of plants and cyanolichens. This recommendation was based on air dispersion modelling that showed air concentrations of SO_2 to be well below those that would cause visible injury to sensitive vegetation, and the lack of any such injury during the first phase of the SO_2 EEM Program. In addition, the concentrations of S (and fluoride) in western hemlock needles were at or near background concentrations reported in the scientific literature. Therefore, emphasis was shifted to changes in biodiversity and health of plants and cyanolichens that might be mediated through long term deposition of SO_4^{2-} and potential changes in soil chemistry.

Scheduled activities for the vegetation component of the SO_2 EEM Program in 2023 included the assessment of the final set of eleven PCMP field plots (Figure 3-16) between June 21st and July 29th; and the analysis and presentation of results. During the reporting process, it was determined in consultation with ENV that a separate annual report should be prepared in addition to an end-of-cycle report, in order for results to be shared in a consistent manner independent of cycle year. Thus, in March 2024, reporting included submission of both the Vascular Plant and Cyanolichen Biodiversity Monitoring Program Third Annual Report (Coosemans and Grossmann 2024), and First End-of-Cycle Report (Coosemans, Grossmann and Schwarz 2024).

Field work undertaken at each of the eleven sites assessed in 2023 included documentation of site characteristics, abundance measures of all low shrub and herb species, vegetation health inspections, and cyanolichen health inspections. All assessments were undertaken between June 21 and June 29 in 2023. In addition, reconnaissance of ten new alternate sites in the Kitimat Valley was undertaken (these new alternate sites, A43-A52, were located but not monumented with plot corners or center, and have not had detailed assessments nor soil sampling undertaken). As a result of the reconnaissance activities, the total number of alternate sites now integrated into the Program (counting A36 and A40 added in 2022) is currently twelve, with four in Low, five in Medium and three in High deposition zones.

The study area experienced relatively warmer and drier weather during the plant health assessment period and for the growing season as a whole (Government of Canada 2024a & 2024b: Kitimat and Terrace area weather station data and their historical averages, respectively), although at this early part of the season, heat stress and drought effects were limited.

While there was a prominence and prevalence of feeding insects during 2023, irrespective of their location in the valley, we noted that vegetation otherwise appeared to be generally healthy/thriving, although there was some sun scald and impacts of dry conditions noted at some sites.

With respect to cyanolichen health, assessors examine specimens noting whether they appear Normal, Stressed or Injured in terms of growth (relative to typical for the region), changes in morphology, colour (e.g., signs of bleaching), or presence of necrotic tissue. In 2023, four lichen species at two sites (B19 & B39; low and medium deposition sites, respectively) appeared dry and/or of low vigour: *Lobaria linita* at B19; *L. oregana* at B19 & B39; *L. pulmonaria* at B39; and *Peltigera* sp. at B19. At high deposition site B31, only "fallen" *L. linita* and *L. oregana* (apparently deposited from the canopy) were found (therefore aren't included with analysis, per protocol), but both were noted to be "of reduced vigour" presumed to be owing to their having fallen away from their substrate.

3.3.1.1 Vascular plant and cyanolichen biodiversity monitoring

The PCMP was designed to detect potential changes in the biodiversity (species richness and abundance) trends of vascular plants in the low shrub and forb layers, and of cyanolichens, in forest ecosystems of the Kitimat Valley (including the Lakelse Watershed). The Program focuses on detecting mid- to long- term effects on plants and cyanolichens associated with acidification due to emissions of SO_2 from Rio Tinto BC Works. As such, initial differences between vegetation and cyanolichen biodiversity between sites are expected—the data collected from plots are not "baseline," but simply "initial." Data from each site will ultimately be compared with itself (year-to-year comparisons), to determine if differential changes (i.e., trends) are occurring over the mid- to long- term correlating with deposition zone. Only once plots have been re-assessed will it be possible to extract initial trend data from the assessment results.

The Program was implemented very much as planned in the summer of 2023, with no notable deviations. Details of cumulative adjustments to the PCMP can be found in Coosemans and Grossmann (2024).

A major component of biodiversity is species richness—the number of species present/observed—which can be readily summarized and presented: Table 3-5 provides species richness assessed during all years (2021 – 2023) of the PCMP for plants in the low shrub and herb layers. As expected, no strong trends between deposition zones are noted in initial plant species richness results.

Table 3-5. Species Richness in the low shrub (B2) and herb (C) layers at each plot (blueberry species combined) for 2021-2023. Text is colour-coded for Deposition Zone: Green = Low; Orange = Medium; and Red = High.

Plot	# Tree Species in B2 Layer	# Non-tree Shrub Species (B2 Layer)	# Herb Species (C Layer)	Total # Species (Richness) in B2 & C Layers
B01AC22	4	13	14	31
B02AC22	3	3	3	9
B03AC22	1	9	14	24
B04AC21	2	6	7	15
B05AC22	2	4	6	12
B06AC23	2	6	20	28
B07AC22	3	5	15	23
B08AC22	1	7	14	22
B09AC21	1	6	9	16
B10AC21	4	5	8	17
B12AC21	4	4	9	17
B15AC22	3	3	8	14
B17AC21	3	6	11	20
B18AC23	4	7	17	28

Plot	# Tree Species in B2 Layer	# Non-tree Shrub Species (B2 Layer)	# Herb Species (C Layer)	Total # Species (Richness) in B2 & C Layers
B19AC23	3	6	15	24
B20AC21	3	3	8	14
B21AC22	3	5	14	22
B22AC21	2	4	8	14
B23AC23	1	9	9	19
B24AC22	3	5	15	23
B25AC22	3	5	10	18
B26AC21	1	2	2	5
B28AC22	2	7	5	14
B29AC22	2	3	10	15
B30AC21	3	6	14	23
B31AC23	2	6	12	20
B32AC21	4	5	10	19
K33AC22	2	3	11	16
K34AC22	0	3	10	13
B35AC23	1	7	15	23
B37AC23	2	7	14	23
B38AC23	3	7	7	17
B39AC23	4	3	3	10
B41AC23	2	5	5	12
B42AC23	3	4	6	13

While 2023 represented the third year of the PCMP program and associated cyanolichen assessment, similar assessments were undertaken by Patrick Williston in 2016/2017, and repeated in 2020 (Williston 2020) at or near many of the cyanolichen plots undertaken during the 2021, 2022 and 2023 PCMP assessments. Although not strictly comparable as methods were less limiting and locations were not precisely the same, the data are, nonetheless, an informative part of the baseline for each site. Table 3-6 summarizes species richness assessed for cyanolichens at all plots that have been assessed as part of the PCMP, including Willison's 2016/17 and 2020 counts, and our own data for each site assessed in 2021 - 2023. As expected, these data generally show that cyanolichen diversity is inversely proportional to increasing deposition zone (largely as an historical artifact of fluoride emissions); however, the data also demonstrate the stochastic nature of this metric (e.g., if a host tree is lost from a plot, a dramatic shift in recorded cyanolichen diversity may occur).

Table 3-6. Cyanolichen richness recorded at assessed sites 2016-2023. Text is colour-coded for Deposition Zone: Green = Low; Orange = Medium; and Red = High.

Site	Cyanolichen richness 2016/17*	Cyanolichen richness 2020*	Cyanolichen richness 2021-2023 PCMP
B01	12	14	5
B02	5	6	2
B03	9	6	4
B04	6	7	6
B05	2	2	1
B07	3	3	1
B08	5	6	4
B09	0	0	0
B10	4	4	5
B12	2	2	4**
B15	8	N/a	5
B17	0	0	0
B20	10	6	10
B21	12	10	4
B22	5	2	2
B24	2	3	1
B25	0	0	0
B26	0	0	0
B28	0	0	0
B29	5	9	3
B30	6	10	4
B32	2	2	0
K33	N/a	N/a	4
K34	N/a	N/a	4
B06	14	12	9
B18	13	10	4
B19	5	3	5
B23	6	6	4
B31	2	1	0***
B35	N/a	N/a	3
B37	N/a	N/a	2
B38	N/a	N/a	4
B39	N/a	N/a	2
B41	N/a	N/a	0
B42	N/a	N/a	4
Range Low Sites	2-14 (n=13)	2-14 (n=12)	0-10 (n=15)
Mean (SD) Low Sites	10.9 (3.7)	7.6 (3.5)	4.6 (2.5)
Range Medium Sites	0-9 (n=6)	2-6 (n=6)	0-5 (n=10)
Mean (SD) Medium Sites	1.8 (1.7)	1.8 (1.7)	2.7 (1.7)
Range High Sites	0-5 (n=8)	0-6 (n=8)	0-4 (n=10)
Mean (SD) High Sites	1.4 (1.8)	1.0 (2.1)	1.0 (1.7)

*from Williston (2020).

**B12 was moved from the original B.C. ENV plot to another area in the same stand.

***two fallen cyanolichen species were, however, observed at site B31 in 2023.

3.3.1.2 Visual inspection and assessment of plant health as part of biodiversity monitoring

2020 was the final year of the previous VMP, wherein the health of vegetation at 23 sites in the vicinity of the smelter was assessed. Visual assessment of plant health continues to be an important activity in the Terrestrial Ecosystem Line of Evidence. New protocols were developed as part of the program design to assure that the assessment of plant health continues. The methods are described in Coosemans and Laurence (2021). Since 2021, vegetation health is now primarily monitored through visual inspection of vegetation (including cyanolichens) at PCMP plots whenever each is assessed (on a three-year, rotating basis).

The eleven assessed sites were visually inspected between June 21 and July 29, as part of the PCMP in 2023 in the Kitimat Valley. Symptoms of visible injury were not noted at any of the plots (e.g., due to either gaseous fluoride or sulphur dioxide). There did not appear to be patterns or substantial differences in the degree of insect feeding or the incidence and severity of plant diseases related to the location of the sites in relation to deposition zones, and the level of insect activity and plant diseases appeared typical for the region in recent years.

3.3.1.3 S and F content in western hemlock needles

Based on the results of the 2019 Comprehensive Review (ESSA et al., 2020a), 2020 was the final year of regularly scheduled sampling of foliage for S and F as the program transitions to a more ecological focus, and it is thus no longer part of the SO_2 EEM Program. We do refer the reader, however, to Coosemans, Grossmann and Laurence (2024) for background and results of the VMP, related not to the EMP, but to the P2 Permit conditions associated with the restart of the smelter, which took place from 2022 to 2023, following the labour disruption of 2021.

Per the amended schedule, soil samples were not collected at sites as part of the PCMP field session, as they were collected at all of the Program's established sites in 2022 (with the exception of Site B06, for which soil sampling was attempted but could not be obtained owing to the presence of deep organic layers). At that time, composite mineral soil samples, collected at 0-10cm and 10-20cm depths near the four outer corners of each PCMP field plot, were subsequently analysed for pH, exchangeable cations and exchangeable acidity. Those 2022 results are summarized below, though they were not part of the 2023 Program.

In analysed samples, pH ranged from 4.03 (B40 0-10cm sample) to 6.10 (B23 0-10cm sample), and averaged 4.84. CEC ranged from 4.8 (B23 0-10cm sample) to 65.0 (B24 0-10cm sample), and averaged 29.6 meq/100g. Of exchangeable cations, potassium and sodium were below detection limits in all samples; calcium ranged from undetectable to 2120 mg/kg (B08 0-10cm sample), averaging 520.63 mg/kg; and magnesium ranged from undetectable to 173 mg/kg (B36 0-10cm sample), averaging 100.79 mg/kg. This information can inform a ranking of sites that may be more sensitive than others to acidification: Sites most sensitive to acidic deposition have soil pH <5 at both 0–10 cm and 10–20 cm depths (but mostly <4.5, as Al^{3+} is only present below this pH), and exchangeable Ca <1.0 meq/100g; based on this, the more sensitive PCMP sites potentially include B02, B04, B10, B20, B40 and B42.

The Program's requirements for soil sampling have been fulfilled to the degree possible, for all established sites, and no further sampling is scheduled to occur unless a new, previously unsampled site is added to the Program. As described in Laurence et al. (2020), "[t]he purpose of sampling is to assess the sensitivity of the soils to acidification, not to measure and detect differential changes in soil chemistry over time." Similarly, in accordance with Laurence et al. (2020), Ion Exchange Resin (IER) columns have not been deployed at any of the PCMP sites in 2021, 2022 or 2023. Use of IER columns would be triggered if necessary to establish causality, if biologically significant differential changes in vascular plant or cyanolichen communities are detected between low and high S deposition sites, and in that case will be planted vertically in the soil to measure SO_4^{2-}, base cations, and aluminum. Additionally, if triggered as described, above-ground IER columns may be used at selected locations to quantify actual S deposition depending on the risk of soil acidification.

3.3.2 End-of-Cycle

The Program is designed to detect potential *differential trends* across deposition zones in the biodiversity of vascular plants in the low shrub and forb layers, and of arboreal cyanolichens, in forest ecosystems of the Kitimat Valley. Figure 3-17 shows all sites in the Kitimat & Kemano Valleys that are established as active sites, those removed from the Program ("dropped plots"), and alternate sites. As only one assessment of each site has been made at this first end-of-cycle juncture, it is not yet possible to analyse those trends for species and sites. Instead, we have taken advantage of the moment to examine the balance of the sites in relation to deposition zones, and determine if there are any initial trends or issues to be aware of. These results are documented in full in Coosemans, Grossmann and Schwarz (2024), and key points are summarized here.

Overall, a number of relatively minor logistical challenges were met and adjusted for over the initial three years of the program. Investigation of the data through a statistical/analytical lens suggests that the challenges encountered and adjustments made are robust and support effective future analysis. While a total of two sites have been lost, or "dropped" from the program during this time, this has not had a negative material impact on the program because they were dropped and subsequently replaced during the initial measurement period, and thus there has been no loss of data or time required to obtain remeasurement for the program (i.e., it requires two or more assessments over different years to obtain a trend line, and there is no loss when a site is removed during its first assessment if it is replaced during the same time period). Replacement of the two sites will result in a more robust program going forward.

As expected, an examination of plant diversity profiles showed no strong differentiation based on deposition, both for individual sites and for sites grouped by deposition zone. Similar analyses for cyanolichens showed a [pre-existing] differentiation owing to historical injury to lichens in proximity to the smelter, with species richness highest in the low deposition zone and lowest in the high deposition zone. Analysis also demonstrated that the high deposition zone is more dominated by common cyanolichen species.

Dr. Carl J. Schwarz noted in his statistical examination of the data (Coosemans, Grossmann and Schwarz 2024) that a few plots and transects had very low covers. While they did not differentiate by deposition zone, they do provide very limited data, thereby reducing the power to detect future change. We thus recommend that, *in cases of low cover transects*, line transects be conducted on all four plot boundaries in future assessments, rather than just north and east sides, to increase total transect length and subsequently increase the likelihood of encountering vegetation and thus increase power to detect change over time. This recommendation could be tested for efficacy over the next cycle of measurements and then its usefulness could be re-examined. There may also be an interest in examining sites with low abundance on a less frequent schedule, potentially bringing in additional sites to the Program to accommodate a less frequent re-measurement at some sites, and we therefore recommend examining this possibility together with Ministry staff.

Similarly, the examination of the end-of-cycle data again raised the issue of a lack of an effective abundance measure for cyanolichens: While tallies provide some data, they give little indication of whether there is “a little” or “a lot” of any particular cyanolichen species. While this was acknowledged and discussed with Ministry staff prior to implementation of the PCMP, no effective solution resulted. Nonetheless, we recommend trialing “coarse” metrics of abundance during the next cycle of measurements in an effort to create a more meaningful cyanolichen biodiversity assessment in future years of the program.

Analysis of plant and cyanolichen health assessments across the years showed no patterns related to deposition.

An examination of plant phenology suggested that virtually all plants assessed were fully developed (vegetatively) at the time of assessment (ranging from June 14 through July 8 across years). The timing period has been set considering a range of factors, including vegetation emergence and development, and avoidance of extreme effects of potential environmental stressors related to weather, pests and pathogens. Although noted that some species may occasionally emerge later, these are not common species in terms of either presence or abundance in plots, and thus field-timing is thought to be appropriate to meet the objectives of the PCMP. Wherever practical, future field timing will be scheduled to occur during the later part of the established period.

Results from this first end-of-cycle exercise (Coosemans, Grossmann and Schwarz 2024) have shown that the design of the project appears to be robust to individual site differences, and that many species overlap sites across the deposition zones, which will aid future trend analysis comparisons. This deeper dive into the data has resulted in a number of recommendations, and also assurance that the Program is on a good footing going forward: After the collection of three years of data, we find that the results support the goals and objectives of the monitoring program.

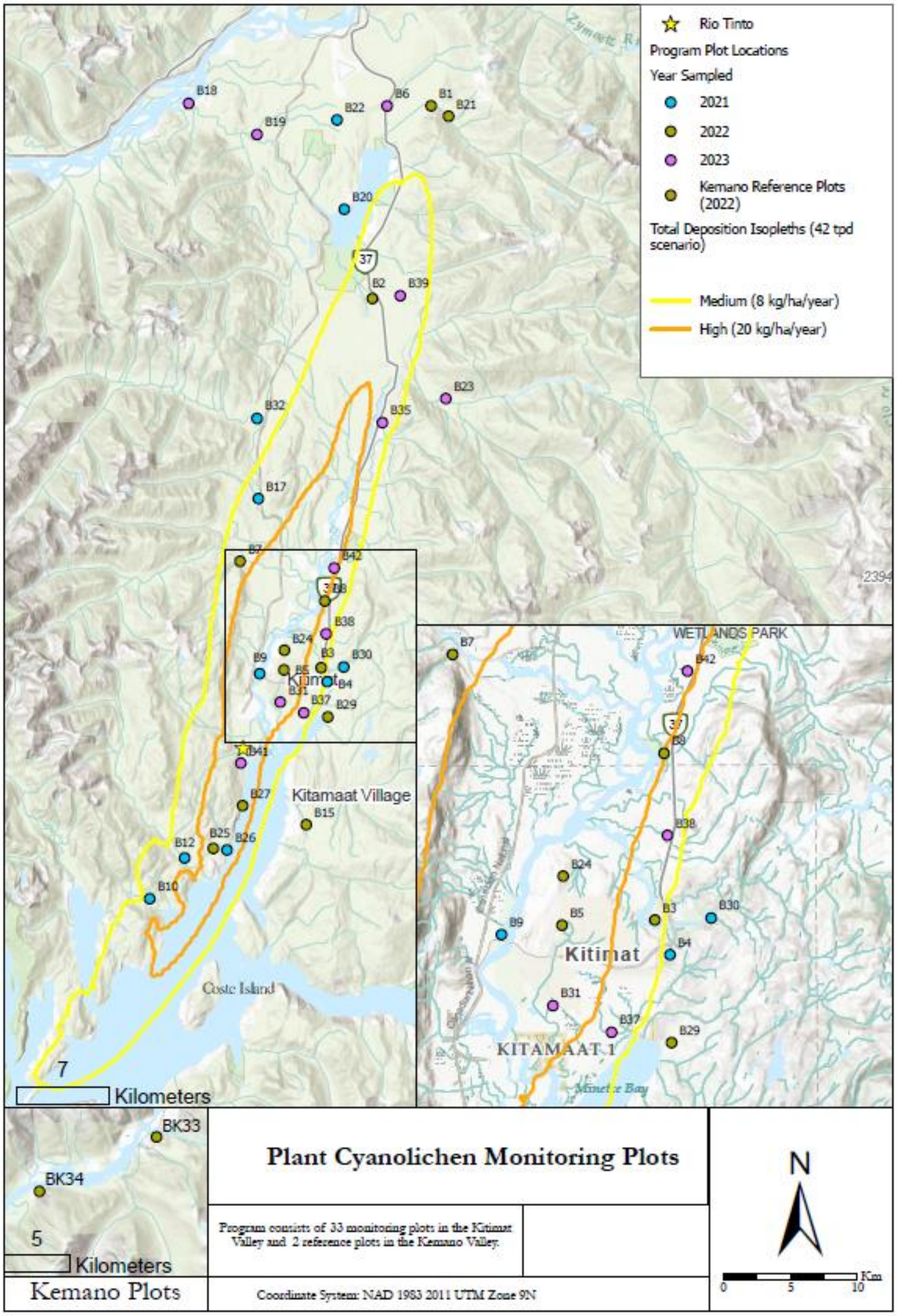

Figure 3-16. Map showing sites assessed during each year (2021-2023) in relation to sulphate deposition isopleths.

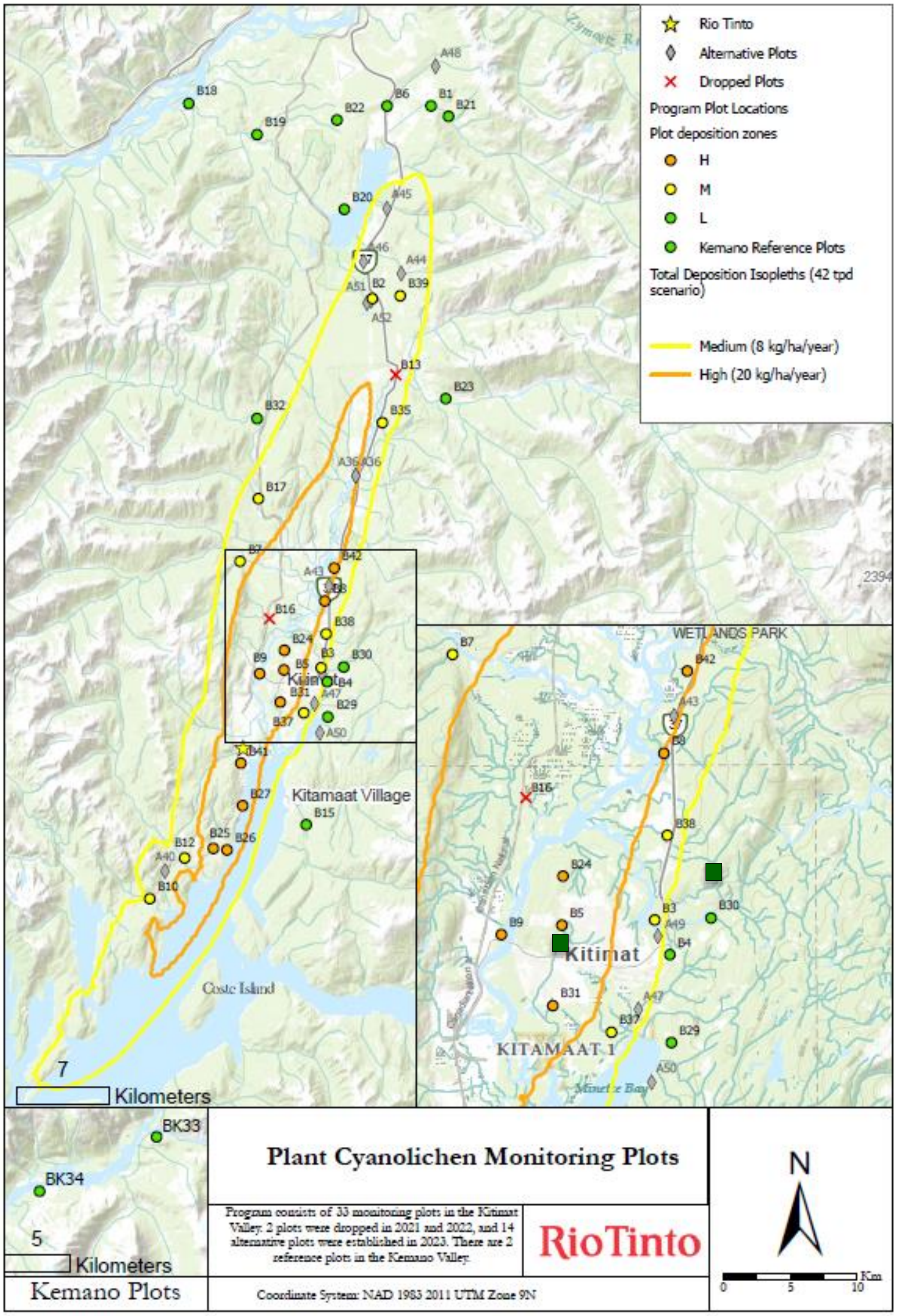

Figure 3-17. Map showing all sites in the Kitimat & Kemano Valleys that are established as active sites, those removed from the Program ("dropped plots"), and alternate sites.

3.3.3 Soils

Trent University returned to Kitimat in 2023 for two weeks to re-sample the permanent soil sample plots, and complete field sampling for two student-led projects on wetland geochemistry and aluminium solubility in soils (see Figure 3-18 for sample site locations).

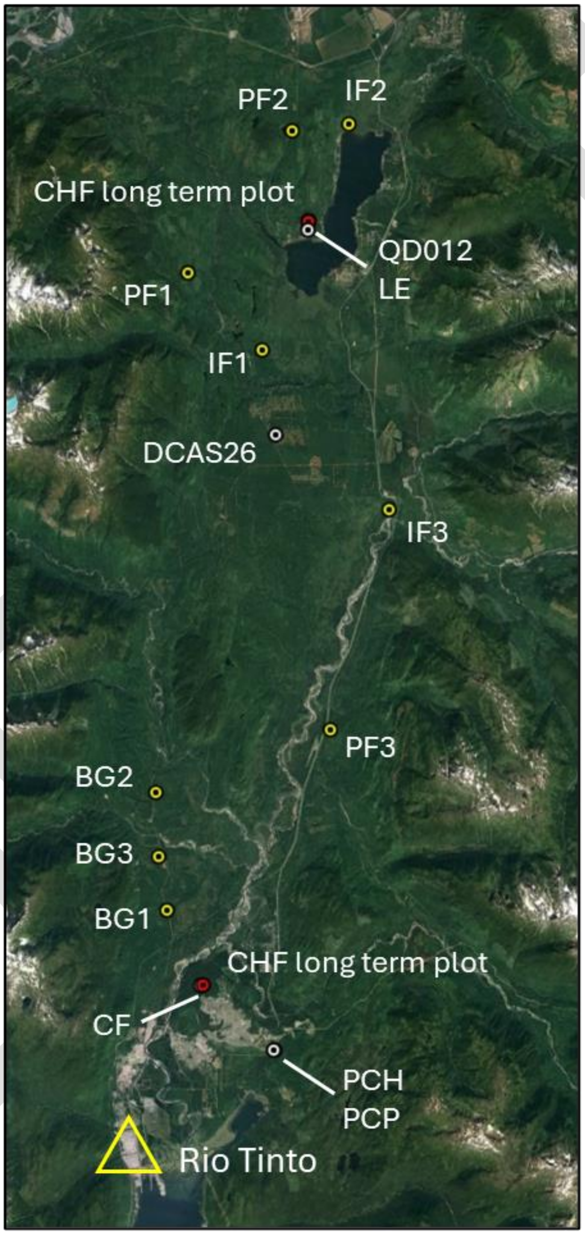

Figure 3-18. Location of study site sampled during May 2023: long term soil plots (red-filled circle; n = 2), wetland geochemistry plots (yellow-filled circle; n = 9), and aluminium geochemistry (white-filled circle; n = 6). See Table 3-7 and Table 3-9 for Site ID.

3.3.3.1 Long Term Soil Plots

The permanent soil monitoring plots at Coho Flats and Lakelse Lake were re-sampled during May 2023 as part of Trent University's project scope in their visit to Kitimat. The re-sampling of the plots in 2023 is five years since the last sampling event in 2018. Sub-plots (2 m x 2 m) of the larger 32 m x 30 m permanent plots were sampled at three depths in the mineral soil: 0–5 cm, 5–15 cm, and 15–30 cm depths (yielding a maximum of 60 soil samples for each plot, i.e., three soil samples by depth within each of the 20 lettered sub-plots). Diameters of trees (at breast height) within the permanent soil plots were also measured. Analysis of the soils will be completed in 2024 and the assessment of the long-term soil acidification KPI will be presented in the 2024 SO_2 EEM Annual Report.

3.3.3.2 Assessment of Wetland Geochemistry and Aluminium Solubility in Mineral Soils

The 2019 Comprehensive Review (ESSA et al., 2020a) identified two data uncertainties in the KPI Critical Load Exceedance. This KPI uses measured soil physical and chemical data from regional surveys to model and map the magnitude and level of exceedance of critical loads of acidity (sulphur) for soils. Firstly, the Comprehensive Review recommended that a survey of wetland geochemistry and sulphur storage be carried out, since wetlands make up ~25% of the exceeded area yet there is no chemical information on wetlands (soil and water) in the Kitimat valley. Secondly, the Comprehensive Review recommended an assessment of aluminium solubility in mineral soils be carried out as it is a key parameter in the determination of critical loads. This work plan describes the field sampling and laboratory analysis of wetland geochemistry, and aluminium solubility in mineral soils.

Wetland Geochemistry

Organic soil and pore water were collected from nine wetland locations within the study domain of the SO_2 EEM program (see Figure 3-18 and Table 3-7). Preliminary site selection was carried out by overlaying wetland coverage data from the BC Freshwater Atlas with the road and trail network from CanMap® (DMTI Spatial[16]). Site selection was primarily focused on site accessibility rather than wetland type (e.g., rich fen, poor fen, swamp, and bog). Field assessment for accessibility and safety was completed by Limnotek prior to field collection by Trent University.

Wetland soils were sampled following established procedures; at each wetland site, a 20 m transect was established, at a distance of 5–10 m from the edge of the wetland, with three sampling locations denoted A, B, and C (i.e., ends and middle of transect). At each of the three sampling locations, porewater (30–60 cm) and organic soil (at 15 cm and 30 cm depths below the vegetation layer) were sampled for chemical analysis. Wetland classification (i.e., bog, poor fen, or intermediate fen) for each study site (n = 9) was based on the average pH of their organic soil[17]. There were three sites for each wetland type (i.e., bog, poor fen, and intermediate fen; see Table 3-7).

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[16] Information: https://www.lightboxre.com/product/canmap

[17] MacKenzie, W., & Shaw, J. (2000). Wetland classification and habitats at risk in British Columbia. In Proceedings of a conference on the biology and management of species and habitats at risk (Vol. 2, pp. 537–47). Rydin, H., & Jeglum, J. K. (2013). The biology of Peatlands, 2e (2nd ed.). Oxford University Press.

Table 3-7. Site coordinates (latitude and longitude), distance from smelter (km), soil pH, and wetland type (bog, poor fen, or intermediate fen) for the nine study sites. See Figure 3-18 for mapped location.

Site ID	Latitude	Longitude	Distance	pH	Wetland Type
	decimal degrees		km	(H_2O)	
BG1	54.10614	−128.67566	20.1	4.18	Bog
BG2	54.15282	−128.68304	28.8	4.05	Bog
BG3	54.12742	−128.68121	24.1	3.50	Bog
PF1	54.35798	−128.66148	68.0	5.44	Poor Fen
PF2	54.41400	−128.59084	79.5	4.72	Poor Fen
PF3	54.17754	−128.56529	36.7	4.76	Poor Fen
IF1	54.32755	−128.61119	62.9	5.78	Intermediate Fen
IF2	54.41705	−128.55238	80.9	5.71	Intermediate Fen
IF3	54.26446	−128.52548	53.8	5.68	Intermediate Fen

All samples were shipped to Trent University for chemical analysis. Wetland soils will undergo chemical analysis for organic matter content, pH, and exchangeable cations following methods described in the 2019 Comprehensive Review (ESSA et al., 2020a) and in the literature[18]. Porewater will undergo chemical analysis for pH, alkalinity, conductivity, and major ion chemistry, similar to lake water samples as described in the Comprehensive Review. Results will be reported in the 2024 SO_2 EEM Annual Report.

Aluminium Solubility in Mineral Soils

The aluminium solubility study focuses on mineral soils, which are defined as soils with an organic matter content below 40%. Forest soil at three depths (0–10 cm, 15–25 cm and 40–50 cm) were collected along a gradient of low to high organic matter content, as organic matter is known to influence the availability and speciation of aluminium (see the 2019 Comprehensive Review (ESSA et al., 2020a)).

Selection of the sampling sites focused on soils previously sampled under several monitoring programs in the Kitimat Valley; as described in the 2019 Comprehensive Review, 93 sites were sampled for soils during 2012–2017 following consistent field sampling and laboratory analysis protocols. A sub-set of six sites were selected for aluminium geochemical analysis, varying from plots with low organic matter content (< 5%) to plots with a high organic matter content (>30%) soils (see Table 3-8).

Similar to the wetlands, mineral soils for geochemical analysis were sampled following established field procedures for mineral forest soils under the Sulphur Dioxide Technical Assessment Report and the 2019 Comprehensive Review. At each sampling location, a 20 m × 20 m plot was established. Mineral soils were sampled at three depths (0–10 cm, 15–25 cm and 40–50 cm below the forest floor) from the plot's four corners and centre point using a soil auger and composited by depth.

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[18] https://acsess.onlinelibrary.wiley.com/doi/full/10.2134/jeq2009.0341

Table 3-8. Site ID, location (latitude and longitude), pH (H2O), and organic matter content (%) for the six aluminium solubility study sites.

Site ID	Latitude	Longitude	pH (H_2O)	Organic matter (%)
QD012	54.37511	−128.58016	5.80	4.9
LE	54.37882	−128.57971	4.60	9.4
DCAS26	54.29401	−128.60208	3.95	22.2
PCP	54.05092	−128.60365	4.34	14.9
PCH	54.05095	−128.60322	3.78	23.0
CF	54.07642	−128.65286	4.55	34.3

All samples were shipped to Trent University for chemical analysis. For each site a composite sample (0–50 cm) was prepared (dried and sieved) and packed into replicate soil leaching columns (three replicates per site). Analysis that will be complete in 2024 include subjecting composite samples from each site to five pH treatments (pH 2.0, 2.5, 3.0, 4.0, and 5.0), as it is well established that soil water pH influences the speciation and mobility of aluminium. Solutions with a range of pH values will be added to each leaching column and the leachate will be collected for chemical analysis of aluminium (using ICP-OES), pH, and DOC (dissolved organic carbon). In addition, a sub-sample of each leachate solution will be passed through a solid phase extraction column (Agilent Bond Elut Jr Strong Cation Exchange) to separate organically bound from free aluminum following established methods[19], and again analysed for aluminium by ICP-OES. Results will be reported in the 2024 SO_2 EEM Annual report.

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[19] https://pubs.acs.org/doi/10.1021/es020077i

3.4 Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)

This section contains a condensed summary of the major actions and knowledge gained in 2023 with respect to the Aquatic Ecosystems receptor. Further detail can be found in the Aquatic Ecosystems Actions and Analyses Technical Memo W12 (provided in Appendix C) and the Technical Report of Lake Monitoring in 2023 (provided in Appendix D).

3.4.1 Major Actions Taken in 2023

The Phase III EEM sampling plan includes eleven lakes: seven sensitive lakes, one less sensitive lake, and three control lakes (ESSA et al., 2023). The three control lakes (NC184, NC194 and DCAS14A) are all located outside of the zone of sulphur deposition from B.C. Works, and have pre-KMP baseline data for 2013 from sampling as part of the Kitimat Airshed Emissions Effects Assessment (ESSA et al., 2014). Sampling of these eleven EEM lakes was conducted in accordance with the EEM Phase III Plan.

LAK027 was added for one-time sampling in 2021, as agreed to by B.C. ENV and Rio Tinto in May 2021. The intent was to resample one of the Sulphur Dioxide Technical Assessment Report (STAR) (ESSA et al., 2013) lakes located relatively close to the smelter to check the validity of the conclusions made in the STAR, based on sampling completed in 2012, nine years prior to 2021. LAK027 was chosen because it was the only candidate that was moderately sensitive, whereas all the other lakes in the southern portion of the Kitimat Valley were determined to be insensitive based on the sampling during the STAR (except for LAK028, which was already included in the SO_2 EEM Program because of its sensitivity). LAK027 was sampled again in 2022 and 2023, as per rationale summed up in the following recommendation from the SO_2 EEM Program 2022 EEM Annual Report: "*We recommend sampling LAK027 again in 2023. In 2021, the widely-observed storm-driven dilution event negated the ability of the sampling data to provide a meaningful comparison against the initial STAR data as intended. In 2022, the combination of exceptionally low deposition and particularly dry hydrologic conditions again negate the ability to provide the intended comparison.*"

We examined the empirical changes in water chemistry between the pre-KMP baseline (2012) and the last three years (2021-2023, representing the current post-KMP period), especially with respect to the KPI thresholds (Table 3-9). We also conducted statistical analyses on the changes between these two periods, repeating two sets of analyses applied in (and since) the 2019 Comprehensive Review (ESSA et al., 2020a) with the more recent years of data: 1) the Bayesian "Method 1" to assess the % belief that any of the lakes had exceeded their KPI or informative indicator thresholds; and 2) the "Method 3" before-after control-impact (BACI) analyses of the differential trends between the sensitive EEM lakes (individually and as a group) and the control lakes for the same four metrics.

The five lakes that were unable to be sampled in 2020 (due to COVID-related constraints on helicopter flights) were sampled again in 2021, 2022 and 2023 as per previous years and therefore these lakes once no longer have any missing data within the post-KMP 3-year averaging period.

Finally, we applied the simplified evidentiary framework with the results from the Bayesian statistical analyses, as per previous years. The current version of the evidentiary framework was developed in 2020 to more fully align with the two-threshold structure of the KPI and acidification informative indicators in the EEM Phase III Plan. The revision and rationale with respect to the version from the 2019 Comprehensive Review are described in Section 2.6 of Technical Memo W09.

3.4.2 Knowledge Gained from Actions taken in 2023

3.4.2.1 Annual Context – Very Dry Conditions plus Increase in Emissions from 2022 Low

Precipitation / Hydrologic Context
This year we are using data from the two NADP stations (Haul Road, BC22; Lakelse Lake, BC23) to provide the precipitation context (and by proxy, the hydrologic context of the lakes) for 2023, which is a significant improvement over the use of publicly available precipitation in previous years.

British Columbia experienced significant and widespread drought conditions across much of the province in 2023. This broad pattern is borne out in the precipitation data from the Haul Road and Lakelse Lake NADP sites, which show that 2023 was exceptionally dry relative to recent years for the Kitimat Valley as well.

On September 30, 2023 (i.e., when all lakes are sampled), the cumulative precipitation for August-September was notably lower than any of the previous 4 years. Similarly, total precipitation in the month of September alone was much lower in 2023 than in each of the previous 4 years at Haul Road, and lower or similar for Lakelse Lake.

Emissions Context
As described in detail in last year's EEM Annual Report, 2022 was exceptional in the 11-year history of the SO_2 EEM Program. Emissions from the smelter were dramatically less than in any previous year of the SO_2 EEM Program due to a reduction in smelter operations associated with a labour dispute. In August 2021, emissions dropped by approximately 83%. Emissions did not begin to increase meaningfully until July 2022, after 11 months of emissions <5.3 tpd, and did not reach pre-dispute levels until May 2023.

At the time of the annual sampling at the end of September 2022, the 12-month and 6-month average emissions were only 21% and 24%, respectively, of the levels prior to the labour dispute. The comparable time periods relevant to 2023 annual sampling were at 82% and 104% of the pre-reduction levels. We therefore do not consider 2023 to be exceptional in terms of absolute emissions levels. However, 2023 does represents the most substantial year-over-year increase in emissions. Given that 5 of 7 sensitive lakes have water residence times less than or equal to 9 months, this rapid increase could potentially have a notable impact on lake chemistry, albeit perhaps simply offsetting the changes associated with the original reduction.

In the 2022 Annual Report, we stated:

> *We expected that the decline in SO_2 emissions would cause a decline in lake [SO_4], and possibly an increase in CBANC, Gran ANC and pH, in at least the 5 sensitive EEM lakes with short water residence times. Increases in lake [SO_4] are generally associated with increases in lake base cations, due to*

> *cation exchange processes in the watershed. The converse also holds: decreases in lake [SO_4] would be expected to result in lower base cation concentrations.*
>
> *The dominant responses in the 2022 data were generally consistent with our expectations […]*

Given the significant increase in emissions from 2022 to 2023, we might expect to see the reverse of the consistent, regional patterns observed in 2022; however, the responses in the 2023 only partially align with that hypothesis:

- [SO_4] did increase in all sensitive lakes, except LAK028
- Gran ANC only decreased in roughly half of the sensitive lakes (3 of 7) and increased slightly in the others
- CBANC only decreased in roughly half of the sensitive lakes (4 of 7)
- pH only decreased in roughly half of the sensitive lakes (4 of 7); however, all 7 sensitive lakes had changes of only <0.1 pH units

3.4.2.2 Empirical Changes in Water Chemistry

Empirical changes in CBANC, pH, Gran ANC, SO_4^{2-}, DOC, sum of base cations, chloride, and calcium are shown in Table 3-9. Changes are reported in terms of the difference between the current post-KMP averaging period (2021-2023) and the pre-KMP baseline (2012 for the sensitive and less sensitive lakes; 2013 for the control lakes). The sensitive EEM lakes and less sensitive EEM lakes are presented separately within each of the tables. The inter-annual changes presented in this report use the mean annual values whenever multiple within-season samples were acquired from a given lake in a given year.

The mean values of CBANC for the post-KMP averaging period indicate that there have been no exceedances of the KPI thresholds (Table 3-11). However, the formal analysis of the KPI is done with the results of the Bayesian statistical analyses.

To protect aquatic ecosystems in the sensitive lakes, we want to avoid declines in recent post-KMP measurements of CBANC, Gran ANC, BCS, and pH (i.e., the KPI and other acidification informative indicators) that are greater than the established thresholds (Table 3-11), using 2012 as a pre-KMP baseline. We use the average of the most recent 3 years to dampen the effects of an unusual year.

Five of the seven sensitive lakes show increases in CBANC since the 2012 baseline (Table 3-9). LAK012 and LAK028 are the only two lakes that show a long-term decline in CBANC (-12.5 µeq/L in LAK012, and -0.7 µeq/L in LAK028; (Table 3-9). For context, the lake-specific *change limit* threshold for ANC in LAK012 is -16.3 µeq/L, but the mean CBANC over the last 3 years (101.9 µeq/L) is well above the *level of protection* threshold (20 µeq/L). For LAK028, the magnitude of decline has decreased over the past two years (from -7.9 µeq/L to -2.9 µeq/L to -0.7 µeq/L); these changes are less than the *change limit* threshold ANC for LAK028 of -13.4 µeq/L and the current mean CBANC (15.3 µeq/L) is below the *level of protection* threshold (20 µeq/L) but similar to the 2012 baseline (16.0 µeq/L). LAK012 and LAK028 also continue to be the only two sensitive lakes with a long-term decline in BCS. The decline in BCS for LAK012 (-16.7 µeq/L) is greater in magnitude than the previous three years, but the decline for LAK028 (-9.8 µeq/L) is less than the previous three years.

LAK012 shows a mix of responses. There have been declines in CBANC and BCS, but a small long-term increase in Gran ANC (2.3 µeq/L, relative to an ANC *change limit* threshold of -16.3 µeq/L) and the largest increase in pH across all EEM lakes (+0.4 pH units, relative to a pH *change limit* threshold of -0.3 pH units).

In LAK028 (the lake closest to the smelter with the highest deposition) mean [SO_4^{2-}] is estimated to have increased by 37.8 µeq/L since 2012, almost exactly balanced by an increase in total base cations (ΣBC*) of 37.6 µeq/L. The changes in ΣBC* and SO_4^{2-} essentially explain the negligible change in CBANC, a decline of 0.7 µeq/L. CBANC equals the sum of base cations minus the sum of strong acid anions, and ΔΣBC* - Δ[SO_4^{2-}] = 37.6 – 37.8 = –0.1, very close to the -0.7 µeq/L change in CBANC. Gran ANC shows a long-term increase (6.8 µeq/L) in LAK028 and there continues to be no decline in mean pH, similar to the results reported in the last couple years. LAK028 showed a decline in BCS of -9.8 µeq/L since the pre-KMP period (Table 3-9) though BCS has shown considerable variation in LAK028, with its lowest value occurring in 2013. The BCS *change limit* threshold is -13 µeq/L.

None of the sensitive or less sensitive lakes are showing any decline in pH. LAK022, which in the prior two EEM reports had been the only lake with a decline in pH, now shows no long-term change. All other sensitive and less sensitive lakes show a long-term increase in pH within the range of 0.1 to 0.4 pH units. By contrast, two of the control lakes (DCAS14A and NC194) show a long-term decline (-0.2 pH units) with the third control showing no change (NC184). The causes for the 0.2 pH unit declines in DCAS14A and NC194 are not clear, but they are not related to SO_2 emissions, since [SO_4] has declined slightly in all three control lakes (Table 3-9) and there is no statistical evidence of a long-term increase in [SO_4] (Table 3-9).

For the CBANC KPI, only 2 of the 7 sensitive lakes (LAK028 and LAK044) have values for the post-KMP averaging period (2021-2023) below the *level of protection* threshold. Both of those lakes were already below that threshold in 2012 (and the alternate, transition period baseline) and neither of those lakes have exceeded the *change limit* threshold (LAK028 shows a decrease of -0.7 µeq/L; LAK044 shows an increase of +8.8 µeq/L). None of the 7 sensitive lakes exceeded the *change limit* threshold and only two lakes (LAK012 and LAK028) show long-term decreases in CBANC of any magnitude. In the sensitivity analyses with the alternate, transition period baseline (2012-2014), LAK012 is the only lake with an estimated long-term, albeit minor, decrease in CBANC (-2.0 µeq/L). The empirical data therefore indicate that none of the lakes exceeded the KPI (albeit the formal evaluation of the KPI is conducted with the results of the statistical analysis).

For the pH informative indicator (highlighted here due to being the former KPI in Phase II), 5 of the 7 sensitive lakes (LAK022, LAK023, LAK028, LAK042, and LAK044) have values for the post-KMP averaging period (2021-2023) below the *level of protection* threshold (a pH of 6.0). As described in the STAR (section 9.4.1.2.4), all 7 sensitive lakes were already below pH 6.0 in 2012, reflecting primarily the influence of organic acids and in some cases the effects of historical smelter emissions (particularly in LAK028). Four of the lakes have been at or below pH 6.0 throughout the entire period of record. None of the sensitive lakes show any decrease in pH relative to 2012 and therefore none have exceeded the *change limit* threshold. In the sensitivity analyses with the alternate, transition period baseline (2012-2014), LAK022 shows a decrease of ~0.2 pH units, LAK028 shows a decrease of ~0.1 pH units, and the other 5 sensitive lakes show no change. The empirical data therefore indicate that none of the lakes have exceeded the pH informative indicator.

Resampling of LAK027

The results for LAK027 are shown in Table 3-6 in Technical Memo W12. LAK027 was resampled for a third year in 2023 due to the influence of anomalous regional hydrologic and emissions conditions in 2021 and 2022. We compared conditions in 2023 to those in 2012 to achieve the original intent of resampling this lake. CBANC, Gran ANC, BCS, SO_4, DOC, base cations, and Cl all roughly doubled from 2012 to 2023, and pH increased by 0.1 pH units. The relative difference between the 2012 to 2023 increases in ΣBC^* (219.5 µeq/L) and SO_4^{2-} (124.2 µeq/L) almost perfectly explains the 94.6 µeq/L increase in CBANC between 2012 and 2023 (i.e., 219.5 – 124.2 = 95.3 µeq/L). The data suggest that LAK027 demonstrates a high level of watershed neutralization of deposited SO_4^{2-}, as well as hydrologic change. The implied F-factor ($\Delta BC^*/\Delta SO_4^* = 219.5 / 124.2 = 1.76$) is greater than 1.0 (indicative of complete neutralization of all deposited acidity), indicating that other factors besides cation exchange likely contributed to the increase in base cations (e.g., higher rates of weathering due to warmer temperatures, less runoff).

Table 3-9. Empirical changes in CBANC, Gran ANC, BCS, pH, SO_4^{2-}, DOC, base cations, chloride, and calcium for EEM lakes. These values represent the difference between the post-KMP averaging period (2021-2023) and the 2012 baseline. Numbers shown are the value in the later period minus the value in the earlier year. Increases are shaded in green; decreases are shaded in red. The Gran ANC and pH values are based on the "integrated" time series (i.e., values from the Trent University laboratory from 2012 to 2019 with the 2020, 2021, 2022, and 2023 values imputed from the values measured by the BASL laboratory ("integ"); see details in Section 2.1 of Technical Memo W12).

SITE	CBANC (µeq/L)	Gran ANC (integ) (µeq/L)	BCS (µeq/L)	pH (integ)	SO4* (µeq/L)	DOC (mg/L)	∑ BC* (µeq/L)	Cl (µeq/L)	Ca* (µeq/L)
LAK006	19.0 [-]	10.8 [-]	15.7 [+]	0.2 [+]	3.3 [-]	0.7 [-]	22.5 [-]	0.4 [-]	12.2 [-]
LAK012	-12.5 [-]	2.3 [-]	-16.7 [-]	0.4 [+]	6.2 [-]	0.8 [-]	-6.0 [-]	1.6 [-]	-7.2 [-]
LAK022	7.2 [+]	1.3 [+]	5.4 [+]	0.0 [+]	5.1 [-]	0.4 [-]	12.4 [+]	0.3 [ ]	6.5 [+]
LAK023	8.8 [-]	3.1 [-]	3.4 [-]	0.2 [ ]	-1.3 [+]	1.1 [-]	8.1 [-]	0.2 [-]	5.5 [-]
LAK028	-0.7 [+]	6.8 [+]	-9.8 [+]	0.1 [+]	37.8 [-]	1.8 [-]	37.6 [-]	1.9 [-]	27.1 [-]
LAK042	10.3 [-]	26.0 [+]	19.5 [+]	0.4 [+]	1.4 [-]	-1.8 [-]	11.8 [-]	-0.5 [ ]	6.9 [-]
LAK044	8.8 [+]	4.5 [+]	8.0 [+]	0.2 [ ]	-2.8 [-]	0.2 [-]	6.2 [ ]	0.3 [-]	1.8 [-]
Total ↑	**5**	**7**	**5**	**6**	**5**	**6**	**6**	**6**	**6**
Total ↓	**2**	**0**	**2**	**1**	**2**	**1**	**1**	**1**	**1**

SITE	CBANC (µeq/L)	Gran ANC (integ) (µeq/L)	BCS (µeq/L)	pH (integ)	SO4* (µeq/L)	DOC (mg/L)	∑ BC* (µeq/L)	Cl (µeq/L)	Ca* (µeq/L)
LAK016	8.7 [-]	19.9 [-]	-1.0 [+]	0.1 [+]	9.0 [-]	1.9 [-]	18.3 [-]	1.1 [-]	10.5 [-]
Total ↑	**1**	**1**	**0**	**1**	**1**	**1**	**1**	**1**	**1**
Total ↓	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**

SITE	CBANC (µeq/L)	Gran ANC (integ) (µeq/L)	BCS (µeq/L)	pH (integ)	SO4* (µeq/L)	DOC (mg/L)	∑ BC* (µeq/L)	Cl (µeq/L)	Ca* (µeq/L)
DCAS14A	19.5 [+]	4.1 [+]	18.2 [+]	-0.2 [+]	-2.9 [+]	0.2 [-]	13.8 [+]	-2.4 [+]	8.4 [+]
NC184	5.6 [+]	13.4 [+]	15.1 [+]	0.0 [+]	-1.6 [+]	-1.9 [-]	3.9 [+]	-4.7 [+]	6.7 [+]
NC194	2.7 [+]	-1.8 [+]	1.5 [+]	-0.2 [+]	-1.9 [-]	0.2 [-]	0.9 [+]	-1.6 [+]	1.1 [+]
Total ↑	**3**	**2**	**3**	**1**	**0**	**2**	**3**	**0**	**3**
Total ↓	**0**	**1**	**0**	**2**	**3**	**1**	**0**	**3**	**0**

3.4.2.3 Statistical Analyses of Changes in Water Chemistry

We have summarized the key results of the statistical analyses of changes in lake chemistry in Table 3-9 and Figure 3-19. These results applied Bayesian Method 1, described in Appendix F of the 2019 Comprehensive Review (ESSA et al., 2020b).

We evaluated the KPI and the informative indicators using the two-threshold structure (Table 4-2 in Technical Memo W12). **None of the 11 EEM lakes have a high % belief in exceedance of either the KPI or any of the informative indicators.** None of the 11 EEM lakes have even a moderate % belief in exceedance of the KPI – **all lakes show a low % belief in exceedance of the CBANC KPI.** However, two sensitive EEM lakes and one control lakes show moderate % belief of one or two of the informative indicators:

- LAK022 shows moderate % belief in exceedance of pH
- LAK028 shows moderate % belief in exceedance of BCS

- NC184 (a control lake) shows moderate % belief in exceedance of Gran ANC and pH (unrelated to the smelter, as discussed above)

The results of the Bayesian statistical analyses are very similar to our previous report. The only changes in classification (across all lakes and metrics) from last year are the changes from moderate to low for Gran ANC in LAK022, BCS and pH in LAK042, and pH in NC194. All other results are the same as last year in terms of final classification.

This is now the fourth year that the Bayesian analyses were performed on CBANC. Despite the widespread changes in numerous water chemistry metrics observed in both 2021 and 2022, the CBANC results remain remarkably similar to the 2020 results for almost all of the lakes, suggesting that the CBANC metric may be robust to anomalous conditions.

This is the sixth year that the Bayesian analyses were performed for Gran ANC and pH. That length of time provides an opportunity to see how the results have changed since these analyses were first implemented in the 2019 Comprehensive Review. The results have remained very stable over these six years. For Gran ANC, there are only two of eleven lakes that have showed any change in category over the six years of repeating the analyses: LAK022 and NC194 changed from low to moderate, albeit still at the low end of the moderate range (~30% belief), and LAK022 has returned to low again in 2023. For pH, 2 sensitive lakes, 1 less sensitive lake, and all 3 control lakes changed categories – from low to moderate in all cases. In all cases, the shift occurred with the 2021 results (likely driven by high precipitation in September 2021[20]) and the 2022 results remained quite similar. LAK042 and LAK016, which were only in the low end of the moderate category for pH change, have returned to low in 2023. LAK022, DCAS14A, NC184, and NC194 are in the lower-mid-range of the moderate category. Decreases in pH in the control lakes must be driven by factors other than the smelter because they are well outside the deposition plume, and all three control lakes have a low percent belief in any sulphate increase.

The key outcomes from the BACI (before-after control-impact) analyses include:

- For, Gran ANC, BCS, and pH (i.e., all four primary metrics analyzed) none of the lakes showed a statistically significant effect (i.e., before-after differences that were significantly different than the before-after changes in the control lake group)
- The direction of the BACI effects (i.e., changes in the sensitive lakes versus changes in the control lakes):
    - For CBANC, changes were more positive for all lakes
    - For pH and Gran ANC, changes were mixed
    - For BCS, changes were predominantly more negative
    - However, none of these differences were statistically significant
- When analysed as a group with all seven sensitive EEM lakes combined:
    - Changes in CBANC, Gran ANC, BCS, and pH were not statistically significant
- Two previously statistically significant results (from 2022) are no longer statistically significant:
    - ΔpH in LAK012 was more positive than controls
    - ΔpH in sensitive lakes (as group) more positive than controls

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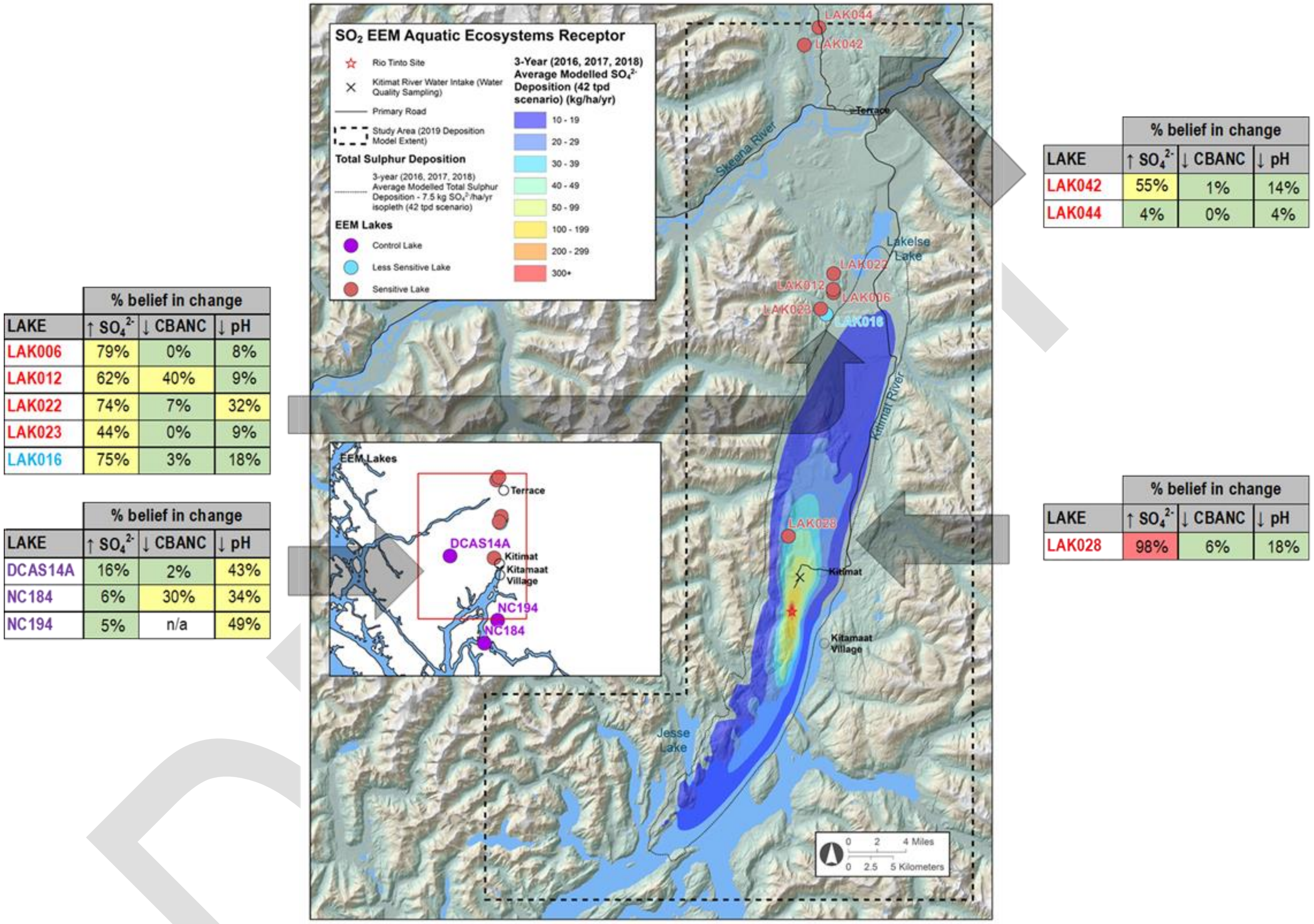
[20] Note: 4 out of these 5 lakes were not sampled in 2020, meaning the 2020 results were based only on 2018-2019, and therefore it is not actually possible to determine whether the shifts that show up in the 2021 results reflect changes in lake chemistry in 2020, 2021 or both

Table 3-10. Summary of findings across all lakes monitored in the SO_2 EEM Program. The % belief values are derived from the Bayesian version of Method 1, as described in Aquatic Appendix F of the 2019 Comprehensive Review (ESSA et al., 2020b). Values of % belief < 20% are coloured green, 20-80% yellow, and >80% red.

	Changes in SO4	**Exceedance of *CHANGE LIMIT***				**Exceedance of *LEVEL OF PROTECTION***				**KPI and Informative Indicator Evaluation**			
	(% belief that threshold exceeded; from Bayesian analysis method 1)	(% belief that metric value has decreased by more than the threshold; from Bayesian analysis method 1)				(% belief that metric value is below threshold; from Bayesian analysis method 1)				(Classification of % belief that both the *change limit* and *level of protection* thresholds are exceeded)			
Metric	**SO4**	**CBANC**	**Gran ANC (integ)**	**BCS**	**pH (integ)**	**CBANC**	**Gran ANC (integ)**	**BCS**	**pH (integ)**	**CBANC**	**Gran ANC (integ)**	**BCS**	**pH (integ)**
Thresholds	Increase > 0	Lake-spec.	Lake-spec.	Δ 13 ueq/L	Δ 0.3 pH units	20 ueq/L	30.7 ueq/L	0 ueq/L	6.0 pH units	KPI	Inform. Indic.	Inform. Indic.	Inform. Indic.
LAK006	79%	0%	1%	2%	8%	0%	0%	0%	28%	LOW	LOW	LOW	LOW
LAK012	62%	40%	14%	62%	9%	0%	0%	0%	44%	LOW	LOW	LOW	LOW
LAK022	74%	7%	18%	8%	32%	0%	65%	0%	75%	LOW	LOW	LOW	MOD
LAK023	44%	0%	1%	2%	9%	0%	100%	0%	100%	LOW	LOW	LOW	LOW
LAK028	98%	6%	6%	43%	18%	100%	100%	100%	100%	LOW	LOW	MOD	LOW
LAK042	55%	1%	5%	12%	14%	0%	100%	21%	100%	LOW	LOW	LOW	LOW
LAK044	4%	0%	1%	0%	4%	99%	100%	0%	100%	LOW	LOW	LOW	LOW
LAK016	75%	3%	2%	25%	18%	0%	0%	0%	0%	LOW	LOW	LOW	LOW
DCAS14A	16%	2%	4%	9%	43%	0%	0%	0%	4%	LOW	LOW	LOW	LOW
NC184	6%	30%	26%	31%	34%	0%	48%	0%	82%	LOW	MOD	LOW	MOD
NC194	5%	▨	▨	6%	49%	0%	100%	0%	5%	noRel	noRel	LOW	LOW



LAK E	% belief in change ↑ SO$_4^{2-}$	↓ CBANC	↓ pH
LAK006	79%	0%	8%
LAK012	62%	40%	9%
LAK022	74%	7%	32%
LAK023	44%	0%	9%
LAK016	75%	3%	18%

LAKE	% belief in change ↑ SO$_4^{2-}$	↓ CBANC	↓ pH
DCAS14A	16%	2%	43%
NC184	6%	30%	34%
NC194	5%	n/a	49%

LAKE	% belief in change ↑ SO$_4^{2-}$	↓ CBANC	↓ pH
LAK042	55%	1%	14%
LAK044	4%	0%	4%

LAKE	% belief in change ↑ SO$_4^{2-}$	↓ CBANC	↓ pH
LAK028	98%	6%	18%

Figure 3-19. Spatial distribution of percent belief in chemical change from 2012 to 2021-2023. Numbers show % belief in: a) SO$_4$ increase [no threshold], b) CBANC decrease below lake-specific threshold, and c) pH decrease below 0.3 threshold. The % belief values are derived from the Bayesian version of Method 1, as described in Aquatic Appendix F of the 2019 Comprehensive Review (ESSA et al., 2020b). NC194 does not have an estimated ANC threshold because it did not have appropriate titration data available. NC194 does not have an estimated ANC threshold because it did not have appropriate titration data available.

3.4.2.4 Application of the Evidentiary Framework

We applied the evidentiary framework using the updated results of the statistical analyses (Figure 3-20; detailed results in Table 4-3 of Technical Memo W12). A lake may appear in different parts of the evidentiary framework depending on whether we use CBANC or pH as criteria (CBANC is the KPI and pH is an informative indicator). To be precautionary, we consider the lake's appropriate assignment to be the furthest position into the evidentiary framework. Results show that: a) 1 sensitive lake (LAK044) and all 3 control lakes[21] land within the first box, *"smelter not causally linked to changes in lake chemistry"*; b) 1 sensitive lake (LAK012) and 1 less sensitive lake (LAK016) land within the second box, *"lake is healthy, and not acidifying"*; and c) 5 sensitive lakes (LAK006, LAK022, LAK023, LAK028 and LAK042) land within the third box, *"some evidence of acidification; closely monitor"*. The situation for the lakes landing in the third box is expanded upon below.

For LAK028, this classification is based on: a) values for the post-KMP averaging period (2021-2023) below the *level of protection* for both CBANC and pH, and b) moderate support for a decline in CBANC (56% belief) and pH (40% belief), but with low support for exceedance of either *change limit* threshold (6% belief for CBANC and 18% belief for pH). The overall result is the same as last year and the percent belief values are relatively similar.

For LAK006, LAK022, LAK023, and LAK042, this classification is based on pH only. All five lakes have 0% belief in CBANC being below the *level of protection.*

> LAK023 and LAK042 show: a) values for the post-KMP averaging period (2021-2023) below the *level of protection* for pH only, and b) moderate support for declines in pH (24% and 23% belief, respectively), but with low support for exceedance of the *change limit* threshold for pH (9% and 14%, respectively).
>
> LAK022 shows: a) a moderate belief in exceeding the *level of protection* for pH (75% belief), and b) moderate support for declines in pH (50% belief), with moderate support for exceedance of the *change limit* threshold (32% belief).
>
> LAK006 shows: a) a moderate belief in exceeding the *level of protection* for pH (28% belief), and b) moderate to low support for declines in pH (21% belief), with low support for exceedance of the *change limit* threshold (8% belief).

There are no lakes that have acidification exceedances.

The only change in lake classification from last year's Annual Report is LAK012, due to the percent belief in a decrease in pH changing from 20% to 18% and thus being identified as a low level of support for such a change. This is an exact reversal of the change reported last year (having increased from 18% to 20%). This small change is within the range of variability

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[21] All of the control lakes are classified in the first box regardless of increases in sulphate because any such increases cannot be causally linked to the smelter due to their location well outside the smelter plume. In both 2022 and 2023, all three control lakes showed a low percent belief in SO_4 changes since 2013.

from repeat runs of the Bayesian analyses. It is a negligible difference between years but happens to span the defined boundary between low and moderate classifications.

All of the other lakes have the same classification and generally very similar underlying results as last year. The only changes of >25% belief in the underlying results for the sensitive lakes were: a) the percent belief in exceeding the *level of protection* for pH for LAK006 and LAK012 decreased by 42% and 33%, respectively, while both still remaining within the range of "moderate", and b) the percent belief for a decline in CBANC for LAK012 increased by 33%, while still remaining within the range "moderate".

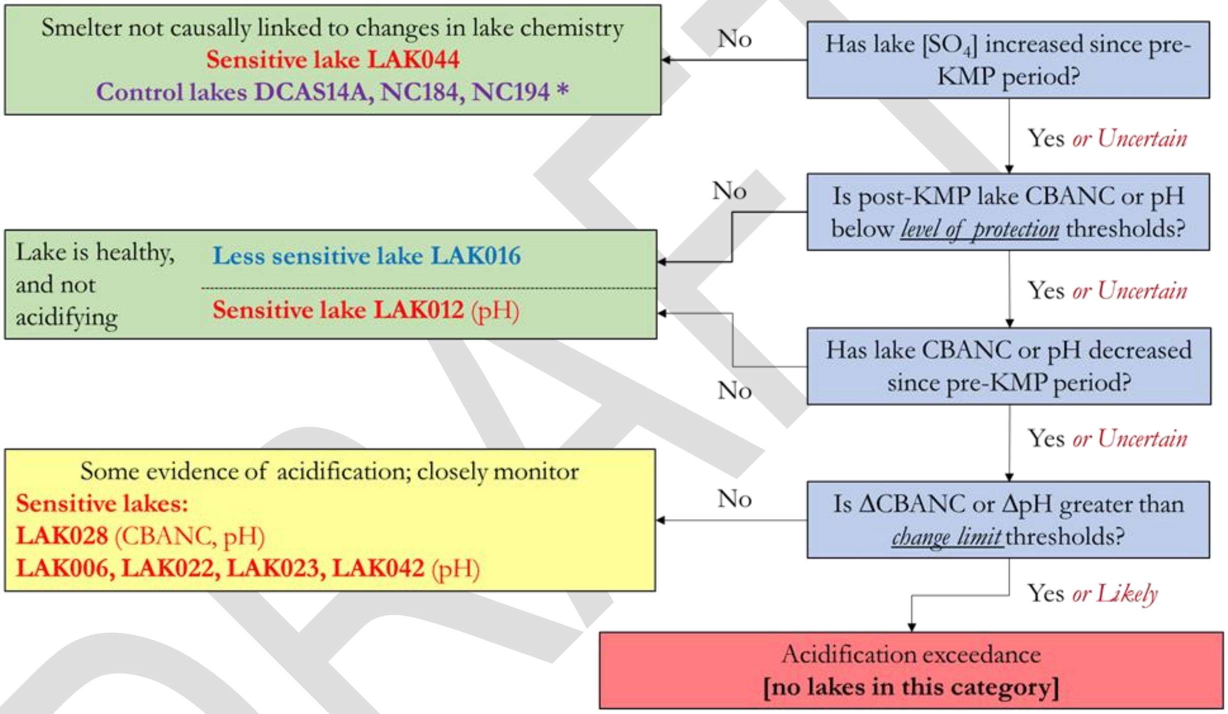

Figure 3-20. Classification of EEM lakes according to the simplified evidentiary framework. LAK028 has moderate support for declines in CBANC and pH but low support for exceeding either *change limit* threshold. LAK006, LAK022, LAK023, and LAK042 have moderate support for declines pH with low to low-moderate support for exceeding the *change limit* thresholds; however, they are all still above the CBANC *level of protection*. The control lakes (*) are all classified in the first box regardless of increases in sulphate (as observed in some past years) because any such increases cannot be causally linked to the smelter due to their location well outside the smelter plume.

Table 3-11. Thresholds for *level of protection* and *change limits* for aquatic acidification KPI and informative indicators. Source: ESSA et al., 2023

Indicators	Type	Level of Protection (i.e., absolute threshold)	Change Limit (i.e., relative threshold)
CBANC	KPI	Decrease below 20 μeq/L	Decrease greater than lake-specific thresholds†
pH	Informative	Decrease below 6.0 pH units	Decrease ≥0.3 pH units
Gran ANC	Informative	Decrease below 30.7 μeq/L	Decrease greater than lake-specific thresholds†
BCS	Informative	Decrease below 0 μeq/L	Decrease greater than 13 μeq/L

† The lake-specific thresholds for CBANC and Gran ANC are shown in Table 14 of the SO_2 EEM Phase III Plan (ESSA et al., 2023) and Appendix 5 of Technical Memo W12.

3.4.3 Recommendations for 2024

We recommend sampling LAK027 again in 2024. It has been resampled in multiple years, but each year was subject to anomalous regional conditions that have reduced or even negated the ability of the sampling data to provide a meaningful comparison against the initial STAR data as intended: a) 2021 had a widely-observed storm-driven dilution event, b) 2022 had a combination of exceptionally low deposition and particularly dry hydrologic conditions, and c) 2023 had a substantial increase in emissions (returning to previous levels) and even drier hydrologic conditions. LAK027 does not show any evidence of acidification. With another year, we will have sampling across four different types of years and should be able to make a more robust confirmation of that conclusion.

We also recommend further consideration of sampling LAK028 and LAK006 near the end of October and again in mid-November to provide water chemistry samples that span the time period of likely rainstorms and episodic declines in pH. This information might help to distinguish hydrologically driven episodes (which would show decreases in CBANC, Gran ANC, BCS, pH, base cations, *and* SO_4) from smelter driven episodes (which would show similar declines but with an increase in SO_4). However, a decision by Rio Tinto to proceed with this sampling would need to consider the added safety risks of conducting the sampling in the late fall. Water chemistry can change rapidly during a rainstorm (Wiggington et al. 1996), so this added sampling may not be sufficient to clearly indicate the drivers of acidic episodes.

We do not recommend any other changes or adjustments to next year's program.

4 Climate Change

This chapter is still in process and is expected to be completed for V.3 or V.4.

5 List of Cited Reports

Coosemans, A., and J. Laurence. 2021. Field manual, Vascular Plant Biodiversity and Cyanolichen Monitoring Program; Revised June 4th, 2021. Prepared for Rio Tinto B.C. Works, 44 pp.

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6 List of Cited EEM Technical Memos

The numbering of Technical Memos continues from the numbers in the previous Annual Reports. The Human Health KPI Calculations Memo for 2023 is provided in Appendix A, and Technical Memo W12 is provided in Appendix B.

Human Health KPI Calculations for 2023 (May 2024, Trinity Consultants.)

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Technical Memo D02. Atmospheric Sulphur Dioxide – Method for Estimating Dry Deposition: 2017 Update (June 2018, Trent University)

Technical Memo P07. Atmospheric Sulphur Dioxide – Passive Diffusive Sampler Network: 2023 Results (April 2024, Trinity Consultants)

Technical Memo W09. Aquatic Ecosystems Actions and Analyses (July 2019, ESSA Technologies Ltd.)

Technical Memo W12. Aquatic Ecosystems Actions and Analyses (April 2024, ESSA Technologies Ltd.)

Appendix A: Technical Memo P07 – Atmospheric Sulphur Dioxide – Passive Diffusive Sampler Network: 2023 Results

The following pages contain **B.C. Works SO_2 EEM Program Technical Memo P07**, in PDF format.

RioTinto

B.C. Works SO_2 EEM Program – Technical Memo P07

Atmospheric Sulphur Dioxide

Passive Diffusive Sampler Network: 2023 Results

April 2024

Prepared for:

Rio Tinto, BC Works
1 Smeltersite Road, P.O. Box 1800,
Kitimat, BC, Canada V8C 2H2

Prepared by:

Trinity Consultants
4525 Wasatch Blvd. Suite 200
Salt Lake City, UT 84124

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1 Introduction

The network of passive samplers was redeployed in the Kitimat Valley during 2023 following the same procedures that were utilized in previous years. The network was deployed at 22 sites within the Kitimat Valley (Figure 1), starting May 5th, 2023[1]. The network was primarily focused along the Wedeene and Bish roads to capture the plume path. This network is referred to as the plume path network and historically referred to as the valley network.[2]

2 Overview

During 2023, the sulphur dioxide (SO_2) passive diffusive sampler network in the Kitimat Valley began monitoring on May 5th and finished on November 5th, following (approximately) six one-month exposures.

Based on Trinity Consultant's 2020 passive sampling plan, a detailed site evaluation was conducted and documented during the 2020 deployment. The original 15 sites deployed in 2020 were deployed in 2023. In addition, the six sites added in 2021 based on reconnaissance performed in early 2021 were also deployed in 2022 and 2023.[3] Location A05 (Kitamaat Village) was added in 2022 to understand the extent of the plume to the southeast and for another site to compare with continuous ambient SO_2 monitoring.

As detailed in the Phase III EEM work plan's 2021-Specific Work Plan for Passive Sampling (ESSA et. al., 2021), the network changed from employing IVL SO_2 passive samplers to Bureau Veritas (BV) All-Season Passive Air Sampling System (PASS) and laboratory. All 2023 sample analysis was performed using the BV PASS system.

3 Study Design

Six deployments, with an approximate exposure time of one-month (27-34 days), were carried out under the plume path network between May and November 2023. West Lake (V17) had five deployments from June to November 2023, because V17 was not accessible due to snow in May 2023. Lake 28 samples had six deployments from May- October 2023, on a schedule consistent with other Lake 28 sampling activities.

In 2023, there were 174 sample exposures across the plume path network collected and analyzed during the six deployments. These included duplicate samplers deployed approximately 22% of the time (43 duplicate exposures). Blanks were deployed approximately 11% of the time (28 blank exposures).

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[1] The V17 West Lake was deployed later than the other sites, on June 4 , 2023.

[2] A second network of passive samplers deployed in the urban and residential areas of Kitimat was in continuous operation from June 2018 through December 2019. The urban network study concluded in 2019 (before the time period of this report)

[3] Three of the six new 2021 sites (V17, V18/V18b, and V20) were added east and west of V01 create an east-west transect to better understand the eastern and western boundaries of the plume path. The remaining three new 2021 sites (V21, V22, and V23) were added farther north near Terrace to better understand the northern boundary of the plume path (and to verify where the plume is not).

4 Results

The observed data show elevated atmospheric SO_2 along the plume path results shown in Figure 1 and Figure 2 are uncalibrated because the BV PASS results need to undergo a new calibration analysis (different from the historic calibration based on IVL sampler data). The BV PASS calibration analysis will be performed after sufficient data have been collected from BV PASS samplers co-located at continuous monitoring stations.

The 2023 results within the plume path network are similar to the 2021 and 2022 observations. Higher concentrations were monitored during the 2023 year due to the restart and increased smelting capacity coming on-line. The spatial pattern is consistent with previous years. It is recommended that deployments are continued during 2024 to further define the plume into the transition to normal operation.

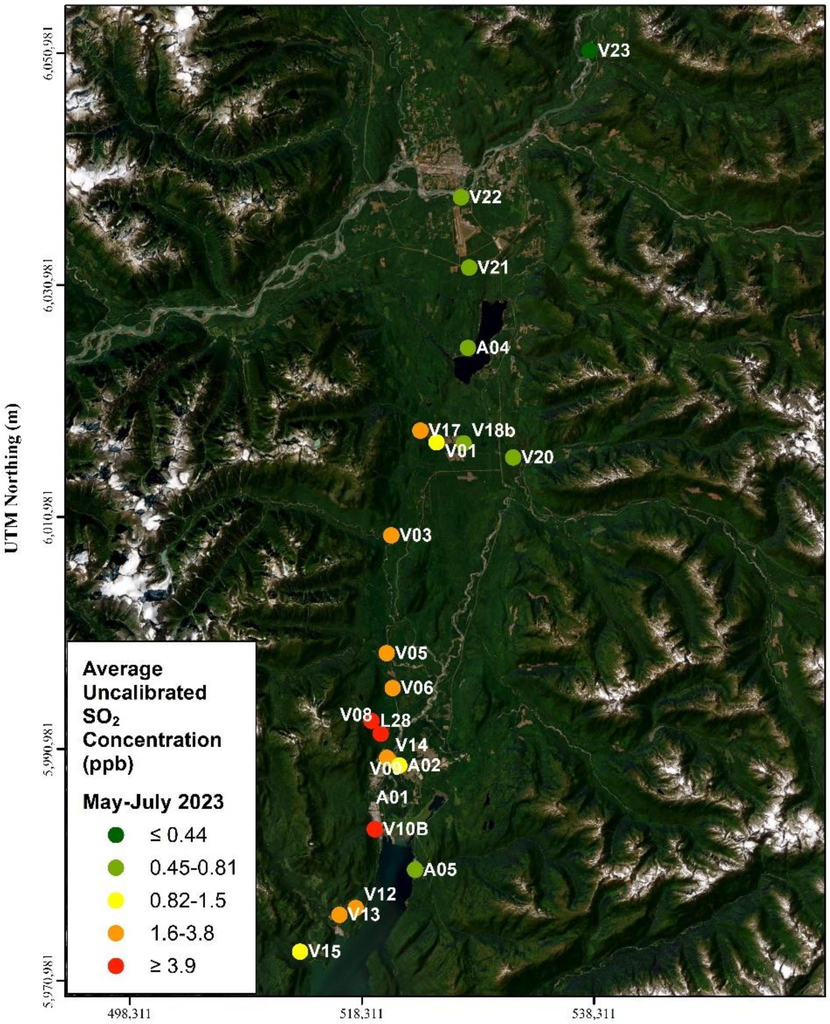

Figure 1 Average Atmospheric Sulphur Dioxide (SO_2) Concentration during May to July 2023 in the Kitimat Valley Passive Diffusive Monitoring Network (uncalibrated).

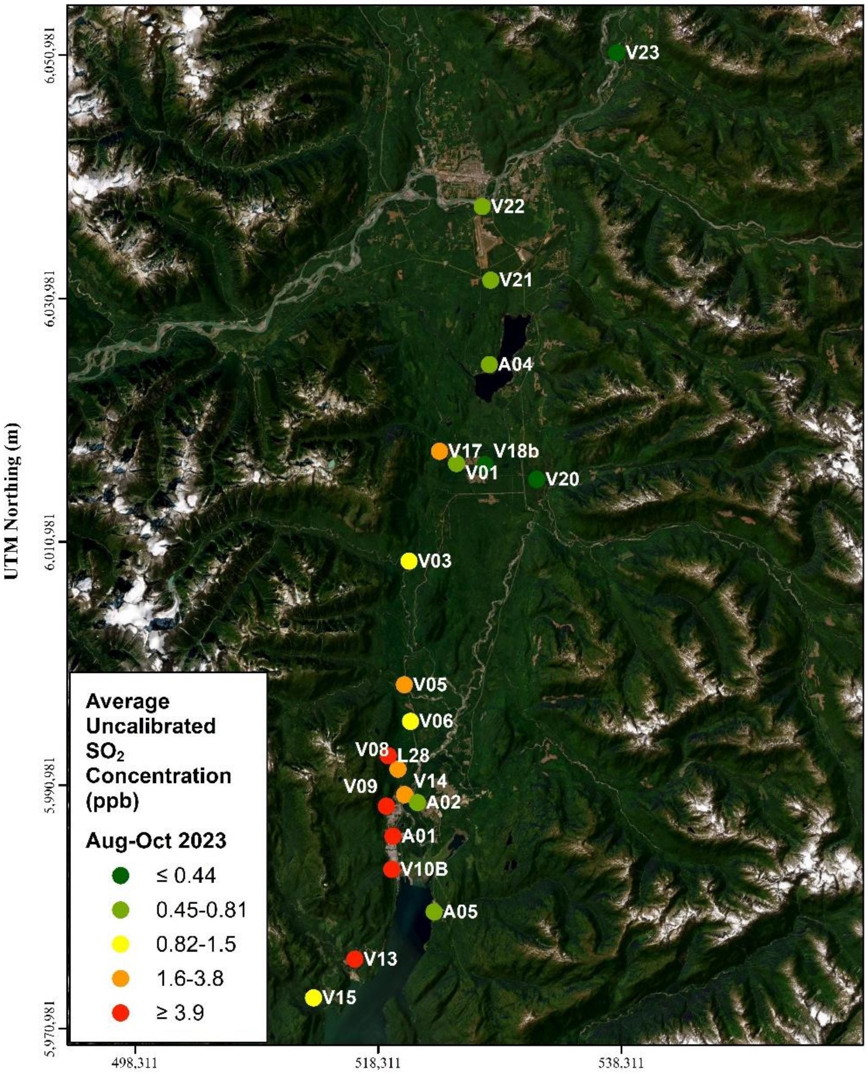

Figure 2 ***Average Atmospheric Sulphur Dioxide (SO_2) Concentration August to October 2023 in the Kitimat Valley Passive Diffusive Monitoring Network (uncalibrated).***

Ambient SO_2 data were collected from the continuous SO_2 analyzers at Haul Road, Riverlodge, Lakelse, and Kitamaat Village were compared to the passive SO_2 sampling data to understand accuracy and precision of the passive method. In general, there was good correlation between passive and active at three of the sites however, correlation decreases at sites that have average concentrations consistently below 1 ppb.

Tables 1 and 2 present a comparison of the ambient sampler results with the collocated passive SO_2 samples analyzed by Bureau Veritas laboratory collected for the Haul Road (AO1), Riverlodge (AO2), Lakelse (A04), and Kitamaat Village (A05) monitoring stations. SO_2 comparisons were made on a 30-day sampling basis.

Table 1 Comparison of SO_2 Passive Sampling Data to Ambient SO_2 Data at Station A01 and A02

	Haul Road (A01)			Riverlodge (A02)		
End Date (2023)	**Bureau Veritas Passive (ppb)**	**Active (ppb)**	**Diff. (ppb)**	**Bureau Veritas Passive (ppb)**	**Active (ppb)**	**Diff. (ppb)**
May	8.2	5.3	2.9	1.2	0.7	0.5
June	12.0	6.5	5.5	0.7	0.6	0.1
July	8.1	5.6	2.5	0.7	0.5	0.2
August	8.4	5.3	3.1	1.0	0.7	0.3
Sept.	8.4	5.7	2.7	0.7	0.6	0.1
Oct	3.3	2.4	0.9	0.7	0.6	0.1
		Average	2.93		Average	0.22
		St. Dev.	1.35		St. Dev.	0.15

Table 2 Comparison of SO_2 Passive Sampling Data to Ambient SO_2 Data at Station A04 and A05

	Lakelse (A04)			Kitimaat Village (A05)		
End Date (2023)	**Bureau Veritas Passive (ppb)**	**Active (ppb)**	**Diff. (ppb)**	**Bureau Veritas Passive (ppb)**	**Active (ppb)**	**Diff. (ppb)**
May	0.7	0.7	0.0	N/C	-0.4	N/A
June	0.5	0.6	-0.1	0.4	0.1	0.3
July	0.5	0.6	-0.1	1.1	0.5	0.6
August	0.7	0.8	-0.1	0.7	0.6	0.1
Sept.	0.5	0.7	-0.2	0.6	0.5	0.1
Oct	0.2	0.5	-0.3	0.5	0.4	0.1
		Average	-0.12		Average	0.25
		St. Dev.	0.09		St. Dev.	0.19

The statistical differences between the active and passive monitors are shown below in Table 3. The averages column shows the average concentration difference between the active and passive monitors. The standard deviations and correlation coefficients (r^2) for the difference between active and passive monitors are also listed.

Table 3 Statistical Analysis of Active to Passive Concentrations

Statistic	**Haul Road**	**Riverlodge**	**Lakelse**	**Kitimaat Village**
Average (ppb)	2.93	0.22	-0.12	0.25
Standard Deviation	1.35	0.15	0.09	0.19
r^2	0.91	0.67	0.86	0.36

The correlation coefficient for the Haul Road and Lakelse is high, but the correlation coefficients are much lower for the other locations. The passive and active sampling at the Haul Road and Lakelse show clear trends and provide similar results. The passive sampling appears to be biased high compared to the active sampling across all sites that have colocation. The Riverlodge colocation has a moderate correlation, but the results are not as significant as at the Haul Road and Lakelse locations. The Kitamaat Village station specifically does not show a correlation between the passive and active sampling values, this is likely due to the very low ambient SO_2 concentrations monitored at this location.

5 Conclusion

The 2023 results demonstrate a similar spatial pattern in SO_2 compared with 2021 and 2022. Higher concentrations were monitored compared to 2023 due to the restart and increased smelting capacity coming on-line.

In summary, the results from the 2023 network continue to support the use of passive samplers to provide empirical observations of atmospheric SO_2 concentrations to (a) assess spatial and temporal changes, (b) evaluate modelled concentration fields, and (c) estimate dry deposition of SO_2. It is recommended that deployments are continued during 2024, to evaluate the ongoing spatial distribution after the restart was completed.

Appendix A.

Table 4: Passive SO_2 Sampling Network Station Identifier, Name, and UTM Location

ID	Site Name	UTM E	UTM N
A01	Haul Road Station	519527	5986823
A02	Riverlodge Station	521538	5989580
A04	Lakelse Lake NADP Station	527457	6025573
A05	Kitamaat Village Station	522907	5980600
V01	Onion Lake Ski Trail North	524757	6017435
V03	Mound TKTP92	520853	6009407
V05	LNG Muster Station	520457	5999250
V06	Sand Pit	520970	5996240
V08	Claque Mountain Trail at Powerline	519938	5992329
V09	Sand Hill at Powerline	518985	5989292
V10B	Pullout before Bish FSR	519425	5984090
V12	Bish Road Pullout 4	517790	5977294
V13	Bish Road at Chevron LNG	516389	5976708
V14	Industrial Area Kitimat Hotel	520490	5990236
V15	Bish Mainline	512994	5973534
V17	West Lake	523359	6018434
V18B	Wedeene mainline	527088	6017351
V20	Pipeline laydown	531354	6016121
V21	South of airport	527566	6032493
V22	Kitselas Development	526862	6038551
V23	Gitaus water tower	537941	6051192
L28	Lake 28 Sampling	519138	5993424

Table 5 Passive Sampling Results in ppb

Station	May (ppb)	June (ppb)	July (ppb)	August (ppb)	September (ppb)	October (ppb)
A01	7.8	10.9	7.7	5.3	8.8	3.3
A02	1.2	0.8	0.7	0.9	0.8	0.7
A04	0.7	0.6	0.5	0.7	0.5	0.2
A05	0.4	0.4	1.0	0.7	0.6	0.7
V01	1.8	1.2	1.4	1.0	0.9	0.4
V03	1.8	1.9	2.0	2.5	1.3	0.6
V05	1.9	2.7	3.1	3.2	2.6	0.7
V06	2.8	2.1	2.5	1.5	1.7	0.5
V08	3.9	3.9	3.9	2.2	2.9	1.1
V09	7.8	9.2	10.7	6.5	5.9	2.8
V10B	7.1	7.4	4.8	2.2	3.2	8.7
V12	5.1	3.2	3.1	4.6	5.3	16.9
V13	3.4	1.6	2.0	1.3	2.9	8.0
V14	2.9	2.0	1.4	1.6	2.2	1.0
V15	1.2	0.9	1.1	0.9	0.8	1.1
V17	Not Collected	2.0	3.0	1.6	2.8	0.2
V18B	0.7	0.8	0.7	0.7	0.4	0.2
V20	0.6	0.5	0.4	0.5	0.3	0.2
V21	0.8	0.6	0.7	0.9	0.6	0.3
V22	0.5	0.5	0.8	0.7	0.6	0.2
V23	0.4	0.4	0.4	0.4	0.2	0.1
L28	5.1	9.2	6.1	8.1	5.7	1.2

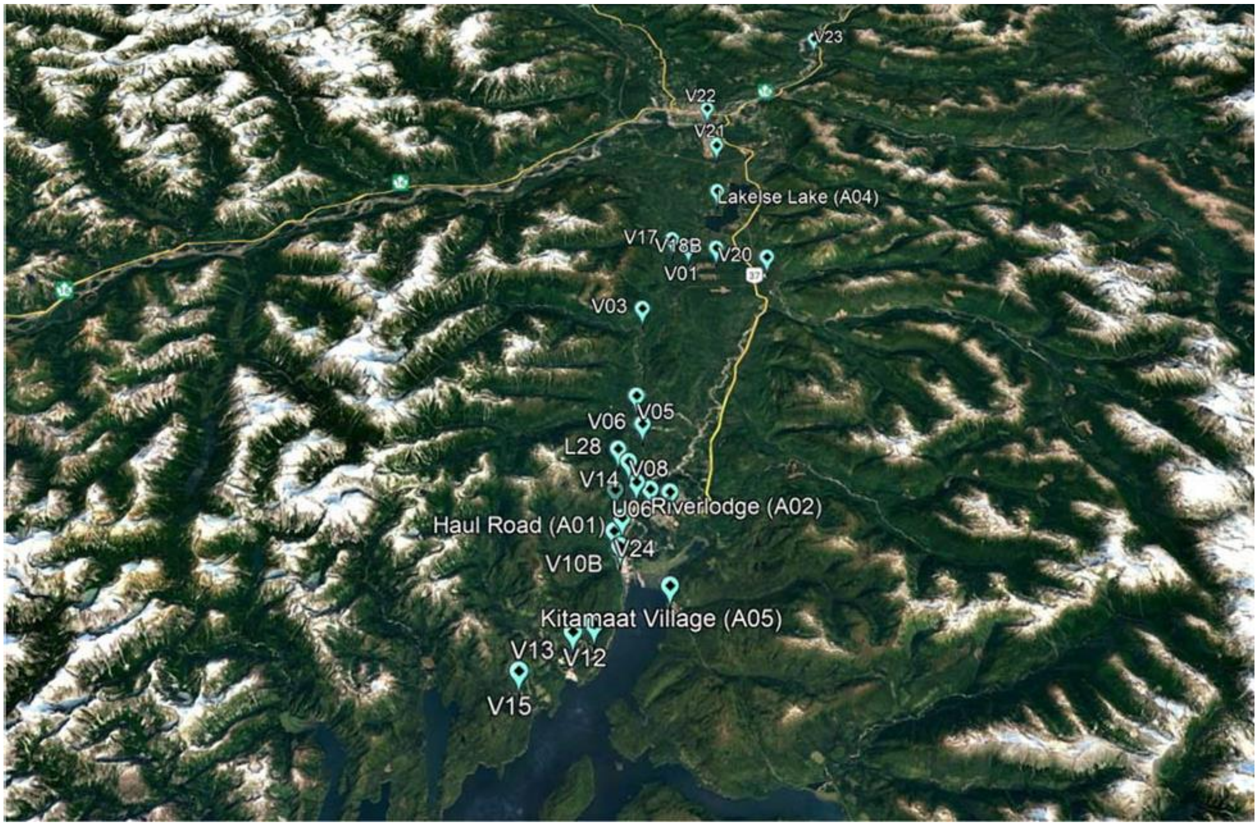

Figure 3 : Site Locations and IDs for the Kitimat Urban (U) and Ambient (A) Passive Diffusive Sampler Network; see Figure A1 and Table A1 for Further Details on Site Locations.

Appendix B: Human Health KPI Calculations Memorandum for 2023

The following pages contain the **Memorandum for the Human Health KPI Calculations for 2023**, in PDF format.

Trinity Consultants

MEMORANDUM

To: Mr. Shawn Zettler - Rio Tinto

From: Anna Henolson, Cara Keslar - Trinity Consultants

Date: March 20, 2024

RE: Human Health KPI Calculations for 2023

The SO_2 Environmental Effects Monitoring (EEM) Program establishes Key Performance Indicators (KPIs) of various pathways in order to monitor effects of SO_2 from Rio Tinto's Kitimat aluminum smelter. This memorandum describes the SO_2 monitoring data collected in 2021 through 2023 in the Kitimat area and the methodology used in order to compare to the human health KPI for reporting year 2023.

Health KPI

British Columbia Ministry of Environment and Climate Change Strategy (BC ENV) updated the province-wide interim SO_2 ambient air quality objective (IAAQO) in 2016, which became the SO_2 health KPI of EEM Program starting 2017. Starting January 1, 2020, the SO_2 health KPI implemented the SO_2 Canadian Ambient Air Quality Standards (CAAQS). In 2020, the CAAQS value was 70 ppb. The SO_2 health KPI is used to assess residential SO_2 ambient air quality.

Exceptional Events

Exceptional events may occur from:

- Fire within the community that may emit SO_2;
- Emergency conditions at the facilities within the Kitimat airshed;
- Vandalism or corruption of data from other point sources such as vehicle emissions in close proximity to the ambient air monitoring station; and
- Temporary global events that impact SO_2 levels such as a volcano eruption.

These types of exceptional events could affect the determination of the health KPI.

The restarting of the smelter in 2023 may be considered an exceptional event causing unusual SO_2 emission levels from the smelter. If elevated levels occur, those can be investigated under the Exceptional Events Guidance. However, no exceptional events that caused unusually high levels of ambient SO_2 were identified in 2023.

Calculation Methodology

The monitoring data at residential areas in Kitimat is collected at three residential monitoring stations: Riverlodge, Whitesail, and Kitamaat Village[1]. The Industrial Avenue monitoring station (located in Service Centre) is also designated as a KPI attainment site per the decision issued by B.C. ENV on October 25,

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[1] Note that the BC ENV Envista database lists the Kitamaat Village monitoring station as the Haisla Village monitoring station.

2022.[2] The effective date listed in the decision is January 1, 2023. The station began collecting data in May 2020. Following the January 1, 2023 effective date in the ENV decision, the station is collecting data for KPI attainment purposes beginning January 1, 2023.[3]

Ambient SO_2 monitors collect the SO_2 measurements continuously and hourly measurements are reported to BC ENV's Envista database[4]. The measurements at these monitor stations are reviewed and validated by BC ENV on an annual basis:

- ► Monitoring data for 2021 was validated as of January 20, 2023.
- ► Monitoring data for 2022 was not validated as of the date of this memorandum (March 20, 2024)
- ► Monitoring data for 2023 was not validated as of the date of this memorandum (March 20, 2024)

The hourly measurements for calendar years 2021, 2022, and 2023 were downloaded from the Envista database after the validation was complete if possible, and then processed following the procedures described in *Guidance Document on Achievement Determinations for Canadian Ambient Air Quality Standards for Sulphur Dioxide*[5] (the Guidance). Following the Guidance, the monitoring data were processed in the following steps:

1. Check daily data completeness and determine the daily 1-hour maximum concentration.
   - Daily measurements are the hourly readings from 1 AM to 12 AM marked for the same day.
   - A valid daily value is calculated as the maximum hourly reading from the day:
   - Where at least 18 hourly measurements are available in a day, the daily value is the maximum value from those readings in the same day; or
   - Where less than 18 hourly measurements are available in a day but at least one hourly measurement exceeds 70 ppb, the daily value is the maximum value from available readings in the same day.[6]
   - All values are reported to the nearest 0.1 ppb.
   - A summary of daily completeness is provided in Attachment 1.

2. Check quarterly and annual data completeness. A summary of quarterly and annual data completeness is provided in Table 1.
   - The dataset is considered complete when there are at least 60% of all daily maximum 1-hour measurements in each quarter and at least 75% of all daily maximum 1-hour measurements in each year.
   - Periods which do not satisfy the data completeness criteria are flagged. All periods were complete for all four stations for 2021 – 2023.

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[2] Letter from Douglas Hill (B.C. ENV) to Shawn Zettler (Rio Tinto). October 25, 2023. https://j200.gov.bc.ca/pub/ams/download.aspx?PosseObjectId=150676770

[3] The Janauary 1, 2023 effective date was based on the expectation that the smelter was expected to reach normal operations. As of May 2023, the smelter has not yet reached normal operation.

[4] BC Air Data Archive Website (Envista database), available at https://envistaweb.env.gov.bc.ca/.

[5] *Guidance Document on Achievement Determination for Canadian Ambient Air Quality Standards for Sulphur Dioxide,* CCME, 2020, available at https://ccme.ca/en/res/gdadforcaaqsforsulphurdioxide_en1.0.pdf.

[6] In this case, there were no SO_2 readings higher than 70 ppb from the three monitoring stations in any day in 2021, 2022, and 2023.

Table 1. Quarterly and Annual Data Completeness

Period [a]	Site	2021	2022	2023
Q1	Kitamaat Village	100.0%	100.0%	100.0%
	Riverlodge	100.0%	100.0%	98.9%
	Whitesail	97.8%	98.9%	98.9%
	Industrial Ave	100%	76.7%	88.89%
Q2	Kitamaat Village	100.0%	100.0%	100.0%
	Riverlodge	100.0%	100.0%	100.0%
	Whitesail	98.9%	96.7%	63.7%
	Industrial Ave	94.5%	100.0%	97.80%
Q3	Kitamaat Village	98.9%	98.9%	100.0%
	Riverlodge	98.9%	100.0%	95.7%
	Whitesail	98.9%	95.7%	98.9%
	Industrial Ave	89.1%	100.0%	100.00%
Q4	Kitamaat Village	97.8%	100.0%	100.0%
	Riverlodge	100.0%	98.9%	100.0%
	Whitesail	97.8%	97.8%	100.0%
	Industrial Ave	88.0%	100.0%	98.9%
Annual	Kitamaat Village	99.2%	99.7%	100.0%
	Riverlodge	99.7%	99.7%	98.6%
	Whitesail	98.4%	97.3%	90.4%
	Industrial Ave	92.9%	94.2%	96.4%
	[a] Q1 refers to January to March, Q2 refers to April to June, Q3 refers to July to September, and Q4 refers to October to December.			

3. Calculate the 99th percentile value of daily 1-hour maximum values for each year at each station.
   - Firstly, all daily 1-hour maximum values for the year are sorted from highest to lowest. For example, there were 360 valid daily 1-hour maximum values at Riverlodge for 2023, and these 360 values were ordered from highest to lowest.
   - Secondly, count the number of valid daily values, and determine the corresponding rank for the annual 99th percentile value following Table 5-2 of the Guidance. For example, the corresponding rank equivalent to annual 99th percentile is 4 for Riverlodge for 2023, as there were more than 300 daily values.
   - Lastly, report the value in the corresponding rank equivalent to annual 99th percentile of the daily 1-hour maximum values. The value is reported to the nearest 0.1 ppb as specified in the Guidance. For example, the 4th highest daily value is reported for Riverlodge for 2023 is 27.3 ppb.
4. Calculate the three-year average of annual 99th percentile of the daily 1-hour maximum values at each station.

The annual 99th percentile value of daily 1-hour maximum values for each year at each station and the three-year average values at each station are summarized in Table 2. The three-year average of annual 99th percentile of daily 1-hour maximum over 2021, 2022, and 2023 at all three monitor stations are also compared to the SO_2 CAAQS of 70 ppb, as shown in Table 2. Since all 99th percentile values are below 70 ppb, all three monitor stations are considered in the attained status regarding this human health KPI. In addition, all hourly measurements in 2021, 2022, and 2023 are below 70 ppb.

Table 2. Annual 99th Percentile and Three-Year Average

Monitor Station	Annual 99th Percentile of Daily 1-hour Maximum [a] (ppb)			Three-Year Average [a] (ppb)	Health KPI Attainment Status
	2021	2022	2023		
Kitamaat Village	9.1	9.8	21.2	13.4	Attained
Riverlodge	29.2	9.9	27.3	22.1	Attained
Whitesail	15.6	5.7	20.8	14.0	Attained
Industrial Ave	33.4	18.6	40.0	30.7	Attained

a. All values are reported with one decimal per Table 5-4 of the CCME Guidance

2023 Monitoring Data Review

The BC ENV began a pilot project in Kitimat to issue alerts when SO_2 levels equal or exceed 36 ppb. According to the ENV information page, "It is expected that 1-hour SO_2 levels of 35 ppb and lower will pose little or no additional health risk to even sensitive individuals."[7] The periods of time in 2023 with elevated SO_2 concentrations at these three residential monitor stations were infrequent. There was only one hourly SO_2 measurements equal to or higher than 36 ppb at each station in 2023. The periods of time that the Industrial Avenue site had elevated SO_2 concentrations were also infrequent, there were six (6) hours at Industrial Avenue that were higher than 36 ppb in 2023. The date and hour with hourly SO_2 measurements equal to or higher than 36 ppb include:

- At Kitamaat Village, between 2 PM and 3 PM on October 7, 2023 (40.3 ppb)
- At Riverlodge, between 10 AM and 11 AM on June 23, 2023 (39.9 ppb)
- At Whitesail, between 10 AM and 11 AM on June 23, 2023 (38.7 ppb)
- At Industrial Ave, between 10 AM and 11 AM on May 12, 2023 (39.5 ppb)
- At Industrial Ave, between 8 AM and 9 AM on June 9, 2023 (44.7 ppb)
- At Industrial Ave, between 9 AM and 10 AM on June 26, 2023 (40 ppb)
- At Industrial Ave between 10 AM and 11 AM on August 22, 2023 (41.1 ppb)
- At Industrial Ave between 12 PM and 2 PM on October 6, 2023 (40.8 ppb & 37.3 ppb)

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[7] https://www2.gov.bc.ca/gov/content/environment/air-land-water/air/air-quality/measuring/kitimat-so2-alert-pilot-project

Attachment 1

Daily 1-hour Maximum Concentrations and Completeness

Note: The daily completeness is calculated by the number of valid hourly measurements in the day divided by 24. Where the daily completeness is below 75% (less than 18 measurements), the daily 1-hr maximum value for the given day is not calculated unless the daily 1-hr maximum exceeds 70 ppb.

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
1/1/2023	1.1	8.4	2.3	1.4	95.8%	95.8%	95.8%	95.8%
1/2/2023	0.5	1.6	0.5	0.5	95.8%	95.8%	91.7%	95.8%
1/3/2023	1.7	2.3	0.3	0.2	75.0%	95.8%	95.8%	91.7%
1/4/2023	0.3	2.4	0.3	0.2	95.8%	95.8%	95.8%	95.8%
1/5/2023	0.3	0.2	0.6	0.1	95.8%	95.8%	95.8%	95.8%
1/6/2023	0.4	3.6	0.2	0.4	95.8%	91.7%	95.8%	95.8%
1/7/2023	0.3	3	0.2	0.2	95.8%	95.8%	95.8%	95.8%
1/8/2023	0.7	3.2	0.2	0.1	95.8%	95.8%	95.8%	95.8%
1/9/2023	0.8	2.2	0.2	0.1	95.8%	91.7%	91.7%	95.8%
1/10/2023	0.7	3.1	0.2	0.1	95.8%	95.8%	95.8%	95.8%
1/11/2023	0.9	4.5	0.7	0.1	91.7%	95.8%	95.8%	87.5%
1/12/2023	0.7	1.7	0.2	0.2	95.8%	95.8%	95.8%	95.8%
1/13/2023	0.9	3.9	0.3	0.2	95.8%	95.8%	95.8%	95.8%
1/14/2023	0.9	2.4	0.2	0.2	95.8%	95.8%	95.8%	95.8%
1/15/2023	0.1	3.1	0.2	0.1	95.8%	95.8%	95.8%	95.8%
1/16/2023	0.7	3	0.2	1.1	95.8%	95.8%	95.8%	95.8%
1/17/2023	0.2	4.3	0.7	2	95.8%	95.8%	95.8%	95.8%
1/18/2023	0.3	4.1	0.4	0.4	95.8%	95.8%	95.8%	95.8%
1/19/2023	1.1	1.1	0.2	0.2	95.8%	95.8%	95.8%	95.8%
1/20/2023	1.1	4.6	0.3	0.2	95.8%	95.8%	95.8%	95.8%
1/21/2023	0.3	6.7	0.3	0.2	95.8%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
1/22/2023	0.4	2.9	0.2	0.2	95.8%	95.8%	95.8%	95.8%
1/23/2023	0.1	11.2	0.3	0.2	95.8%	91.7%	95.8%	95.8%
1/24/2023	0.2	2.5	0.3	0.2	95.8%	95.8%	95.8%	95.8%
1/25/2023	0.7	14.3	0.3	0.2	95.8%	95.8%	91.7%	95.8%
1/26/2023	0.2	5.5	0.2		79.2%	95.8%	95.8%	58.3%
1/27/2023	0.3	4.7	0.3	0.2	95.8%	95.8%	95.8%	95.8%
1/28/2023	0.2	1.2	0.2	0.1	95.8%	95.8%	95.8%	95.8%
1/29/2023	0.2	1.7	0.2	0.2	95.8%	95.8%	95.8%	95.8%
1/30/2023	1.3	4.6	3.1	0.8	95.8%	95.8%	95.8%	95.8%
1/31/2023	0.2	2.3	0.2	0.2	91.7%	91.7%	91.7%	91.7%
2/1/2023	1.7	4	1.2	2.7	95.8%	95.8%	95.8%	95.8%
2/2/2023	0.2	3.5	0.3	0.4	95.8%	95.8%	95.8%	95.8%
2/3/2023	1.2	2.6	2.8	3.1	95.8%	95.8%	95.8%	95.8%
2/4/2023	0.8	4	0.5	1.1	95.8%	95.8%	95.8%	95.8%
2/5/2023	0.5	5.1	0.4	0.3	95.8%	95.8%	95.8%	95.8%
2/6/2023	0.3	3.6	0.7	0.8	95.8%	95.8%	95.8%	95.8%
2/7/2023	0.6	3.6	0.2	0.3	95.8%	95.8%	95.8%	95.8%
2/8/2023	0.5	2.2	0.6	0.5	95.8%	95.8%	95.8%	95.8%
2/9/2023	1	3.7	1.6	1.4	95.8%	95.8%	95.8%	95.8%
2/10/2023	2.1	11	3.9	6	95.8%	91.7%	91.7%	95.8%
2/11/2023	0.2	2.8	0.3	0.1	95.8%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
2/12/2023	0.8	7.8	0.3	0.1	95.8%	95.8%	95.8%	95.8%
2/13/2023	0.8	5.1	0.8	0.1	95.8%	95.8%	95.8%	95.8%
2/14/2023	2.8	15.1	17	8.8	95.8%	95.8%	95.8%	95.8%
2/15/2023	1.1	3.4	0.4	0.2	95.8%	91.7%	95.8%	95.8%
2/16/2023	0.5	2.9	0.4	0.1	95.8%	95.8%	95.8%	91.7%
2/17/2023	0.4	2.8	0.2	0.1	95.8%	95.8%	91.7%	95.8%
2/18/2023	0.4	6.3	0.5	0.1	91.7%	95.8%	95.8%	91.7%
2/19/2023	0.3	2.5	0.7	0.1	95.8%	95.8%	95.8%	95.8%
2/20/2023	0.5	3.3	0.4	0.7	95.8%	95.8%	95.8%	95.8%
2/21/2023	0.4	0.3	0.2	0.1	95.8%	95.8%	95.8%	95.8%
2/22/2023	0.2	0.2	0.2	0.2	95.8%	95.8%	95.8%	95.8%
2/23/2023	0.3	0.2	0.2	0.3	95.8%	95.8%	95.8%	95.8%
2/24/2023	2.6	17.9	7.4	8.8	95.8%	95.8%	95.8%	95.8%
2/25/2023	4.5	0.5	0.5	0.6	95.8%	95.8%	95.8%	95.8%
2/26/2023	3.2	4.9	0.2	0.2	95.8%	95.8%	95.8%	95.8%
2/27/2023	1.7	12	8.5	1.3	95.8%	95.8%	95.8%	95.8%
2/28/2023	0.3	5.1	0.3	0.2	91.7%	91.7%	91.7%	91.7%
3/1/2023	0.2	5.4		0.5	95.8%	95.8%	62.5%	83.3%
3/2/2023	0.1	9.9	5.4	0.1	87.5%	91.7%	95.8%	91.7%
3/3/2023	0.2	8.3	2.1	5.6	100.0%	100.0%	100.0%	100.0%
3/4/2023	0.2	5.6	0.2	0.1	95.8%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
3/5/2023	0.4	0.5	0.2	0.2	95.8%	95.8%	95.8%	95.8%
3/6/2023	0.5	0.3	0.2	0.2	95.8%	95.8%	95.8%	95.8%
3/7/2023	0.6	2.2	0.2	0.2	95.8%	95.8%	95.8%	95.8%
3/8/2023	0.5	1.3	0.2	0.2	95.8%	95.8%	95.8%	91.7%
3/9/2023	0.4	2.5	0.2	0.2	95.8%	95.8%	95.8%	95.8%
3/10/2023	0.3	2.4	0.2	0.3	91.7%	91.7%	91.7%	91.7%
3/11/2023	0.4		0.2	0.3	95.8%	37.5%	95.8%	95.8%
3/12/2023	0.4		0.2	0.3	95.8%	0.0%	91.7%	95.8%
3/13/2023	0.8		0.8	0.9	83.3%	50.0%	95.8%	91.7%
3/14/2023	0.3	1.7	0.4	0.5	95.8%	95.8%	95.8%	95.8%
3/15/2023	0.4	8	0.9	0.2	95.8%	95.8%	95.8%	95.8%
3/16/2023	0.4		7.4	4.7	95.8%	54.2%	95.8%	95.8%
3/17/2023	9.2		0.2	0.7	95.8%	54.2%	95.8%	95.8%
3/18/2023	0.4	2.8	0.2	0.2	95.8%	100.0%	95.8%	95.8%
3/19/2023	2.6		0.5	1.6	95.8%	66.7%	95.8%	95.8%
3/20/2023	0.3		0.2	0.9	95.8%	45.8%	95.8%	83.3%
3/21/2023	1.2	18.1	4.1	3.9	95.8%	95.8%	95.8%	91.7%
3/22/2023	6.4	17.7	12.6	5.5	95.8%	95.8%	91.7%	95.8%
3/23/2023	0.3	10.8	9.2	9.1	75.0%	100.0%	95.8%	95.8%
3/24/2023	0.4	9.1	5.5	3.2	95.8%	75.0%	95.8%	95.8%
3/25/2023	1.5		4.2	3.5	95.8%	0.0%	95.8%	95.8%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
3/26/2023	3.3		1.3	1.9	95.8%	0.0%	95.8%	91.7%
3/27/2023	0.2		0.2	0.2	91.7%	58.3%	95.8%	95.8%
3/28/2023	0.4	2.3	0.2	0.4	100.0%	100.0%	95.8%	100.0%
3/29/2023	2.9	10.4	3.5	2.8	95.8%	91.7%	95.8%	95.8%
3/30/2023	1.4	6.9	3	4.8	95.8%	95.8%	95.8%	95.8%
3/31/2023	0.2	7.4	2.2	7.9	91.7%	91.7%	91.7%	91.7%
4/1/2023	0.2	2.3	2	1	95.8%	87.5%	95.8%	95.8%
4/2/2023	4.6		3.1	4.2	95.8%	45.8%	95.8%	95.8%
4/3/2023	0.2	2.9	0.4	0.3	95.8%	75.0%	95.8%	95.8%
4/4/2023	3.1		5.7	5.7	95.8%	41.7%	91.7%	91.7%
4/5/2023	0.7	18.6	21.2	12.6	91.7%	95.8%	95.8%	91.7%
4/6/2023	1.1	4.8	5.3	3.4	95.8%	95.8%	95.8%	95.8%
4/7/2023	0.3	2.2	0.3	0.3	95.8%	95.8%	95.8%	95.8%
4/8/2023	1.5	10.2	2.2	1.7	95.8%	95.8%	95.8%	91.7%
4/9/2023	0.7	9.9	3		95.8%	95.8%	95.8%	45.8%
4/10/2023	0.2	10	3.1		95.8%	95.8%	95.8%	0.0%
4/11/2023	0.2	4.9	0.6		91.7%	95.8%	95.8%	37.5%
4/12/2023	0.2	15.9	7.2	3.4	95.8%	95.8%	91.7%	95.8%
4/13/2023	0.2	11.1	8.4		95.8%	95.8%	95.8%	50.0%
4/14/2023	21.2	15.2	20.7		95.8%	95.8%	95.8%	0.0%
4/15/2023	0.5	9.7	4.4		95.8%	95.8%	95.8%	0.0%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
4/16/2023	3.3	5.3	2.5		95.8%	95.8%	95.8%	0.0%
4/17/2023	3	1.1	0.5		95.8%	95.8%	95.8%	0.0%
4/18/2023	2.7	6.7	5.1		95.8%	95.8%	95.8%	0.0%
4/19/2023	1.7	11.9	2.1		95.8%	95.8%	95.8%	0.0%
4/20/2023	0.8	3.5	4.8		95.8%	95.8%	95.8%	0.0%
4/21/2023	22	16.1	13.9		95.8%	83.3%	95.8%	0.0%
4/22/2023	5	20.4	13.1		95.8%	95.8%	95.8%	0.0%
4/23/2023	6.3	30.8	23.1		95.8%	95.8%	95.8%	0.0%
4/24/2023	0.2	7.9	16.3		95.8%	95.8%	95.8%	0.0%
4/25/2023	0.2	19.7	12.7		95.8%	95.8%	95.8%	0.0%
4/26/2023	0.1	11	2.3		95.8%	95.8%	95.8%	0.0%
4/27/2023	20.2	19.7	14.9		95.8%	95.8%	91.7%	0.0%
4/28/2023	1.1	0.8	0.4		91.7%	95.8%	95.8%	0.0%
4/29/2023	3.2	3.9	3.7		95.8%	95.8%	95.8%	0.0%
4/30/2023	0.2	24.2	12.2		91.7%	91.7%	91.7%	0.0%
5/1/2023	3	1.8	0.4		100.0%	100.0%	100.0%	4.2%
5/2/2023	3.6	10.1	6.5		95.8%	95.8%	95.8%	0.0%
5/3/2023	0.2	10.5	1.7		95.8%	95.8%	95.8%	0.0%
5/4/2023	4.4	8.1	8.7		95.8%	95.8%	95.8%	0.0%
5/5/2023	0.4	4.1	1.1		95.8%	95.8%	95.8%	0.0%
5/6/2023	0.2	5.5	0.1		95.8%	95.8%	95.8%	0.0%

Date	Daily Max 1-hr (ppb)				Daily Completeness			
	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
5/7/2023	0.1	2.7	0.4		95.8%	95.8%	95.8%	0.0%
5/8/2023	5.5	16.9	11		91.7%	95.8%	95.8%	0.0%
5/9/2023	1.6	12.6	7.2		95.8%	95.8%	95.8%	0.0%
5/10/2023	1.3	26.1	3.1		95.8%	95.8%	87.5%	0.0%
5/11/2023	9.9	32.5	20.5		95.8%	95.8%	95.8%	0.0%
5/12/2023	0.2	39.5	20.8		95.8%	95.8%	87.5%	45.8%
5/13/2023	4.4	7.2	2.8	1.1	95.8%	95.8%	95.8%	95.8%
5/14/2023	2.2	0.8	0.2	0.3	95.8%	91.7%	95.8%	95.8%
5/15/2023	2.6	20.7	3.9	10.8	91.7%	95.8%	95.8%	95.8%
5/16/2023	3.7	12.1	3.3	4	95.8%	91.7%	95.8%	95.8%
5/17/2023	2.6	16.8	4.5	7.3	95.8%	95.8%	95.8%	95.8%
5/18/2023	2.6	4.7	3	2.9	95.8%	95.8%	95.8%	95.8%
5/19/2023	0.2	6.7	0.3	0.3	95.8%	95.8%	95.8%	95.8%
5/20/2023	10.3	12.5	10.8	12.2	95.8%	95.8%	91.7%	95.8%
5/21/2023	0.2	3.8	0.1	0.2	91.7%	95.8%	95.8%	91.7%
5/22/2023	0.5	3.6	0.9	1.1	95.8%	83.3%	95.8%	95.8%
5/23/2023	2.3	5.1	4.9	3.2	95.8%	95.8%	95.8%	95.8%
5/24/2023	0.3	4.9	0.2	0.3	95.8%	95.8%	95.8%	95.8%
5/25/2023	3.6	4.3	4.4	5.5	95.8%	95.8%	95.8%	95.8%
5/26/2023	0.5	3	0.4	0.2	75.0%	95.8%	95.8%	91.7%
5/27/2023	0.7	15.2	15.3	18.7	95.8%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
5/28/2023	0.6	16.5	0.9	0.5	95.8%	95.8%	95.8%	95.8%
5/29/2023	0.4	15.3	4.4	1.2	95.8%	95.8%	95.8%	95.8%
5/30/2023	0.3	19.7	5.6	0.8	100.0%	100.0%	100.0%	95.8%
5/31/2023	0.3	4	4.7	0.3	91.7%	91.7%	91.7%	91.7%
6/1/2023	1.3	15.2	11.8	8.6	95.8%	95.8%	95.8%	95.8%
6/2/2023	1	10.4	6.9	7.5	95.8%	95.8%	95.8%	95.8%
6/3/2023	0.3	9.6	4.6	5.7	95.8%	95.8%	95.8%	95.8%
6/4/2023	0.3	7.5	3.8	0.2	95.8%	95.8%	95.8%	95.8%
6/5/2023	0.4	7.3	1.7	1.5	95.8%	95.8%	95.8%	95.8%
6/6/2023	2.7	7.2	4.4	5.1	95.8%	87.5%	95.8%	95.8%
6/7/2023	1.9	23.1	3	5	95.8%	95.8%	91.7%	91.7%
6/8/2023	2	22.6	3.6	6.8	83.3%	95.8%	95.8%	95.8%
6/9/2023	0.1	44.7	3.2	1	95.8%	95.8%	87.5%	95.8%
6/10/2023	0.6	7	4.7	6.6	95.8%	95.8%	95.8%	95.8%
6/11/2023	6	8.8	9.1	5.3	95.8%	95.8%	95.8%	95.8%
6/12/2023	0.4	6.6	1.1	0.2	95.8%	95.8%	91.7%	95.8%
6/13/2023	0.4	4.8	3.1	3.7	91.7%	95.8%	95.8%	91.7%
6/14/2023	0.6	8.8	2	2.9	95.8%	95.8%	83.3%	91.7%
6/15/2023	0.3	2.2	6.1	4	95.8%	95.8%	95.8%	95.8%
6/16/2023	0.3	18.2	3.4	0.3	95.8%	95.8%	95.8%	95.8%
6/17/2023	0.3	11.5	4.7	1.3	95.8%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
6/18/2023	3	12.7	10.7	8.9	95.8%	95.8%	95.8%	95.8%
6/19/2023	0.4	0.9	0.8	2.2	95.8%	95.8%	95.8%	95.8%
6/20/2023	3.9	17.8	7.8	6.1	95.8%	95.8%	95.8%	95.8%
6/21/2023	0.3	1.7	0.2	0.3	95.8%	95.8%	95.8%	91.7%
6/22/2023	0.3	5.4	1.5	3.5	95.8%	95.8%	95.8%	95.8%
6/23/2023	1.6	34.3	39.9	38.7	95.8%	95.8%	95.8%	95.8%
6/24/2023	0.2	6.3	0.5	0.4	95.8%	95.8%	95.8%	95.8%
6/25/2023	0.2	5	1.1	0.8	95.8%	95.8%	95.8%	91.7%
6/26/2023	0.2	40	19	3.1	95.8%	95.8%	95.8%	95.8%
6/27/2023	3.2	8.8	2.7	3.8	95.8%	91.7%	95.8%	95.8%
6/28/2023	0.3	7.3	0.9	0.1	95.8%	87.5%	87.5%	87.5%
6/29/2023	0.5	3.9	0.4	0.2	91.7%	91.7%	95.8%	95.8%
6/30/2023	0.2	6.2	1.6	0.3	91.7%	91.7%	91.7%	91.7%
7/1/2023	0.2	14.2	10.4	0.5	100.0%	100.0%	100.0%	100.0%
7/2/2023	8.7	14	3.6	1.8	95.8%	95.8%	95.8%	95.8%
7/3/2023	3.4	3.6	3.9	2.6	95.8%	95.8%	95.8%	95.8%
7/4/2023	3.8	6.5	5.9	3.9	91.7%	95.8%	95.8%	91.7%
7/5/2023	3.5	4.3	4.7	5.3	95.8%	95.8%	91.7%	95.8%
7/6/2023	3.4	5.9	5.5	5.7	91.7%	95.8%	95.8%	91.7%
7/7/2023	1.6	22.5	11.2	1.6	95.8%	95.8%	83.3%	95.8%
7/8/2023	0.3	1.8	0.6	0.6	95.8%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
7/9/2023	0.3	2.1	0.2	0.3	95.8%	95.8%	95.8%	95.8%
7/10/2023	0.3	1.9	0.4	0.3	95.8%	95.8%	95.8%	95.8%
7/11/2023	0.2	7.9	0.2	0.3	95.8%	95.8%	95.8%	95.8%
7/12/2023	18	20.4	14.7	11.9	100.0%	95.8%	95.8%	95.8%
7/13/2023	0.3	11.3	15.1	13.5	95.8%	95.8%	95.8%	91.7%
7/14/2023	0.2	19.5	14.1	9.2	95.8%	95.8%	95.8%	95.8%
7/15/2023	0.2	32.1	4.7	1.5	95.8%	95.8%	95.8%	91.7%
7/16/2023	0.2	1.3	0.4	0.2	95.8%	95.8%	95.8%	95.8%
7/17/2023	0.2	13.3	3	0.7	95.8%	95.8%	95.8%	95.8%
7/18/2023	0.1	2.1	0.4	0.3	95.8%	87.5%	95.8%	95.8%
7/19/2023	17.5	11.2	11	11.6	95.8%	95.8%	95.8%	95.8%
7/20/2023	6.6	7.1	5.9	7.4	95.8%	95.8%	95.8%	95.8%
7/21/2023	0.3	13.5	1.6	0.4	95.8%	95.8%	95.8%	95.8%
7/22/2023	0.4	9.8		0.5	95.8%	91.7%	33.3%	95.8%
7/23/2023	4.1	8.5		6.5	95.8%	95.8%	0.0%	95.8%
7/24/2023	5	5.2		4	95.8%	95.8%	0.0%	95.8%
7/25/2023	0.6	8.5		0.8	95.8%	95.8%	41.7%	95.8%
7/26/2023	0.2	3.8	0.3	0.5	95.8%	95.8%	95.8%	95.8%
7/27/2023	3	0.5	0.3	0.6	95.8%	95.8%	95.8%	95.8%
7/28/2023	0.9	1.6	0.6	0.8	95.8%	95.8%	87.5%	95.8%
7/29/2023	1.2	6.6	5.7	4.1	91.7%	95.8%	95.8%	91.7%

	Daily Max 1-hr (ppb)				**Daily Completeness**			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
7/30/2023	0.2	15.2	1	0.4	100.0%	100.0%	100.0%	100.0%
7/31/2023	0.2	3.9	0.3	0.5	91.7%	91.7%	91.7%	91.7%
8/1/2023	0.4	9.4	0.6	0.9	95.8%	95.8%	95.8%	95.8%
8/2/2023	12.6	3.5	5.3	3.7	95.8%	95.8%	95.8%	95.8%
8/3/2023	3.2	10.6	7.8	3.8	95.8%	95.8%	95.8%	95.8%
8/4/2023	2.3	4.5	3.5	4	95.8%	95.8%	95.8%	95.8%
8/5/2023	14.4	6	6.4	7.6	95.8%	95.8%	95.8%	95.8%
8/6/2023	0.2	12.7	1.6	1.1	95.8%	95.8%	95.8%	95.8%
8/7/2023	0.2	5.9	0.2	0.3	95.8%	95.8%	95.8%	95.8%
8/8/2023	0.2	2.9	1.9	2	95.8%	87.5%	95.8%	95.8%
8/9/2023	0.3	5.2	0.2	0.3	91.7%	95.8%	95.8%	91.7%
8/10/2023	0.2	1.2	0.3	0.2	95.8%	95.8%	95.8%	95.8%
8/11/2023	0.4	3.2	0.2	0.3	95.8%	95.8%	95.8%	95.8%
8/12/2023	0.3	1.3	0.2	0.2	95.8%	95.8%	95.8%	95.8%
8/13/2023	0.3	2.5	0.2	0.2	95.8%	95.8%	95.8%	95.8%
8/14/2023	0.4	4.4	0.6	0.4	95.8%	91.7%	95.8%	95.8%
8/15/2023	0.3	3.3	0.4	0.4	95.8%	95.8%	95.8%	95.8%
8/16/2023	0.2	21.2	5.5	0.6	95.8%	95.8%	95.8%	95.8%
8/17/2023	0.2	6.9	1.7	0.6	95.8%	95.8%	95.8%	95.8%
8/18/2023	8.5	22.1	21.4	9.1	95.8%	95.8%	95.8%	95.8%
8/19/2023	9	12.4	10.9	12.5	95.8%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				**Daily Completeness**			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
8/20/2023	0.1	6.5	5.2	3.4	95.8%	95.8%	87.5%	95.8%
8/21/2023	1.4	1.2	1.6	1.6	91.7%	95.8%	95.8%	91.7%
8/22/2023	1.1	41.1	33.5	2.2	95.8%	95.8%	95.8%	75.0%
8/23/2023	0.2	0.6	0.4	0.3	95.8%	95.8%	95.8%	95.8%
8/24/2023	5.9	6.2	5.4		83.3%	95.8%	83.3%	62.5%
8/25/2023	4.2	6.3	4.8	5.9	95.8%	95.8%	95.8%	95.8%
8/26/2023	15.5	13.7	8.1	4.6	95.8%	95.8%	95.8%	95.8%
8/27/2023	3.2	26.9	9.6	6.8	95.8%	95.8%	95.8%	95.8%
8/28/2023	4.5	7.5	7.2	0.9	95.8%	95.8%	87.5%	83.3%
8/29/2023	0.2	3.2	0.2	0.4	95.8%	95.8%	95.8%	87.5%
8/30/2023	0.1	8.4	0.5	0.4	95.8%	95.8%	95.8%	95.8%
8/31/2023	0.3	34.6	27.3	20.8	95.8%	95.8%	95.8%	95.8%
9/1/2023	2	13.9	9.4	3.9	95.8%	95.8%	95.8%	95.8%
9/2/2023	0.2	15.3	2.9	0.9	95.8%	95.8%	95.8%	95.8%
9/3/2023	5.9	8	6.8	9.9	95.8%	95.8%	95.8%	95.8%
9/4/2023	1.1	2.4	1.1	0.5	95.8%	95.8%	95.8%	95.8%
9/5/2023	0.2	27.6	18.6	12.3	95.8%	95.8%	95.8%	87.5%
9/6/2023	0.1	4.1	0.9	1.3	95.8%	79.2%	95.8%	95.8%
9/7/2023	0.1	4.4	0.9	0.3	95.8%	95.8%	95.8%	95.8%
9/8/2023	0.9	33.6	20.1	24.1	95.8%	95.8%	95.8%	95.8%
9/9/2023	4	23.3	17.7	10.6	95.8%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
9/10/2023	3.7	4.5	4.9	4.1	95.8%	95.8%	95.8%	95.8%
9/11/2023	0.2	1.8	0.7	1	95.8%	95.8%	95.8%	95.8%
9/12/2023	0.2	11.1	0.3	0.4	91.7%	95.8%	91.7%	91.7%
9/13/2023	0.2	7.4	1.8	0.4	91.7%	87.5%	91.7%	91.7%
9/14/2023	0.2	9.9	1.5	0.3	95.8%	95.8%	95.8%	95.8%
9/15/2023	0.1	12.7	3.2	0.4	95.8%	95.8%	95.8%	95.8%
9/16/2023	4.7	19.1	9.2	8.3	95.8%	95.8%	95.8%	95.8%
9/17/2023	0.1	30.7	5.2	0.6	95.8%	95.8%	95.8%	95.8%
9/18/2023	0.1	15.4	2.1	0.4	95.8%	95.8%	95.8%	95.8%
9/19/2023	1.3	5.4	2.6	6.7	95.8%	91.7%	95.8%	100.0%
9/20/2023	11.6	32.5	17.2	9.6	83.3%	95.8%	79.2%	87.5%
9/21/2023	0.2	1.2	0.3	0.6	95.8%	95.8%	87.5%	95.8%
9/22/2023	0.2	2.2	0.8	1.2	95.8%	95.8%	95.8%	95.8%
9/23/2023	2.1	8.2	2.9	2.8	95.8%	95.8%	95.8%	95.8%
9/24/2023	0.4	1.1	0.4	0.4	95.8%	95.8%	95.8%	95.8%
9/25/2023	1	2.6	1.3	0.6	95.8%	95.8%	95.8%	95.8%
9/26/2023	1.2	6.3	4.6	8.3	95.8%	95.8%	95.8%	95.8%
9/27/2023	0.3	2.9	0.2	0.4	95.8%	95.8%	95.8%	95.8%
9/28/2023	0.2	3.7	1.1	1.4	95.8%	95.8%	95.8%	95.8%
9/29/2023	7.7	3.3	7.2	9.3	95.8%	91.7%	95.8%	95.8%
9/30/2023	6.5	7.7	7.2	8.4	91.7%	91.7%	91.7%	91.7%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
10/1/2023	2.2	4.1	2.2	1.7	100.0%	100.0%	100.0%	100.0%
10/2/2023	0.5	9.2	0.9	0.6	95.8%	95.8%	95.8%	91.7%
10/3/2023	0.4	3	0.5	0.3	95.8%	95.8%	95.8%	87.5%
10/4/2023	0.4	1.6	1.2	0.4	95.8%	91.7%	95.8%	95.8%
10/5/2023	5.3	13.8	13	5.7	95.8%	95.8%	91.7%	95.8%
10/6/2023	0.7	40.8	27.7	24.8	91.7%	95.8%	95.8%	91.7%
10/7/2023	40.3	16.9	24.4	6.5	95.8%	95.8%	95.8%	95.8%
10/8/2023	1.2	6	3.5	5.2	95.8%	95.8%	95.8%	95.8%
10/9/2023	0.4	1.6	0.5	0.9	95.8%	95.8%	95.8%	95.8%
10/10/2023	1.6	2.1	1.9	1.7	95.8%	95.8%	95.8%	95.8%
10/11/2023	0.2	1.4	0.4	0.4	95.8%	95.8%	95.8%	95.8%
10/12/2023	7.6	2	1	0.7	95.8%	95.8%	95.8%	95.8%
10/13/2023	0.2	0.6	0.3	0.5	95.8%	95.8%	95.8%	95.8%
10/14/2023	0.2	19.1	11.5	3.6	95.8%	95.8%	95.8%	95.8%
10/15/2023	1.7	2	1	2.7	95.8%	95.8%	95.8%	95.8%
10/16/2023	0.2	1.1	0.4	0.4	95.8%	95.8%	95.8%	95.8%
10/17/2023	0.5	1.9	0.6	0.4	95.8%	95.8%	95.8%	95.8%
10/18/2023	0.2	3.2	0.3	0.3	95.8%	95.8%	95.8%	95.8%
10/19/2023	0.3	1.3	0.3	0.2	95.8%	95.8%	95.8%	95.8%
10/20/2023	0.5	6.6	2.6	5.4	95.8%	95.8%	95.8%	95.8%
10/21/2023	0.1	1	0.3	0.3	95.8%	95.8%	95.8%	95.8%

Date	Daily Max 1-hr (ppb)				Daily Completeness			
	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
10/22/2023	0.2	1.1	0.4	0.3	95.8%	91.7%	83.3%	95.8%
10/23/2023	0.4	0.6	0.3	0.4	87.5%	95.8%	95.8%	95.8%
10/24/2023	0.1	0.4	0.4	0.5	95.8%	95.8%	95.8%	95.8%
10/25/2023	5.2	0.5	0.4	0.4	95.8%	91.7%	95.8%	95.8%
10/26/2023	4	1.2	0.4	0.4	95.8%	95.8%	95.8%	95.8%
10/27/2023	2.2	2.5	0.3	0.2	95.8%	95.8%	95.8%	87.5%
10/28/2023	4.8	2.7	4.3	4.7	95.8%	87.5%	91.7%	83.3%
10/29/2023	0.2	1	0.3	0.3	91.7%	95.8%	95.8%	91.7%
10/30/2023	0.4	1.7	0.5	0.7	100.0%	100.0%	100.0%	100.0%
10/31/2023	0.2	0.9	0.5	0.3	91.7%	91.7%	91.7%	91.7%
11/1/2023	0.2	0.7	0.3	0.2	95.8%	95.8%	95.8%	95.8%
11/2/2023	0.4	1.9	0.4	0.4	95.8%	95.8%	95.8%	79.2%
11/3/2023	1.3	2.1	0.4	0.6	95.8%	95.8%	95.8%	95.8%
11/4/2023	0.8	1.2	0.4	0.2	95.8%	95.8%	95.8%	95.8%
11/5/2023	0.2	3.7	0.5	0.9	95.8%	95.8%	95.8%	95.8%
11/6/2023	0.4	12.9	1.8	1.3	95.8%	95.8%	95.8%	95.8%
11/7/2023	0.2	18.2	6.7	0.2	95.8%	95.8%	95.8%	95.8%
11/8/2023	0.3	2.4	1.6	0.8	95.8%	95.8%	95.8%	95.8%
11/9/2023	0.7		1	0.9	95.8%	45.8%	95.8%	95.8%
11/10/2023	2.2	3.4	2.1	1.4	95.8%	95.8%	95.8%	95.8%
11/11/2023	0.8	8.6	1.5	0.5	95.8%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
11/12/2023	0.3	1	0.5	0.2	95.8%	95.8%	95.8%	95.8%
11/13/2023	0.7	15.4	0.9	1.1	91.7%	95.8%	95.8%	91.7%
11/14/2023	0.2	12.9	15.4	3.5	95.8%	87.5%	95.8%	95.8%
11/15/2023	0.2	13.9	4.5	0.5	95.8%	95.8%	95.8%	95.8%
11/16/2023	0.2	19.2	0.6	0.4	95.8%	95.8%	95.8%	95.8%
11/17/2023	0.2	1.5	0.7	0.3	95.8%	91.7%	95.8%	95.8%
11/18/2023	1.2	2	0.6	1.1	95.8%	95.8%	95.8%	95.8%
11/19/2023	0.9	19.6	6.9	0.7	95.8%	95.8%	95.8%	95.8%
11/20/2023	9.4	6.3	8.1	13.2	95.8%	95.8%	91.7%	95.8%
11/21/2023	0.5	6	2.1	0.6	91.7%	95.8%	95.8%	91.7%
11/22/2023	0.3	3.5	0.5	0.5	95.8%	95.8%	95.8%	95.8%
11/23/2023	0.8	3.2	0.6	0.7	95.8%	95.8%	95.8%	95.8%
11/24/2023	0.3	1.9	0.3	0.4	95.8%	95.8%	95.8%	95.8%
11/25/2023	0.3	2.9	0.3	0.3	95.8%	95.8%	95.8%	95.8%
11/26/2023	2.2	2.5	1.4	0.4	95.8%	95.8%	95.8%	95.8%
11/27/2023	3	8.9	5.4	2.2	95.8%	87.5%	95.8%	95.8%
11/28/2023	0.3	3.6	0.4	0.2	95.8%	83.3%	95.8%	95.8%
11/29/2023	0.4	1	0.4	0.3	95.8%	95.8%	95.8%	95.8%
11/30/2023	0.3	0.7	0.4	0.3	91.7%	91.7%	91.7%	91.7%
12/1/2023	0.2	1	0.4	0.2	100.0%	100.0%	100.0%	100.0%
12/2/2023	0.2	1.1	0.5	0.6	75.0%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				Daily Completeness			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
12/3/2023	0.9	2	1.3	1.9	100.0%	95.8%	95.8%	95.8%
12/4/2023	0.3	1.6	0.4	0.5	95.8%	95.8%	91.7%	95.8%
12/5/2023	0.2	9.1	1.5	0.3	95.8%	91.7%	95.8%	95.8%
12/6/2023	0.2	1.9	0.5	0.3	95.8%	95.8%	95.8%	95.8%
12/7/2023	0.2	1.2	0.4	0.4	95.8%	87.5%	95.8%	95.8%
12/8/2023	0.5	2.5	0.6	0.6	95.8%	95.8%	95.8%	95.8%
12/9/2023	0.2	1.9	0.3	0.5	95.8%	95.8%	95.8%	95.8%
12/10/2023	0.5	3.2	0.5	0.7	95.8%	95.8%	95.8%	91.7%
12/11/2023	18.2	2.4	2.8	8.3	95.8%	95.8%	95.8%	95.8%
12/12/2023	1.8	4.4	0.8	1.7	95.8%	95.8%	91.7%	95.8%
12/13/2023	0.2	4.9	0.5	0.4	95.8%	95.8%	91.7%	95.8%
12/14/2023	14	3.4	1	2	91.7%	95.8%	95.8%	91.7%
12/15/2023	22.6	1.8	0.4	2.2	95.8%	95.8%	95.8%	95.8%
12/16/2023	0.3	1.5	0.3	0.4	95.8%	95.8%	95.8%	95.8%
12/17/2023	0.1	1.1	0.1	0.2	95.8%	95.8%	95.8%	95.8%
12/18/2023	0.1	0.3	0.2	0.3	79.2%	95.8%	87.5%	95.8%
12/19/2023	0.1	1.1	0.2	0.3	95.8%	95.8%	95.8%	95.8%
12/20/2023	0.4	12.6	0.2	0.2	95.8%	95.8%	95.8%	95.8%
12/21/2023	1.5	2.4	0.6	0.7	95.8%	95.8%	95.8%	95.8%
12/22/2023	0.4	13.1	6.8	0.5	95.8%	95.8%	95.8%	95.8%
12/23/2023	0.3	1.4	0.3	0.4	95.8%	95.8%	95.8%	95.8%

	Daily Max 1-hr (ppb)				**Daily Completeness**			
Date	Kitamaat Village	Industrial Ave	Riverlodge	Whitesail	Kitamaat Village	Industrial Ave.	Riverlodge	Whitesail
12/24/2023	0.4	1.7	0.5	2.1	95.8%	95.8%	95.8%	95.8%
12/25/2023	0.4	1.1	0.2	0.4	95.8%	95.8%	95.8%	95.8%
12/26/2023	0.4	11.7	6.2	0.5	95.8%	95.8%	95.8%	95.8%
12/27/2023	0.5	1.3	0.2	0.5	95.8%	95.8%	95.8%	95.8%
12/28/2023	0.5	3	0.2	0.3	95.8%	87.5%	95.8%	95.8%
12/29/2023	0.3	1	0.2	0.3	95.8%	95.8%	95.8%	95.8%
12/30/2023	0.6	1.6	0.3	0.7	100.0%	95.8%	100.0%	100.0%
12/31/2023	0.3	1.7	0.2	0.4	91.7%	91.7%	91.7%	91.7%

Appendix C: Technical Memo W12 – Aquatic Ecosystems Actions and Analyses

The following pages contain **B.C. Works SO$_2$ EEM Program Technical Memo W12**, in PDF format.

B.C. Works SO_2 EEM Program – Technical Memo W12

Aquatic Ecosystems Actions and Analyses

April 2024

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1 Introduction

This Technical Memo provides additional information on the data and analyses in support of the 2023 requirements for the Aquatic Ecosystems component of the B.C. Works' Sulphur Dioxide Environmental Effects Monitoring (EEM) Program (SO_2 EEM Phase III Plan, ESSA et al. 2023). These data and analyses thus provide the foundation for Section 3.4 in the SO_2 EEM Program 2023 Annual Report.

This Technical Memo applies methods and approaches that have already been described in detail in other relevant documents. Most of the methods follow those employed in the SO_2 Technical Assessment Report (STAR) (ESSA et al. 2013), the Kitimat Airshed Assessment (KAA) (ESSA et al. 2014a) and the 2019 EEM Comprehensive Review (ESSA et al. 2020a). Full details on the collection, processing and analysis of the water chemistry samples are reported in technical reports prepared by Limnotek for each year's sampling (Perrin et al. 2013; Perrin and Bennett 2015; Limnotek 2016; Bennett and Perrin 2017, 2018; Limnotek 2019, 2020, 2021, 2022, 2023, 2024). Wherever possible, the description of methods in this Technical Memo refers to these reports instead of repeating information that is already well-documented elsewhere.

The following four documents (as described above) are listed here because they are referenced throughout this Technical Memo, often without their full citation:

- The STAR (ESSA et al. 2013)
- The KAA (ESSA et al. 2014a)
- 2019 SO_2 EEM Comprehensive Review (ESSA et al. 2020a)
- The SO_2 EEM Phase III Plan (ESSA et al. 2023)

2 Methods

2.1 Water Chemistry Sampling

EEM Lakes

The SO_2 Phase III EEM Program sampling plan includes eleven lakes: seven sensitive lakes, one less sensitive lake, and three control lakes (ESSA et al. 2023). The three control lakes (NC184, NC194 and DCAS14A) are all located outside of the zone of sulphur deposition from B.C. Works, and have pre-KMP baseline data for 2013 from sampling completed as part of the KAA (ESSA et al. 2014a). The five lakes that were unable to be sampled in 2020 (due to COVID-related constraints on helicopter flights) were sampled again in 2021, 2022 and 2023 as per previous years and therefore these lakes once no longer have any missing data within the current ***post-KMP averaging period*** (i.e., the average of the last three years; currently 2021-2023).

LAK027 was added for one-time sampling in 2021, as agreed to by ENV and Rio Tinto in May 2021. The intent was to resample one of the STAR lakes located relatively close to the smelter to check the validity of the conclusions made in the STAR, based on sampling completed in 2012, nine years prior to 2021. LAK027 was chosen because it was the only candidate that was moderately sensitive, whereas all the other lakes in the southern portion of the Kitimat Valley were determined to be insensitive based on the sampling during the STAR (except for LAK028, which was included in the SO_2 EEM Program because of its sensitivity). LAK027 was sampled again in 2022 and 2023, as per rationale summed up in the following recommendation from the SO_2 EEM Program 2022 EEM Annual Report:

> *We recommend sampling LAK027 again in 2023. In 2021, the widely-observed storm-driven dilution event negated the ability of the sampling data to provide a meaningful comparison against the initial STAR data as intended. In 2022, the combination of exceptionally low deposition and particularly dry hydrologic conditions again negate the ability to provide the intended comparison.*

In 2023, Limnotek sampled the eleven EEM lakes plus LAK027 according to the 2023 Aquatics Work Plan. The sampling methodology is described in detail in Limnotek (2024). Table 2-1 summarizes the sampling history of these 12 lakes. Figure 2-1 shows a map of the lakes sampled in 2023.

Table 2-1. Summary of sampling sites within the SO_2 EEM Phase III Program. The rationale for lakes included in the SO_2 EEM Phase III Program is described in ESSA et al. 2023.

Sample Site	Year of Sampling												Rationale
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	
	STAR	EEM	EEM	EEM	EEM	EEM	EEM	EEM	EEM	EEM	EEM	EEM	
LAK006	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	EEM sensitive lake, included in Phase III
LAK012	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
LAK022	✓	✓	✓	✓	✓	✓	✓	✓	‡	✓	✓	✓	
LAK023	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
LAK028	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
LAK042	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
LAK044	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
LAK016	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	EEM less sensitive lake, included in Phase III.
LAK027	✓									✓	✓	✓	Resampling of STAR lake at southern end of valley.
NC184		✓†		✓	✓	✓	✓	✓	‡	✓	✓	✓	EEM control lakes added to EEM in 2015.
NC194		✓†		✓	✓	✓	✓	✓	‡	✓	✓	✓	
DCAS14A		✓†		✓	✓	✓	✓	✓	‡	✓	✓	✓	

† Sampled as part of the Kitimat Airshed Assessment (ESSA et al. 2014a).

‡ LAK022 and the three control lakes are only accessible by helicopter and therefore were unable to be sampled in 2020 due to COVID protocols.

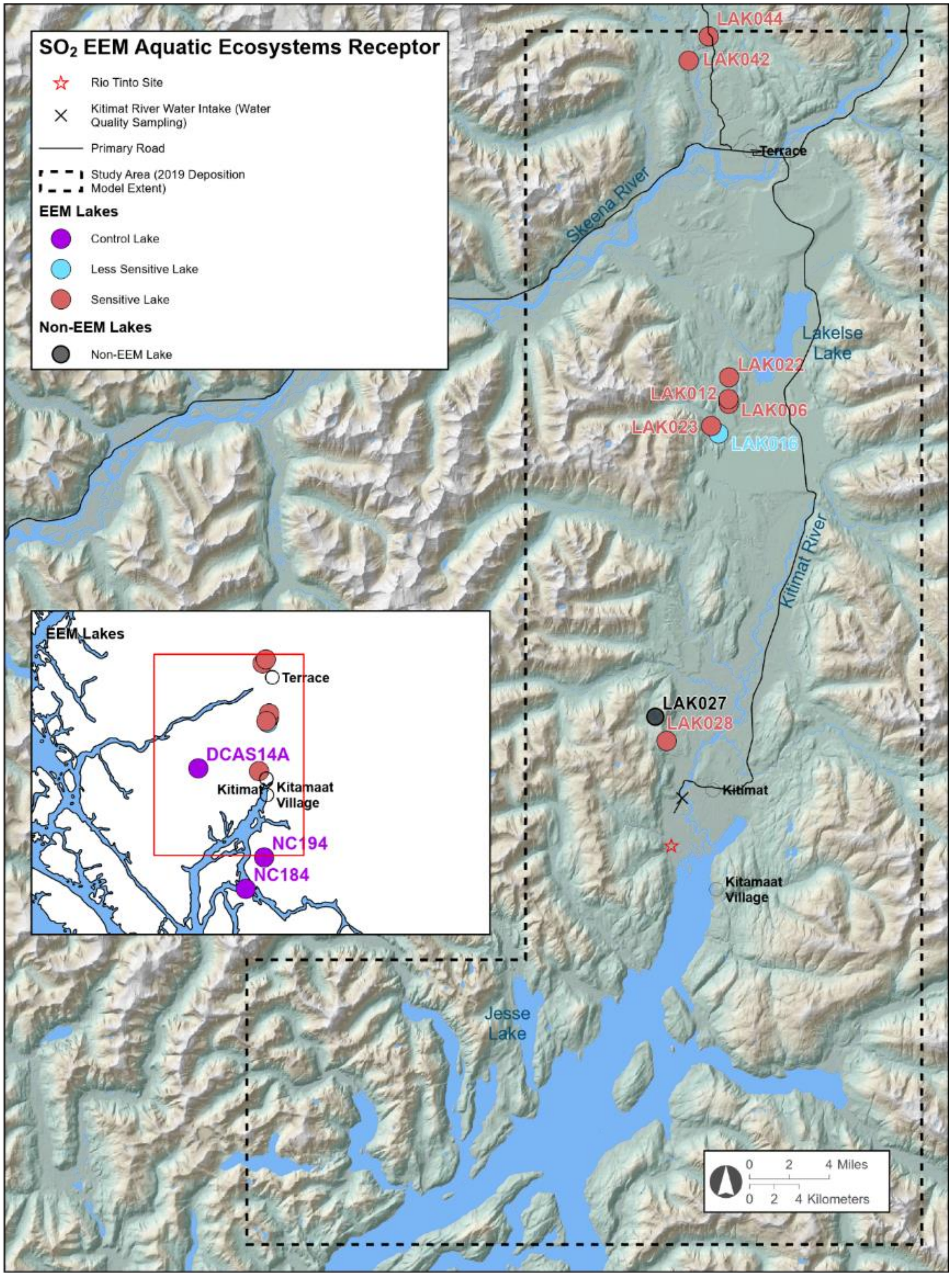

Figure 2-1. Location of the lakes in the EEM Program, including seven sensitive lakes (red), one less sensitive lake (blue) and three control lakes (purple). LAK027 was resampled in 2023 to compare with the STAR results.

Sampling frequency

Sampling frequency remained the same as last year:

- The sensitive lakes LAK006, LAK012, LAK023, LAK028, LAK042, and LAK044 were each sampled on four occasions within the fall index period
- Sensitive lake LAK022, less sensitive lake LAK016, and the three control lakes were each sampled once during the Fall index period (as per previous years)
- LAK027 (not part of current SO_2 EEM Program) was sampled once
- LAK006 and LAK028 had five additional samples with full chemistry analysis taken over May through early September, to assess seasonal variability in lake chemistry

Continuous monitoring

Two lakes (LAK006, LAK028) had continuous monitoring of surface water pH, temperature and lake levels. LAK028 also had a similar instrument installed at depth and continuous temperature monitoring across the depth profile. This work was planned, implemented and documented by Limnotek. The methods and results for 2023 are reported in Limnotek (2024).

Water chemistry data

There were no differences in the water chemistry analyses completed from the 2023 sampling compared to previous years. Continuing from 2020, analyses of Gran ANC are now *only* performed by the BASL facility (University of Alberta).

Integrating laboratory measurements of pH and Gran ANC from Trent and BASL laboratories

The transition of laboratory analysis of pH and Gran ANC from Trent University to the BASL laboratory at the University of Alberta was completed in 2020. In 2019, duplicate samples were sent to both laboratories to facilitate cross-laboratory comparisons (see Limnotek 2020).

To facilitate analyses over the entire period of record, we need an “integrated” data series for each of the two metrics. As in the SO_2 EEM Program 2020 Annual Report, we constructed an integrated time series by imputing Trent values for pH and Gran ANC for 2021-2023 based on the regression of Trent values vs. BASL values from the 2019 data. This method was recommended and developed by Dr. Carl Schwarz (retired professor of statistics from Simon Fraser University) and is described in detail in the SO_2 EEM Program 2020 Annual Report.

2.2 Empirical Changes in Water Chemistry

The methods applied for examining empirical changes are the same as described in the last several years.

2.3 Statistical Analyses of Changes in Water Chemistry

The 2019 Comprehensive Review performed an extensive series of statistical analyses of changes in water chemistry and concluded that the results from the Bayesian statistical analyses provided the greatest ability to assess the level of support for different hypotheses of chemical change. The 2019 Comprehensive Review further recommended that these analyses be re-run on an annual basis to assess status and detect any anomalous patterns. This annual report represents the fifth iteration of re-running those analyses with more recent monitoring data. These methods are described in detail in Appendix F of the 2019 Comprehensive Review (ESSA et al. 2020b) (see Bayesian Method 1 especially). The key metrics of interest are the differences in lake chemistry between the post-KMP averaging period (2021-2023) and the pre-KMP baseline (2012 for the sensitive and less sensitive lakes; 2013 for the control lakes). Appendix 3 includes sensitivity analyses that examine the effect of using an alternative baseline representing the transition period as operations at the old smelter were wound down (2012-2014).

The results of the Bayesian statistical analyses are expressed in terms of: a) the % belief that the values of the post-KMP averaging period have exceeded the *level of protection* thresholds, and b) the % belief that the changes from the baseline period to the post-KMP averaging period have exceeded the *change limit* thresholds. As applied in the 2019 Comprehensive Review, the % belief values are classified as low (< 20%), moderate (20% to <80%), or high (≥ 80%). This classification is done both for ease of interpretation, and to integrate the analyses for the two-threshold structure of the CBANC KPI and informative indicators into a single assessment for each indicator for each lake. As described in the Phase III Plan, the acidification indicators (CBANC, pH, Gran ANC and BCS (Base Cation Surplus)) are only considered to be in exceedance if **both** thresholds are exceeded (i.e., the *level of protection* and the *change limit* thresholds). The single, integrated assessment of each of those indicators is determined according to the rules:

1. If the result for **either** threshold is **"low"**, then the overall assessment is **"low"**
2. The results for **both** thresholds must be **"high"** for an overall assessment of **"high"**
3. If result for **either** threshold is **"moderate"** and the results for the other threshold are **"moderate" or "high"**, then the overall assessment is **"moderate"**.

As described in the SO_2 EEM Program Phase III Plan, the two-threshold structure avoids creating false positives by simultaneously considering the two dimensions of importance to aquatic organisms – the absolute level and the relative change in the water chemistry metrics used as acidification indicators.

Appendix 4 includes results of sensitivity analyses for the uncertainty associated with the imputation procedure associated with developing integrated data series for pH and Gran ANC following the transition of laboratories (details in Section 2.1).

We also evaluated differential trends between the sensitive lakes and the control lakes using the before-after control-impact (BACI) analysis methods described in the 2019 Comprehensive Review (i.e., Method 3: BACI using mean values). Using this method, we evaluated the sensitive lakes individually and as a group, for CBANC (as an informative method, as the KPI is not based on this statistical approach) as well as the pH, Gran ANC, and BCS informative indicators.

2.4 Environmental Data

This section includes supplementary environmental observations or data utilized in the interpretation of the water chemistry results (see Section 4.3).

This year we are using data from the two NADP stations (Haul Road, BC22; Lakelse Lake, BC23) to provide the precipitation context (and by proxy, the hydrologic context of the lakes) for 2023. This is a significant improvement over the use of publicly available precipitation data through ECCC used in previous years. As reported in last year's Aquatic Technical Memo, providing the precipitation context for 2022 was particularly challenging due to extensive missing data from the available climate stations. Using the NADP sites resolves that issue.

British Columbia experienced significant and widespread drought conditions across much of the province in 2023. This broad pattern is borne out in the precipitation data from the Haul Road and Lakelse Lake NADP sites, which show that 2023 was exceptionally dry relative to recent years for the Kitimat Valley as well.

As described in the 2022 EEM Report, 2022 was a dry year with respect to water chemistry sampling (i.e., for the August to October period). This year was even drier. The cumulative precipitation graph (Figure 2-2) shows that cumulative precipitation in 2023 relative to 2022 was a) similarly low in August, and b) much lower in September through mid-October (essentially the extent of the lake sampling program.). The figure shows that a notable precipitation event in roughly mid-October briefly made the cumulative precipitation in 2023 equivalent to the cumulative precipitation in 2022 at the same point; however, this occurred after all but one of the sampling events in the EEM program[1].

For the Haul Road and Lakelse Lake NADP stations, total precipitation levels for August through October in 2023 were 55% and 45% lower than 2022, respectively, and 39% and 28% lower than 2019 (another notably dry year), respectively. However, this comparison to 2022 is somewhat misleading with respect to the potential influence on lake chemistry sampling because a substantial quantity of precipitation fell in late October 2022 (as discussed in detail in last year's report) but none fell in the later half of October 2023. Therefore, the differences in cumulative August to October precipitation between 2022 and 2023 were driven largely by differences *after* the period of sampling – i.e., 2022 was dry with respect to EEM fall sampling period, but not a dry year when looking through to the end of October. The more meaningful period to examine with respect to potential influence on lake chemistry data is August through mid-October, for which 2022 was a dry year and 2023 was similar in August but even drier through September and early October.

On September 30, 2023 (i.e., when all lakes are sampled), the cumulative precipitation for August-September was notably lower than any of the previous 4 years[2]. Similarly, total precipitation in the month of September alone was much lower in 2023 than the previous 4 years at Haul Road (Table 2-2) and lower or similar for Lakelse Lake (Table 2-3).

---

[1] For reference, the last lake samples were taken on October 18, which corresponds to Julian Day 291 on the figures.

[2] Note that the 2019 data are not shown in Figure 2-2, but track very closely to the 2022 data for August and September.

Table 2-2. Total Monthly Precipitation (mm) at Haul Road NADP station (BC22) for 2019-2023.

	2019	2020	2021	2022	2023
	BC22	BC22	BC22	BC22	BC22
August	104	262	55	146	33
September	143	207	468	120	92
October	242	215	304	398	173
Total	489	684	826	664	298

Table 2-3. Total Monthly Precipitation (mm) at Lakelse Lake NADP station (BC23) 2019-2023.

	2019	2020	2021	2022	2023
	BC23	BC23	BC23	BC23	BC23
August	52	162	35	64	15
September	80	64	284	68	62
October	142	142	156	224	119
Total	273	368	476	356	197

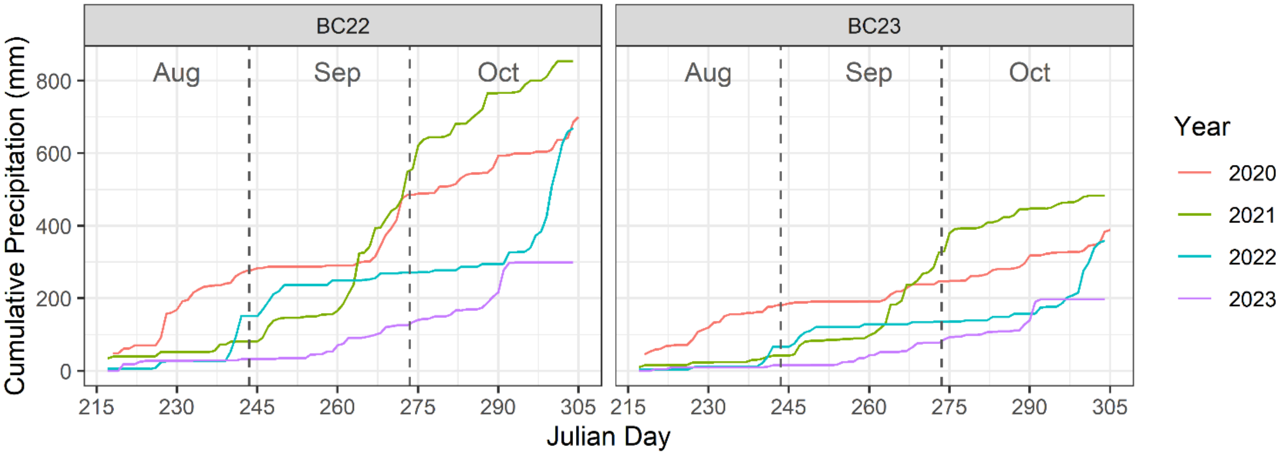

Figure 2-2. Cumulative precipitation at Haul Road (BC22) and Lakelse Lake (BC23) NADP stations for August to October in 2020, 2021, 2022, and 2023.

2.5 Episodic Acidification

We reviewed the data record from the continuous pH monitors installed in LAK006 and LAK028 to identify any notable drops in pH. If any such changes were observed, we compared those results with the lake-level data to determine if they appeared to be correlated with high inflows to the lake.

2.6 Alignment of Evidentiary Framework with EEM Phase III Indicators

The "Simple Evidentiary Framework" developed in the 2019 Comprehensive Review and subsequently built into the SO_2 EEM Program Phase III Plan only considered post-KMP changes in pH and ANC[3] (relative to pre-KMP conditions), especially relative to the *change limit* thresholds, but did not consider the post-KMP state of either of those metrics with respect to the *level of protection* thresholds. The SO_2 EEM Program Phase III Plan made an important advance, moving to a two-threshold structure for the KPI and the pH and ANC informative indicators that consider both relative change and the absolute level of those indicators.

To be consistent with the SO_2 EEM Program Phase III Plan, we revised the Evidentiary Framework in the SO_2 EEM Program 2020 Annual Report by adding an assessment node associated with the *level of protection* threshold (Figure 2-3). The new node was inserted earlier in the logic sequence than the two nodes assessing the level of change. In the two-threshold structure for the KPI and informative indicators, neither of the thresholds takes precedence – an exceedance of the indicator requires that both thresholds are exceeded with a high percent belief. Therefore, there is no inherent sequence between evaluating the *change limit* and *level of protection* thresholds. However, in the Evidentiary Framework, there is an additional node that considers whether there has been any change in the indicator prior to assessing against the *change limit* threshold, which makes the framework more precautionary, so we believe it made more sense to have the *level of protection* node earlier in the sequence than the two change-based nodes.

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[3] Gran ANC in the 2019 Comprehensive Review; CBANC in the SO_2 EEM Program Phase III Plan (consistent with the revised KPI).

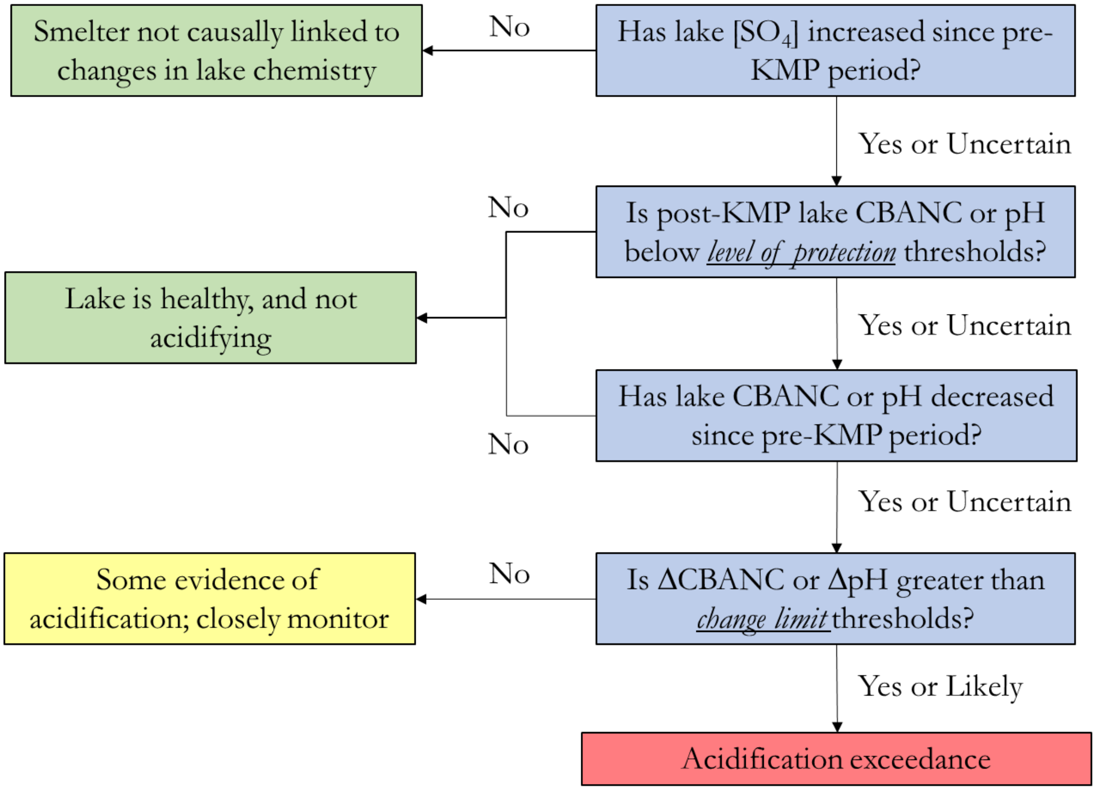


Figure 2-3. The Evidentiary Framework. The framework developed in the 2019 Comprehensive Review was revised in the SO_2 EEM Program 2020 Annual Report order to align with the two-threshold structure for the KPI and informative indicators in the SO_2 EEM Program Phase III Plan.

3 Results

3.1 Empirical Changes in Water Chemistry

Empirical changes in CBANC, Gran ANC, BCS, pH, [SO_4^{2-}], DOC, sum of base cations, chloride, and calcium are shown in Table 3-1. A map of the observed changes in [SO_4^{2-}], CBANC, and pH at the EEM lakes is shown in Figure 3-1. Changes are reported in terms of the difference between the post-KMP averaging period (2021-2023) and the pre-KMP baseline (2012 for the sensitive and less sensitive lakes; 2013 for the control lakes). The sensitive EEM lakes and less sensitive EEM lakes are presented separately within each of the tables. The inter-annual changes presented in this report use the mean annual values whenever multiple within-season samples were acquired from a given lake in a given year.

Unlike the annual reports prior to the 2019 Comprehensive Review, the annual changes between individual years are no longer reported and analyzed in detail. As already stated in previous years (e.g., ESSA 2018, Technical Memo W07), year-to-year changes should be interpreted cautiously:

> *"... annual changes should be interpreted with substantial caution due to the combination of large natural variation (both within and between years) and*

> *limitations on measurement precision… multiple years of observations are required to reliably detect changes in mean pH, Gran ANC and SO_4; it is risky to draw conclusions based only on annual changes".*

Furthermore, in the December 2018 workshop on the terms of reference for the SO_2 EEM Program Comprehensive Review, the ENV external acidification expert recommended that we stop reporting annual changes because inter-annual variability in lake chemistry is too variable to make any meaningful interpretation of the changes between two years. We still examine the annual changes in the context of understanding the extent to which any dominant factors in a particular year (e.g., anomalous hydrologic or emissions conditions) result in a pronounced regional pattern, but we do not analyze or interpret all of the annual changes observed in all of the metrics.

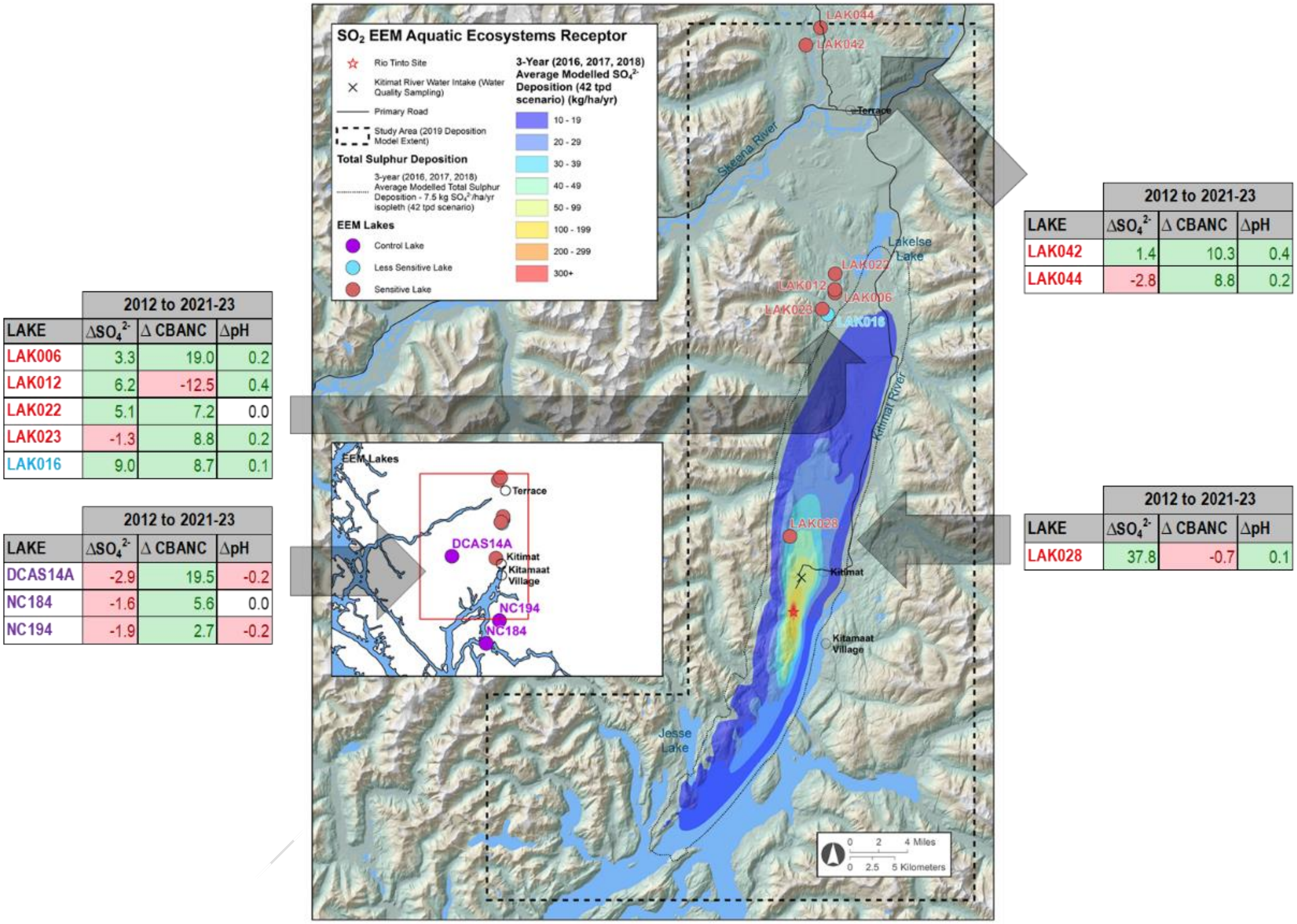
Table 3-1. Empirical changes in CBANC, Gran ANC, BCS, pH, SO_4^{2-}, DOC, base cations, chloride, calcium, and NO_3 for EEM lakes. These values represent the difference between the average of the post-KMP averaging period (2021-2023) and the 2012 baseline. Numbers shown are the value in the later period minus the value in the earlier year. Increases are shaded in green; decreases are shaded in red. The Gran ANC and pH values are based on the "integrated" time series (i.e., values from the Trent University laboratory from 2012 to 2019 with the 2020 to 2023 values imputed from the values measured by the BASL laboratory ("integ"); see details in Section 2.1). Signs after each number show the direction of change in the reported values since the SO_2 EEM Program 2022 Annual Report (i.e., [+] = increase; [-] = decrease; [ ] = identical value).

SITE	CBANC (µeq/L)	Gran ANC (integ) (µeq/L)	BCS (µeq/L)	pH (integ)	SO_4* (µeq/L)	DOC (mg/L)	∑ BC* (µeq/L)	Cl (µeq/L)	Ca* (µeq/L)
LAK006	19.0 [-]	10.8 [-]	15.7 [+]	0.2 [+]	3.3 [-]	0.7 [-]	22.5 [-]	0.4 [-]	12.2 [-]
LAK012	-12.5 [-]	2.3 [-]	-16.7 [-]	0.4 [+]	6.2 [-]	0.8 [-]	-6.0 [-]	1.6 [-]	-7.2 [-]
LAK022	7.2 [+]	1.3 [+]	5.4 [+]	0.0 [+]	5.1 [-]	0.4 [-]	12.4 [+]	0.3 [ ]	6.5 [+]
LAK023	8.8 [-]	3.1 [-]	3.4 [-]	0.2 [ ]	-1.3 [+]	1.1 [-]	8.1 [-]	0.2 [-]	5.5 [-]
LAK028	-0.7 [+]	6.8 [+]	-9.8 [+]	0.1 [+]	37.8 [-]	1.8 [-]	37.6 [-]	1.9 [-]	27.1 [-]
LAK042	10.3 [-]	26.0 [+]	19.5 [+]	0.4 [+]	1.4 [-]	-1.8 [-]	11.8 [-]	-0.5 [ ]	6.9 [-]
LAK044	8.8 [+]	4.5 [+]	8.0 [+]	0.2 [ ]	-2.8 [-]	0.2 [-]	6.2 [ ]	0.3 [-]	1.8 [-]
Total ↑	**5**	**7**	**5**	**6**	**5**	**6**	**6**	**6**	**6**
Total ↓	**2**	**0**	**2**	**1**	**2**	**1**	**1**	**1**	**1**

LAK016	8.7 [-]	19.9 [-]	-1.0 [+]	0.1 [+]	9.0 [-]	1.9 [-]	18.3 [-]	1.1 [-]	10.5 [-]
Total ↑	**1**	**1**	**0**	**1**	**1**	**1**	**1**	**1**	**1**
Total ↓	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**

DCAS14A	19.5 [+]	4.1 [+]	18.2 [+]	-0.2 [+]	-2.9 [+]	0.2 [-]	13.8 [+]	-2.4 [+]	8.4 [+]
NC184	5.6 [+]	13.4 [+]	15.1 [+]	0.0 [+]	-1.6 [+]	-1.9 [-]	3.9 [+]	-4.7 [+]	6.7 [+]
NC194	2.7 [+]	-1.8 [+]	1.5 [+]	-0.2 [+]	-1.9 [-]	0.2 [-]	0.9 [+]	-1.6 [+]	1.1 [+]
Total ↑	**3**	**2**	**3**	**1**	**0**	**2**	**3**	**0**	**3**
Total ↓	**0**	**1**	**0**	**2**	**3**	**1**	**0**	**3**	**0**

SO_4*, BC* and Ca* mean that concentrations of sulfate, base cations and calcium were each reduced using the ratio of each to chloride in seawater, to account for marine sources.



	2012 to 2021-23		
LAKE	ΔSO_4^{2-}	Δ CBANC	ΔpH
LAK006	3.3	19.0	0.2
LAK012	6.2	-12.5	0.4
LAK022	5.1	7.2	0.0
LAK023	-1.3	8.8	0.2
LAK016	9.0	8.7	0.1

	2012 to 2021-23		
LAKE	ΔSO_4^{2-}	Δ CBANC	ΔpH
DCAS14A	-2.9	19.5	-0.2
NC184	-1.6	5.6	0.0
NC194	-1.9	2.7	-0.2

	2012 to 2021-23		
LAKE	ΔSO_4^{2-}	Δ CBANC	ΔpH
LAK042	1.4	10.3	0.4
LAK044	-2.8	8.8	0.2

	2012 to 2021-23		
LAKE	ΔSO_4^{2-}	Δ CBANC	ΔpH
LAK028	37.8	-0.7	0.1

Figure 3-1. Observed changes in SO_4^{2-}, CBANC and pH from the baseline period (2012) to the post-KMP averaging period (2021-2023). Green cells indicate increases and red cells indicate decreases.

Emissions Context for 2023

As described in detail in last year's EEM Annual Report, 2022 was exceptional in the 11-year history of the SO_2 EEM Program. Emissions from the smelter were dramatically less than in any previous year of the SO_2 EEM Program due to a reduction in smelter operations associated with a labour dispute. In August 2021, emissions dropped by approximately 83%. Emissions did not begin to increase meaningfully until July 2022, after 11 months of emissions <5.3 tpd, and then did not reach pre-dispute levels until May 2023. By August 2023, emissions had returned to 32.1 tpd, similar to the annual average of 30.2 tpd observed in 2019.

For comparison, Table 3-2 shows the 12- and 6-month average emissions at the time of fall sampling for each of the past several years, including comparison to the levels prior to the labour dispute.

Table 3-2. Average emissions at the time of fall sampling since the reduction in emissions due to the labour dispute in 2021.

		Average Emissions (SO_4 tpd)	
Time Period	**Relevance of Time Period**	**12-month average**	**6-month average**
June 2021	Before labour dispute	26.1	27.6
September 2021	Relevant to 2021 fall sampling; shortly after initial drop	22.7	19.3
September 2022	Relevant to 2022 fall sampling; after prolonged period of low emissions	5.5	6.5
September 2023	Relevant to 2023 fall sampling; emissions have increased	21.5	28.8

At the time of the annual sampling at the end of September 2022, the 12-month and 6-month average emissions were only 21% and 24%, respectively, of the levels prior to the labour dispute. The comparable time periods relevant to 2023 annual sampling were at 82% and 104% of the pre-reduction levels. We therefore do not consider 2023 to be exceptional in terms of absolute emissions levels. However, 2023 does represents the most substantial year-over-year increase in emissions. Given that 5 of 7 sensitive lakes have water residence times less than or equal to 9 months, this rapid increase could potentially have a notable impact on lake chemistry, albeit perhaps simply offsetting the changes associated with the original reduction.

In the 2022 Annual Report, we stated:

> *We expected that the decline in SO_2 emissions would cause a decline in lake [SO_4], and possibly an increase in CBANC, Gran ANC and pH, in at least the 5 sensitive EEM lakes with short water residence times. Increases in lake [SO_4] are generally associated with increases in lake base cations, due to cation exchange processes in the watershed. The converse also holds: decreases in lake [SO_4] would be expected to result in lower base cation concentrations.*
>
> *The dominant responses in the 2022 data were generally consistent with our expectations:*
>
> - *[SO_4] declined in all sensitive lakes except LAK028 (+3.5 μeq/L); some of the decreases were quite substantial*
> - *Gran ANC went up in ALL lakes*

- *CBANC showed an increase in 4 of the sensitive EEM lakes, a limited decrease in 2 of them, and LAK042 (far north of the study area) decreased by 9.7 µeq/L*
- *pH increased by 0.2-0.8 pH units in all 11 lakes, with the same range across the sensitive lakes*

Given the significant increase in emissions from 2022 to 2023, we might expect to see the reverse of those patterns; however, the responses in the 2023 only partially align with that hypothesis:

- [SO_4] did increase in all sensitive lakes, except LAK028
- Gran ANC only decreased in roughly half of the sensitive lakes (3 of 7) and increased slightly in the others
- CBANC only decreased in roughly half of the sensitive lakes (4 of 7)
- pH only decreased in roughly half of the sensitive lakes (4 of 7); however all 7 sensitive lakes had changes of only <0.1 pH units

Analyses of change based on the recent 3-year average

To protect aquatic ecosystems in the sensitive lakes, we want to avoid declines in recent post-KMP measurements of CBANC, Gran ANC, BCS, and pH (i.e., the KPI and other acidification informative indicators) that are greater than the established thresholds, using 2012 as a pre-KMP baseline. We use the average of the most recent 3 years to dampen the effects of an unusual year.

For LAK012, the long-term decline in CBANC is strongly influenced by a drop in mean CBANC in 2023 to levels on par with the lowest CBANC levels observed for the lake (~90 µeq/L; Table 3-4). For BCS, the 2023 mean value also represents a decrease from the previous year, but not as low as the several lowest post-KMP observations. However, LAK012 shows a small long-term increase in Gran ANC (2.3 µeq/L, relative to an ANC *change limit* threshold of -16.3 µeq/L) and the largest increase in pH across all EEM lakes (+0.4 pH units, relative to a pH *change limit* threshold of -0.3 pH units). LAK012 is the only lake with a decline in base cations (no associated *change limit* threshold).

In LAK028 (the lake closest to the smelter with the highest deposition) mean [SO_4^{2-}] is estimated to have increased by 37.8 µeq/L since 2012, almost exactly balanced by an increase in total base cations (ΣBC*) of 37.6 µeq/L. The changes in ΣBC* and SO_4^{2-} essentially explain the observed change in CBANC, a decline of 0.7 µeq/L. CBANC equals the sum of base cations minus the sum of strong acid anions, and ΔΣBC* - Δ[SO_4^{2-}] = 37.6 – 37.8 = –0.1, very close to the -0.7 µeq/L change in CBANC. Gran ANC shows a long-term increase (6.8 µeq/L) in LAK028 and there continues to be no decline in mean pH, similar to the results reported in the last couple years. LAK028 showed a decline in BCS since the pre-KMP period, though BCS has shown considerable variation in LAK028, with its lowest value occurring in 2013 (Table 3-3). The BCS *change limit* threshold is -13 µeq/L.

Table 3-3. Mean values of BCS in LAK028 by year. Units are µeq/L. Data from Appendix 1.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
BCS (µeq/L)	-5.1	-40.2	4.8	1.5	-24.9	-32.5	-8.4	-18.1	-26.7	-20.5	-10.6	-2.5

None of the sensitive or less sensitive lakes are showing any decline in pH. LAK022, which in the prior two EEM reports had been the only lake with a decline in pH, now shows no long-term change. All other sensitive and less sensitive lakes show a long-term increase in pH within the range of 0.1 to 0.4 pH units. By contrast, two of the control lakes (DCAS14A and NC194) show a long-term decline of 0.2 pH units with the third control showing no change (NC184). The causes for the 0.2 pH unit declines in DCAS14A and NC194 are not clear, but they're not related to SO_2, since [SO_4] has declined slightly in all three control lakes (Table 3-1) and there is no statistical evidence of a long-term increase in [SO_4] (Table 3-7).

Figure 3-2 and Figure 3-3 show the changes in the same water chemistry parameters graphically. These figures provide a regional picture of the distribution and variability in the observed changes in sensitive lakes between 2012 and 2021-2023.

For additional reference, Table 3-4 and Table 3-5 show the CBANC and pH values, respectively, over the period of record for EEM lakes, values for the post-KMP averaging period (2021-2023), and the differences between the post-KMP averaging period and both the pre-KMP baseline (2012) and the transition period baseline (2012-2014). The changes in CBANC are generally similar using both the pre-KMP and the transition period as a baseline (Table 3-4), except for LAK012 which shows a much smaller decrease in CBANC from the transition period baseline than the pre-KMP baseline. The changes in pH were consistently less positive (or more negative) for the sensitive and less sensitive lakes when using the transition period baseline instead of the pre-KMP baseline (Table 3-5). For the control lakes, the two baselines are actually the same because they were only sampled once during the 2012-2014 period (i.e., 2013).

Appendix 2 provides a detailed set of figures showing the inter-annual changes in major water chemistry metrics (CBANC, Gran ANC, BCS, pH, SO_4^{2-}, base cations, calcium, chloride, and DOC) for each of the EEM lakes across the twelve years of annual monitoring (2012-2023). Similar figures are also included for the three control lakes based on their nine years of monitoring (2013, 2015-2019, and 2021-2023).

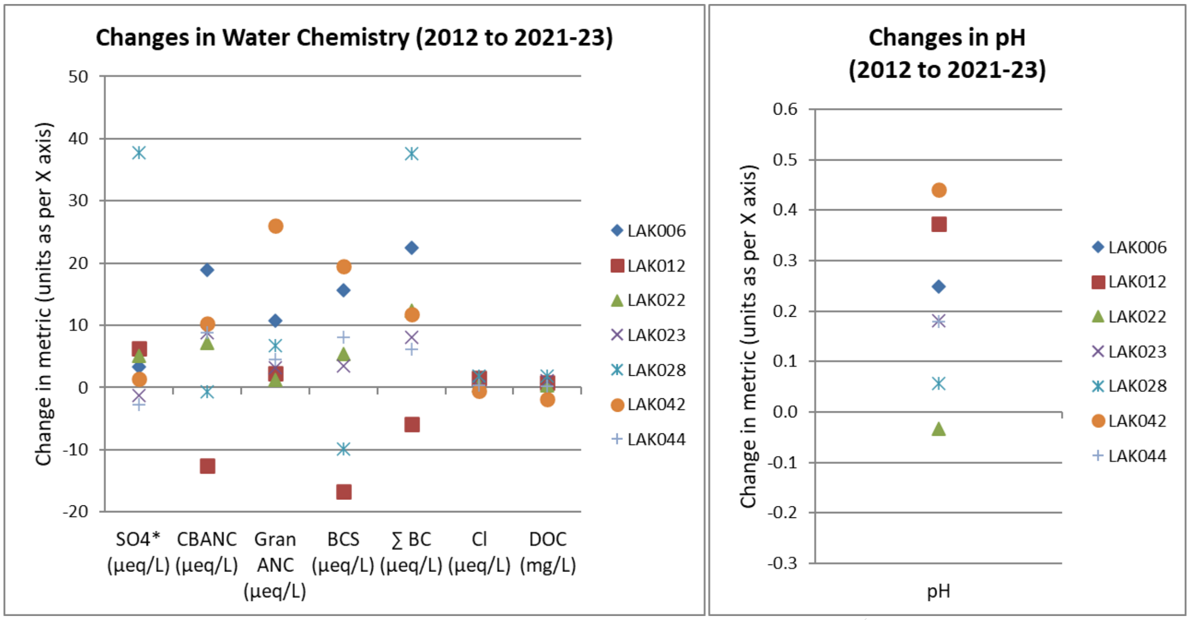


Figure 3-2. Changes in water chemistry metrics (left panel) and pH (right panel) across all of the sensitive EEM lakes, from 2012 to 2021-2023. Values shown are the mean 2021-2023 value minus the mean 2012 value. The large increase in lake SO_4^{2-} in LAK028 has been buffered by a large increase in base cations, due to cation exchange in watershed soils.

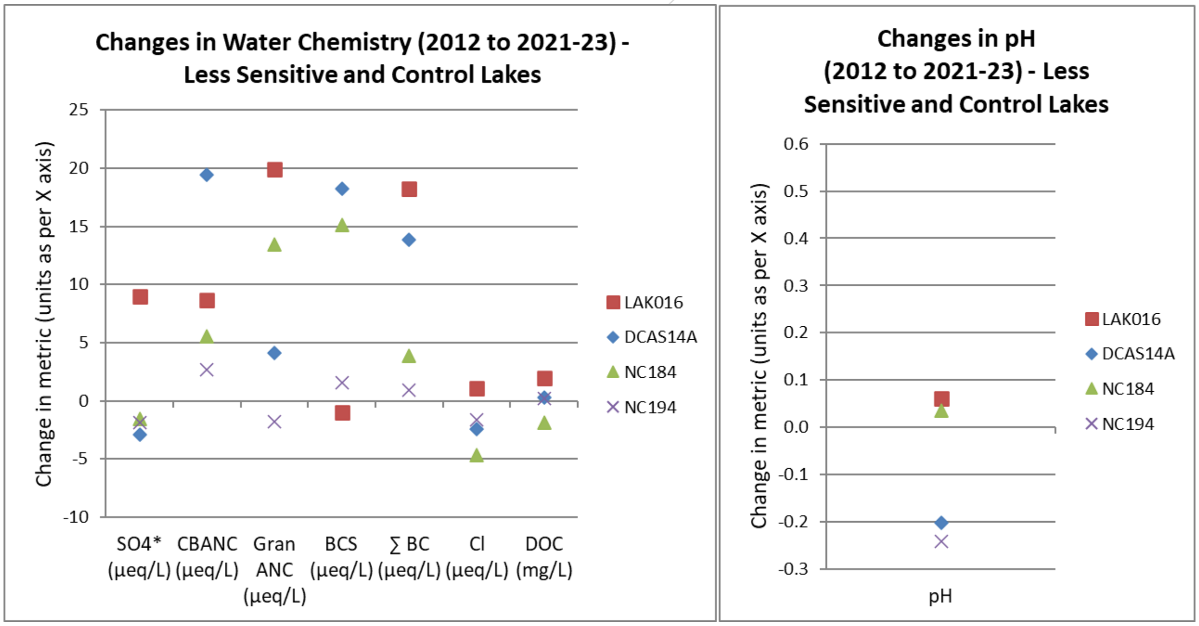


Figure 3-3. Changes in water chemistry metrics (left panel) and pH (right panel) across all of the less sensitive and control lakes, from 2012 to 2021-2023. Values shown are the mean 2021-2023 value minus the mean 2012 value. All three control lakes have shown no increase in SO_4* (left panel); the pH decrease (right panel) largely reflects the very high precipitation in September 2021.

Table 3-4. CBANC values over period of record for EEM lakes, average CBANC values for the post-KMP averaging period and the relative change from the pre-KMP baseline and the transition period baseline. The post-KMP averaging period applied in the 2019 comprehensive review (CR) is also shown for reference. Green represents an increase and red represents a decrease. Bolded purple values are below the 20 µeq/L *level of protection* threshold for CBANC.

	Mean CBANC values (µeq/L)												Post-KMP averaging period		Change from baseline to current post-KMP average (2021-23)	
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2016-18 (CR)	2021-23 (current)	From pre-KMP baseline (2012)†	From transition period baseline (2012-14)†
LAK006	49.2	43.1	52.9	55.1	56.9	58.0	59.3	63.8	70.3	67.8	70.1	66.6	58.0	68.2	19.0	19.8
LAK012	114.5	97.5	99.8	106.1	103.2	101.1	90.4	96.5	142.1	101.2	112.4	92.2	98.2	101.9	-12.5	-2.0
LAK022	67.9	62.0	76.1	75.2	80.3	70.4	76.6	74.8		68.8	75.4	81.4	75.8	75.2	7.2	6.5
LAK023	46.9	37.7	59.4	58.0	59.5	59.9	61.3	59.4	66.6	56.2	54.0	57.0	60.2	55.7	8.8	7.7
LAK028	**16.0**	**-8.1**	31.2	38.6	**12.3**	**0.7**	**8.4**	**4.5**	**8.0**	**11.7**	**19.3**	**14.7**	7.1	15.3	-0.7	2.2
LAK042	47.2	55.1	51.6	55.4	64.0	63.1	50.4	52.1	79.5	62.4	52.8	57.2	59.2	57.5	10.3	6.2
LAK044	**8.0**	**8.9**	**12.6**	**16.4**	**13.9**	**13.8**	**13.2**	**14.8**	**14.5**	**17.1**	**16.8**	**16.7**	13.6	16.9	8.8	7.0
LAK016	127.2	108.7	132.5	147.1	140.8	125.3	138.1	129.8		138.1	141.4	128.1	134.7	135.9	8.7	13.1
DCAS14A†		53.5		74.9	72.7	67.8	79.0	81.1		63.8	70.9	84.2	73.2	73.0	19.5	19.5
NC184†		80.4		73.0	94.6	76.3	95.0	86.1		61.2	85.3	111.5	88.6	86.0	5.6	5.6
NC194†		35.6		40.9	40.0	46.5	43.1	46.7		35.6	36.3	43.1	43.2	38.3	2.7	2.7

†The pre-KMP for the control lakes is 2013. The transition period baseline for the control lakes is also only 2013 because the lakes were not sampled in 2014. Therefore, the results for the two baselines are identical.

Table 3-5. pH values over period of record for EEM lakes, average pH values for the post-KMP period and the relative change from the pre-KMP baseline and the transition period baseline. The post-KMP averaging period applied in the 2019 comprehensive review (CR) is also shown for reference. Green represents an increase and red represents a decrease. Bolded purple values are below the *level of protection* threshold for pH (6.0). As explained in the STAR, the 2012 chemistry of most of the sensitive lakes was influenced by organic acids contributed by DOC. Mean DOC has not changed much in the sensitive lakes since 2012 (Figure 3-2).

	Mean pH values												Post-KMP averaging period		Change from baseline to current post-KMP average (2021-23)	
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2016-18 (CR)	2021-23 (current)	From pre-KMP baseline (2012)†	From transition period baseline (2012-14)†
LAK006	**5.8**	6.2	6.1	6.0	6.0	6.0	6.1	6.1	6.0	**5.8**	6.2	6.2	6.0	6.0	0.2	0.0
LAK012	**5.6**	6.3	6.0	6.0	6.2	6.1	6.2	6.1	6.0	**5.7**	6.2	6.2	6.2	6.0	0.4	0.0
LAK022	**5.9**	6.2	6.3	6.1	6.1	6.1	6.1	6.1		**5.4**	6.1	6.1	6.1	5.9	0.0	-0.2
LAK023	**5.7**	6.0	**5.9**	**5.9**	**5.9**	**5.9**	6.0	**5.8**	**5.9**	**5.7**	6.0	6.0	**5.9**	5.9	0.2	0.0
LAK028	**5.0**	**5.2**	**5.3**	**5.1**	**5.0**	**4.8**	**5.3**	**5.2**	**4.9**	**4.7**	**5.2**	**5.2**	**5.0**	5.0	0.1	-0.1
LAK042	**4.7**	**5.5**	**5.1**	**5.4**	**5.4**	**5.2**	**5.1**	**5.4**	**4.6**	**4.6**	**5.4**	**5.4**	**5.2**	5.1	0.4	0.0
LAK044	**5.4**	**5.7**	**5.8**	**5.8**	**5.5**	**5.6**	**5.5**	**5.5**	**5.6**	**5.5**	**5.7**	**5.6**	**5.6**	5.6	0.2	0.0
LAK016	6.3	6.7	6.7	6.8	6.6	6.7	6.7	6.6		6.1	6.5	6.5	6.7	6.4	0.1	-0.2
DCAS14A†		6.5		6.6	6.6	6.6	6.8	6.6		**5.9**	6.4	6.5	6.6	6.3	-0.2	-0.2
NC184†		**5.7**		**5.5**	**5.8**	**5.4**	6.2	**5.7**		**5.1**	**5.8**	6.4	**5.8**	5.8	0.0	0.0
NC194†		6.6		6.5	6.4	6.4	6.5	6.4		**5.9**	6.3	6.8	6.4	6.3	-0.2	-0.2

†The pre-KMP for the control lakes is 2013. The transition period baseline for the control lakes is also only 2013 because the lakes were not sampled in 2014. Therefore, the results for the two baselines are identical.

Resampling of LAK027

Table 3-6 shows the results for LAK027 for ANC, pH, SO_4^{2-}, DOC, sum of base cations, chloride, and calcium, including the results from the 2012 STAR sampling and the difference between the 2023 and 2012. As explained earlier (and in the recommendations of the SO_2 EEM Program 2021 and 2022 Annual Reports), LAK027 was resampled for a second year in 2022 due to the influence of anomalous hydrologic conditions in fall 2021 across all of the lakes (storm-driven dilution event), and then resampled for a third year in 2023 due to anomalous conditions again in fall 2022 (exceptionally low deposition and particularly dry hydrologic conditions). Therefore, we are primarily focused on comparing 2023 to 2012 to achieve the original intent of resampling this lake. All of the lake chemistry metrics in Table 3-6 show increases, often substantial, from 2012. CBANC, Gran ANC, BCS, SO_4, DOC, base cations, and Cl all roughly doubled from 2012 to 2023, and pH increased by 0.1 pH units The relative difference between the 2012 to 2023 increases in ΣBC* (219.5 μeq/L) and SO_4^{2-} (124.2 μeq/L) almost perfectly explains the 94.6 μeq/L increase in CBANC between 2012 and 2023 (i.e., 219.5 – 124.2 = 95.3 μeq/L). The data suggest that LAK027 demonstrates a high level of watershed neutralization of deposited SO_4^{2-}, as well as hydrologic change. The implied F-factor ($\Delta BC^*/\Delta SO_4^*$ = 219.5 / 124.2 = 1.76) is greater than 1.0 (indicative of complete neutralization of all deposited acidity), indicating that other factors besides cation exchange likely contributed to the increase in base cations (e.g., higher rates of weathering due to warmer temperatures, less runoff).

Table 3-6. CBANC, Gran ANC, BCS, pH, SO_4, DOC, base cations, chloride, and calcium values for LAK027, from the 2012 STAR sampling and the resampling in 2021, 2022, and 2023. The change from 2012 to 2023 is shown. Increases are shaded in green; decreases are shaded in red. The Gran ANC and pH values are based on the "integrated" time series (i.e., values from the Trent University laboratory from 2012 with the 2021, 2022, and 2023 values imputed from the values measured by the BASL laboratory ("integ"); see details in Section 2.1). Note that the imputation uses the regression based on the 2019 data for the EEM Lakes (i.e., LAK027 did not contribute to the regression).

	CBANC (μeq/L)	Gran ANC (integ) (μeq/L)	BCS (μeq/L)	pH (integ)	SO_4* (μeq/L)	DOC (mg/L)	∑ BC* (μeq/L)	Cl (μeq/L)	Ca* (μeq/L)
2012	101.3	69.8	98.8	6.6	110.4	1.1	211.6	3.2	189.3
2021	94.8	56.9	65.9	5.9	90.3	6.4	185.2	8.2	157.9
2022	160.8	124.3	142.5	6.5	174.3	4.3	335.5	5.6	295.2
2023	195.8	155.7	187.4	6.7	234.6	2.3	431.1	6.5	383.0
Change (2012 to 2023)	94.6	85.9	88.6	0.1	124.2	1.2	219.5	3.3	193.7

3.2 Water Chemistry Sampling Results

Appendix 1 reports the results of the water chemistry sampling for the EEM lakes and control lakes from the sampling conducted in 2023 (with the data from 2012-2023 included for reference), for major water chemistry metrics (ANC, pH, DOC, base cations, and major anions).

Sulphate Levels Relative to B.C. Water Quality Guidelines

The B.C. water quality guideline for sulphate concentration in very soft waters is 128 mg/L. The sulphate concentration of the EEM lakes is shown in Figure 3-4 for all water chemistry samples taken in 2023. All of the samples are less than 3.5% of the guideline. Other than LAK028, all other samples for all other lakes are less than 2% of the guideline.

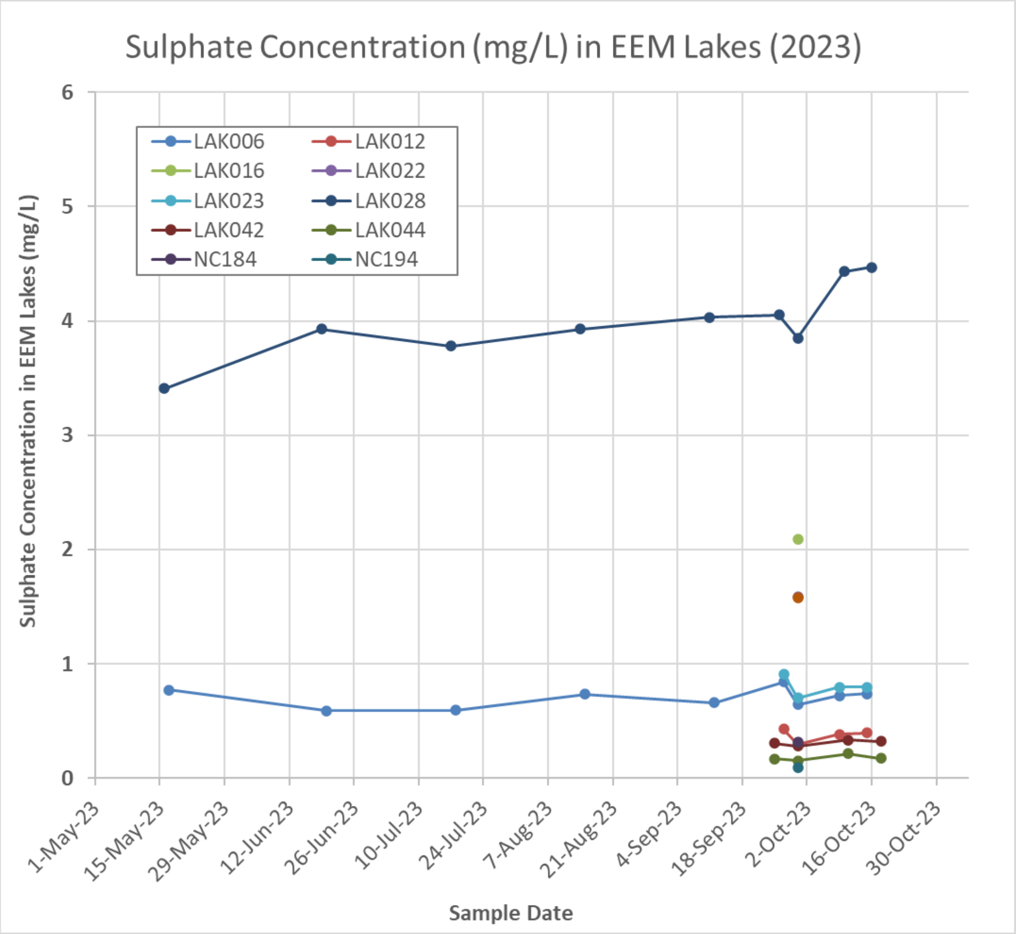


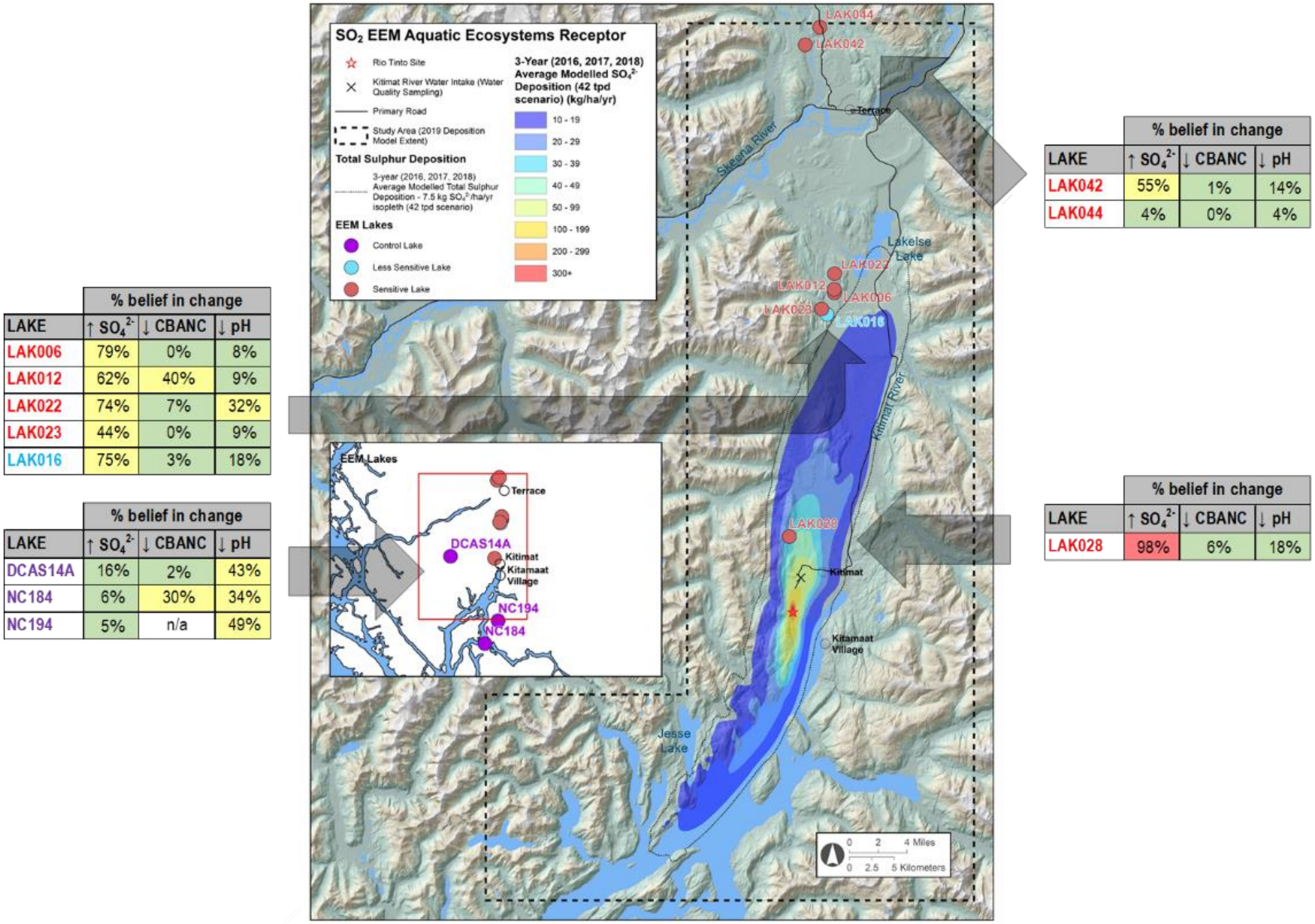
Figure 3-4. Sulphate concentration (mg/L) in EEM lakes during 2023. The applicable B.C. water quality guideline for sulphate concentration (i.e., for very soft waters) is 128 mg/L. All samples in 2023, across all EEM lakes, were <3.5% of the guideline.

3.3 Statistical Analysis of Changes in Water Chemistry

We have summarized the key results of the statistical analyses of changes in lake chemistry across all the lakes in the SO_2 EEM Program in Table 3-7 and Figure 3-5. These results applied Bayesian Method 1, described in Appendix F of the 2019 Comprehensive Review (ESSA et al. 2020b). While six of the sensitive lakes show evidence of increases in SO_4 (the exception being LAK044, located in the north of the study area), the three control lakes do not. None of the lakes show a high percent belief in exceedance of the *change limit* thresholds for CBANC, Gran ANC, BCS or pH. Exceedance of the *level of protection* is to be expected for lakes with a higher percentage of organic anions, which reduces Gran ANC, BCS and pH. In the STAR, all 7 sensitive lakes had pH <6 and >25% organic anions (Table 9.4-8 of the STAR).

Table 3-7. Summary of findings across all lakes monitored in the SO_2 EEM Program. The % belief values are derived from the Bayesian version of Method 1, as described in Aquatic Appendix F of the 2019 Comprehensive Review (ESSA et al. 2020b). Values of % belief < 20% are coloured green, 20-80% yellow, and >80% red. Both the Gran ANC and pH results are based on the integrated ("integ") time series (as per Section 2.1). Note: because NC194 does not have a lake-specific *change limit* threshold for CBANC / Gran ANC, it is not possible to evaluate these indicators).

	Changes in SO_4	**Exceedance of *CHANGE LIMIT***				**Exceedance of *LEVEL OF PROTECTION***			
	(% belief that threshold exceeded; from Bayesian analysis method 1)	(% belief that metric value has decreased by more than the threshold; from Bayesian analysis method 1)				(% belief that metric value is below threshold; from Bayesian analysis method 1)			
Metric	**SO_4**	**CBANC**	**Gran ANC (integ)**	**BCS**	**pH (integ)**	**CBANC**	**Gran ANC (integ)**	**BCS**	**pH (integ)**
Thresholds	Increase > 0	Lake-spec.	Lake-spec.	Δ 13 ueq/L	Δ 0.3 pH units	20 ueq/L	30.7 ueq/L	0 ueq/L	6.0 pH units
LAK006	79%	0%	1%	2%	8%	0%	0%	0%	28%
LAK012	62%	40%	14%	62%	9%	0%	0%	0%	44%
LAK022	74%	7%	18%	8%	32%	0%	65%	0%	75%
LAK023	44%	0%	1%	2%	9%	0%	100%	0%	100%
LAK028	98%	6%	6%	43%	18%	100%	100%	100%	100%
LAK042	55%	1%	5%	12%	14%	0%	100%	21%	100%
LAK044	4%	0%	1%	0%	4%	99%	100%	0%	100%
LAK016	75%	3%	2%	25%	18%	0%	0%	0%	0%
DCAS14A	16%	2%	4%	9%	43%	0%	0%	0%	4%
NC184	6%	30%	26%	31%	34%	0%	48%	0%	82%
NC194	5%	▨	▨	6%	49%	0%	100%	0%	5%



LAKE	% belief in change ↑ SO_4^{2-}	↓ CBANC	↓ pH
LAK006	79%	0%	8%
LAK012	62%	40%	9%
LAK022	74%	7%	32%
LAK023	44%	0%	9%
LAK016	75%	3%	18%

LAKE	% belief in change ↑ SO_4^{2-}	↓ CBANC	↓ pH
DCAS14A	16%	2%	43%
NC184	6%	30%	34%
NC194	5%	n/a	49%

LAKE	% belief in change ↑ SO_4^{2-}	↓ CBANC	↓ pH
LAK042	55%	1%	14%
LAK044	4%	0%	4%

LAKE	% belief in change ↑ SO_4^{2-}	↓ CBANC	↓ pH
LAK028	98%	6%	18%

Figure 3-5. Spatial distribution of percent belief in chemical change. Numbers show % belief in: a) SO_4 increase (no threshold), b) CBANC decrease below lake-specific threshold, and c) pH decrease below 0.3 threshold. The % belief values are derived from the Bayesian version of Method 1, as described in Aquatic Appendix F of the 2019 Comprehensive Review (ESSA et al. 2020b). NC194 does not have an estimated ANC threshold because it did not have appropriate titration data available.

Before-After Control-Impact (BACI) Analyses

The results of the BACI analyses for CBANC, pH, Gran ANC, and BCS are shown in Table 3-8, Table 3-9, Table 3-10, and Table 3-11). None of the seven lakes showed statistically significant differences in Δ CBANC, Δ pH, Δ Gran ANC, or Δ BCS relative to the control lakes.

Table 3-8. BACI analyses of mean CBANC for 7 sensitive and 3 control lakes. "BACI estimate" is a bit counter-intuitive: it is the Δ mean CBANC in the controls (i.e., $\text{CBANC}_{\text{post-KMP}}$ minus $\text{CBANC}_{\text{pre-KMP}}$), averaged over the 3 control lakes, minus the Δ mean CBANC in the sensitive lake. If BACI value is <0, then the Δ CBANC was lower in the controls than in the sensitive lake (and, equivalently, the Δ CBANC was greater (more positive) in the sensitive lake than in the controls), evidence against acidification (if statistically significant). If BACI value is >0, then Δ CBANC in the controls was greater than that in the sensitive lake (and, equivalently, the Δ CBANC was lower (less positive) in the sensitive lake than in the controls), evidence for acidification (if statistically significant). SE is the standard error of the BACI estimate. The p-value is the statistical significance of the test.

Site	BACI estimate	SE	p-value	Interpretation of BACI estimate	Change in interpretation from 2022
LAK006	-9.72	14.14	0.51	Change in CBANC was **more positive** in LAK006 than in the control lakes *(but not statistically significant)*	None
LAK012	21.78	16.54	0.22	Change in CBANC was **more negative** in LAK012 than in the control lakes *(but not statistically significant)*	None
LAK022	2.00	12.27	0.88	Change in CBANC was **similar** in LAK022 to changes in the control lakes *(but not statistically significant)*	None
LAK023	0.42	13.70	0.98	Change in CBANC was **similar** in LAK023 than in the control lakes *(but not statistically significant)*	From more positive to similar
LAK028	9.94	13.69	0.49	Change in CBANC was **more negative** in LAK028 to changes in the control lakes *(but not statistically significant)*	None
LAK042	-1.04	14.79	0.95	Change in CBANC was **similar** in LAK042 than in the control lakes *(but not statistically significant)*	From more positive to similar
LAK044	0.39	13.91	0.98	Change in CBANC was **similar** in LAK044 to changes in the control lakes *(but not statistically significant)*	From more positive to similar

Table 3-9. BACI analyses of mean pH (integrated) for 7 sensitive and 3 control lakes. "BACI estimate" is a bit counter-intuitive: it is the Δ mean pH in the controls (i.e., $pH_{post\text{-}KMP}$ minus $pH_{pre\text{-}KMP}$), averaged over the 3 control lakes, minus the Δ mean pH in the sensitive lake. If BACI value is <0, then the Δ pH was lower in the controls than in the sensitive lake (and, equivalently, the Δ pH was greater (more positive) in the sensitive lake than in the controls), evidence against acidification (if statistically significant). If BACI value is >0, then Δ pH in the controls was greater than that in the sensitive lake (and, equivalently, the Δ pH was lower (less positive) in the sensitive lake than in the controls), evidence for acidification (if statistically significant). SE is the standard error of the BACI estimate. The p-value is the statistical significance of the test.

Site	BACI estimate	SE	p-value	Interpretation of BACI estimate	Change in interpretation from 2022
LAK006	-0.39	0.27	0.19	Change in pH was **more positive** in LAK006 than in the control lakes *(but not statistically significant)*	None
LAK012	-0.51	0.26	0.08	Change in pH was **more positive** in LAK012 than in the control lakes *(but not statistically significant)*	No longer statistically significant
LAK022	-0.10	0.23	0.67	Change in pH was **more positive** in LAK0022 than in the control lakes *(but not statistically significant)*	None
LAK023	-0.32	0.27	0.28	Change in pH was **more positive** in LAK023 than in the control lakes *(but not statistically significant)*	None
LAK028	-0.19	0.25	0.47	Change in pH was **more positive** in LAK028 than in the control lakes *(but not statistically significant)*	None
LAK042	-0.58	0.25	0.05	Change in pH was **more positive** in LAK042 than in the control lakes *(but not statistically significant)*	None
LAK044	-0.32	0.32	0.35	Change in pH was **more positive** in LAK044 than in the control lakes *(but not statistically significant)*	None

Table 3-10. BACI analyses of mean Gran ANC (integrated) for 7 sensitive and 3 control lakes. "BACI estimate" is a bit counter-intuitive: it is the Δ mean Gran ANC in the controls (i.e., Gran ANC $_{post\text{-}KMP}$ minus Gran ANC $_{pre\text{-}KMP}$), averaged over the 3 control lakes, minus the Δ mean Gran ANC in the sensitive lake. If BACI value is <0, then the Δ Gran ANC was lower in the controls than in the sensitive lake (and, equivalently, the Δ Gran ANC was greater (more positive) in the sensitive lake than in the controls), evidence against acidification (if statistically significant). If BACI value is >0, then Δ Gran ANC in the controls was greater than that in the sensitive lake (and, equivalently, the Δ Gran ANC was lower (less positive) in the sensitive lake than in the controls), evidence for acidification (if statistically significant). SE is the standard error of the BACI estimate. The p-value is the statistical significance of the test.

Site	BACI estimate	SE	p-value	Interpretation of BACI estimate	Change in interpretation from 2022
LAK006	-5.55	14.34	0.71	Change in Gran ANC was **more positive** in LAK006 than in the control lakes *(but not statistically significant)*	None
LAK012	2.94	15.98	0.86	Change in Gran ANC was **more negative** in LAK012 than in the control lakes *(but not statistically significant)*	From more positive to more negative
LAK022	3.95	13.56	0.78	Change in Gran ANC was **more negative** in LAK0022 than in the control lakes *(but not statistically significant)*	From similar to more negative
LAK023	2.15	14.22	0.88	Change in Gran ANC was **similar** in LAK023 than in the control lakes *(but not statistically significant)*	From more positive to similar
LAK028	-1.51	14.13	0.92	Change in Gran ANC was **similar** in LAK028 than in the control lakes *(but not statistically significant)*	From more positive to similar
LAK042	-20.80	13.89	0.17	Change in Gran ANC was **more positive** in LAK042 than in the control lakes *(but not statistically significant)*	None
LAK044	0.73	14.29	0.96	Change in Gran ANC was **similar** in LAK044 than in the control lakes *(but not statistically significant)*	From more positive to similar

Table 3-11. BACI analyses of mean BCS (base cation surplus) for 7 sensitive and 3 control lakes. "BACI estimate" is a bit counter-intuitive: it is the Δ mean BCS in the controls (i.e., $BCS_{post\text{-}KMP}$ minus $BCS_{pre\text{-}KMP}$), averaged over the 3 control lakes, minus the Δ mean BCS in the sensitive lake. If BACI value is <0, then the Δ BCS was lower in the controls than in the sensitive lake (and, equivalently, the Δ BCS was greater (more positive) in the sensitive lake than in the controls), evidence against acidification (if statistically significant). If BACI value is >0, then Δ BCS in the controls was greater than that in the sensitive lake (and, equivalently, the Δ BCS was lower (less positive) in the sensitive lake than in the controls), evidence for acidification (if statistically significant). SE is the standard error of the BACI estimate. The p-value is the statistical significance of the test.

Site	BACI estimate	SE	p-value	Interpretation of BACI estimate	Change in interpretation from 2022
LAK006	-4.06	18.96	0.84	Change in BCS was **more positive** in LAK006 than in the control lakes *(but not statistically significant)*	None
LAK012	28.29	20.17	0.20	Change in BCS was **more negative** in LAK012 than in the control lakes *(but not statistically significant)*	None
LAK022	6.22	18.02	0.74	Change in BCS was **more negative** in LAK0022 than in the control lakes *(but not statistically significant)*	From similar to more negative
LAK023	8.21	19.21	0.68	Change in BCS was **similar** in LAK023 than in the control lakes *(but not statistically significant)*	From similar to more negative
LAK028	21.47	17.21	0.25	Change in BCS was **more negative** in LAK028 than in the control lakes *(but not statistically significant)*	None
LAK042	-7.88	18.22	0.68	Change in BCS was **more positive** in LAK042 than in the control lakes *(but not statistically significant)*	None
LAK044	3.62	19.59	0.86	Change in BCS was **more negative** in LAK044 than in the control lakes *(but not statistically significant)*	From more positive to more negative

Table 3-12. BACI analysis of Δ CBANC, Δ pH (integrated), Δ Gran ANC, and Δ BCS, respectively, with all lakes combined. BACI estimate is the Δ mean in the 3 control lakes (i.e., post-KMP averaging period minus pre-KMP baseline, averaged over the 3 control lakes), minus the Δ mean in the 7 sensitive lakes (i.e., post-KMP minus pre-KMP, averaged over the 7 sensitive lakes). SE is the standard error of the BACI estimate. The p-value is the statistical significance of the test.

Metric	BACI estimate	SE	p-value	Interpretation of BACI estimate	Change in interpretation from 2022
CBANC	-1.74	12.02	0.89	Change in CBANC was **more positive** in the sensitive lakes than in the control lakes *(but not statistically significant)*	None
pH (integ)	-0.28	0.13	0.05	Change in pH was **more positive** in the sensitive lakes than in the control lakes *(but not statistically significant)*	No longer statistically significant
Gran ANC (integ)	-7.78	10.97	0.48	Change in Gran ANC was **more positive** in the sensitive lakes than in the control lakes *(but not statistically significant)*	None
BCS	5.22	12.97	0.69	Change in BCS was **more negative** in the sensitive lakes than in the control lakes *(but not statistically significant)*	None

<u>For the BACI analyses of changes in CBANC:</u>

- None of the lakes showed a statistically significant effect – i.e., before-after differences that were significantly different than the before-after changes in the control lake group (all lakes have p-values >>0.01).
- Only two of the seven sensitive lakes showed a Δ CBANC that was more negative than the Δ CBANC observed in the group of control lakes (positive effect in the BACI analysis), but none of these differences were statistically significant at p<0.01.
- The other five of seven sensitive lakes showed Δ CBANC that was either relatively similar (four lakes) to the Δ CBANC observed in the group of control lakes or more positive (one lake), but none of these differences were statistically significant at p<0.01.
- Three lakes changed from "more positive" in 2022 to "similar in 2023.
- When analyzed as a combined group, the sensitive lakes showed ΔCBANC that was still more positive than the Δ CBANC observed in the group of control lakes, as was the case in 2022; however, the results were not statistically significant in either year.
- CONCLUSION: **No support for an effect** across any of the lakes individually or an effect for all lakes combined.

<u>For the BACI analyses of changes in pH:</u>

- All seven sensitive lakes showed Δ pH that was more positive than the Δ pH observed in the group of control lakes (negative effect in the BACI analysis) but none of these differences were statistically significant a p<0.01.
- LAK012 was the only lake that had a significant effect in 2022 (more positive) no longer shows a significant effect (p-value = 0.08).
- LAK042, which showed a significant positive effect in 2021 and only marginally exceeded the criterion for significance in 2022 (p-value = 0.02), had a p-value of 0.05 this year.

- When analyzed as a combined group, the sensitive lakes showed a change that was more positive than in the control lakes; however, the effect is no longer statistically significant (as it was last year).
- CONCLUSION: **No support for an effect** across any of the lakes individually or an effect for all lakes combined.

<u>For the BACI analyses of changes in Gran ANC:</u>

- None of the lakes showed a statistically significant effect – i.e., before-after differences that were significantly different than the before-after changes in the control lake group (all lakes have p-values >0.01).
- Only two of the seven sensitive lakes showed a Δ Gran ANC that was more negative than the Δ Gran ANC observed in the group of control lakes (positive effect in the BACI analysis), but none of these differences were statistically significant at $p<0.01$.
- The other five of seven sensitive lakes showed Δ Gran ANC that was either relatively similar (three lakes) to the Δ Gran ANC observed in the group of control lakes the control lakes or more positive (two lakes), but none of these differences were statistically significant at $p<0.01$.
- The five lakes changed from 2022 were all toward the negative direction - three lakes changed from “more positive” in 2022 to “similar” in 2023, one changed from “more positive” to “negative”, and one changed from “similar” to “more negative”.
- When analyzed as a combined group, the sensitive lakes showed a change that was more positive than in the control lakes; however, the results were not statistically significant.
- CONCLUSION: **No support for an effect** across any of the lakes individually or an effect for all lakes combined.

<u>For the BACI analyses of changes in BCS:</u>

- None of the lakes showed a statistically significant effect – i.e., before-after differences that were significantly different than the before-after changes in the control lake group (all lakes have p-values >0.01)
- Four of the seven sensitive lakes showed a ΔBCS that was more negative than the ΔBCS observed in the group of control lakes (positive effect in the BACI analysis), but none of these differences were statistically significant at $p<0.01$
- Two of the seven sensitive showed a ΔBCS that was more positive than the ΔBCS observed in the group of control lakes and one lake showed a similar ΔBCS, but none of these differences were statistically significant at $p<0.01$
- When analyzed as a combined group, the sensitive lakes showed a change that was more negative than in the control lakes; however, the results were not statistically significant.
- CONCLUSION: **No support for an effect** across any of the lakes individually or an effect for all lakes combined.

3.4 Episodic Acidification

We reviewed the data from the continuous pH monitors installed in LAK006 and LAK028 to identify any acidic episodes (Figure 3-6, Figure 3-7). The lake-level monitoring data are shown in Figure 3-8.

LAK006 shows only one period with a notable decline – late October – albeit the magnitude is quite small (i.e., declines of ~0.2 pH units over a period of one week). This period aligns with increases in lake levels as the result of precipitation events in mid-October. This pH decline is consistent with the pattern observed in previous years of pH decreasing during the end of the monitoring season as precipitation events increase in frequency and magnitude (as also demonstrated in LAK028).

LAK028 showed only one pronounced drop (~0.5 pH units) in mid-October, corresponding with increased precipitation. A moderate drop (<0.2 pH units) can be seen in mid-August but appears to follow only a very minor change in lake levels. The lake levels show anther pronounced increase in mid-September (corresponding with only modest precipitation; see Haul Road Station in Figure 2-2), but that event does not appear to have any effect on pH.

The observed declines are mostly quite small, with one larger decline in mid-October that is entirely consistent with the pattern observed every year – i.e., declines in pH at the end of the monitoring season associated with increasing fall storm events.

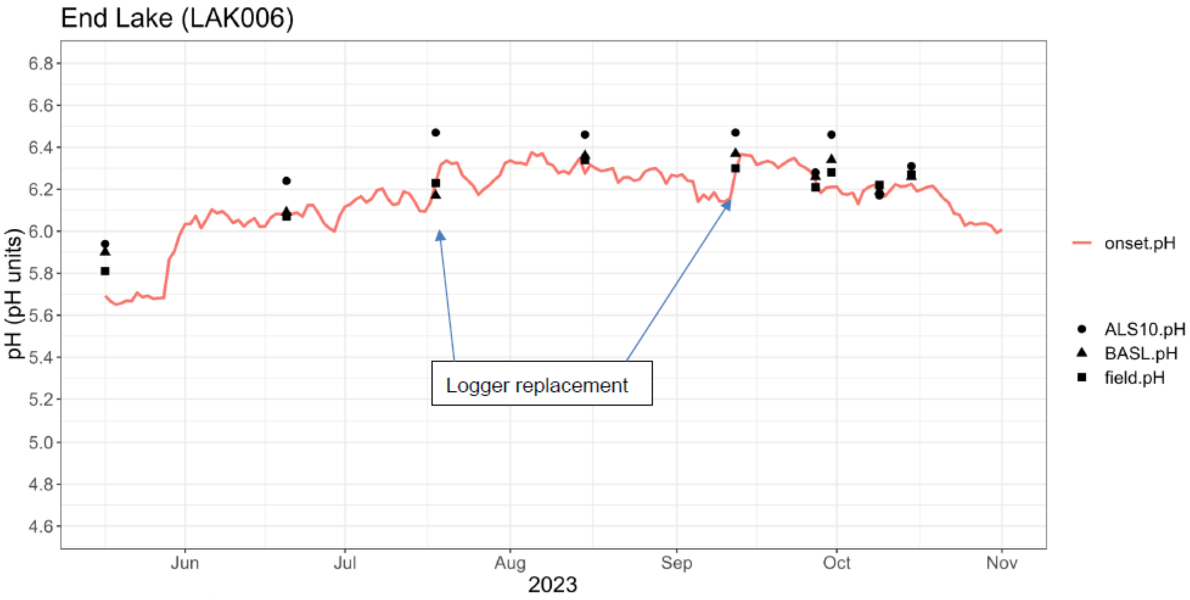


Figure 3-6. LAK006 pH measurements during the 2023 monitoring season, including continuous monitoring as well as field and laboratory measurements. See Limnotek 2024 for details on instrument failure referenced in the figure. Source: Limnotek 2024

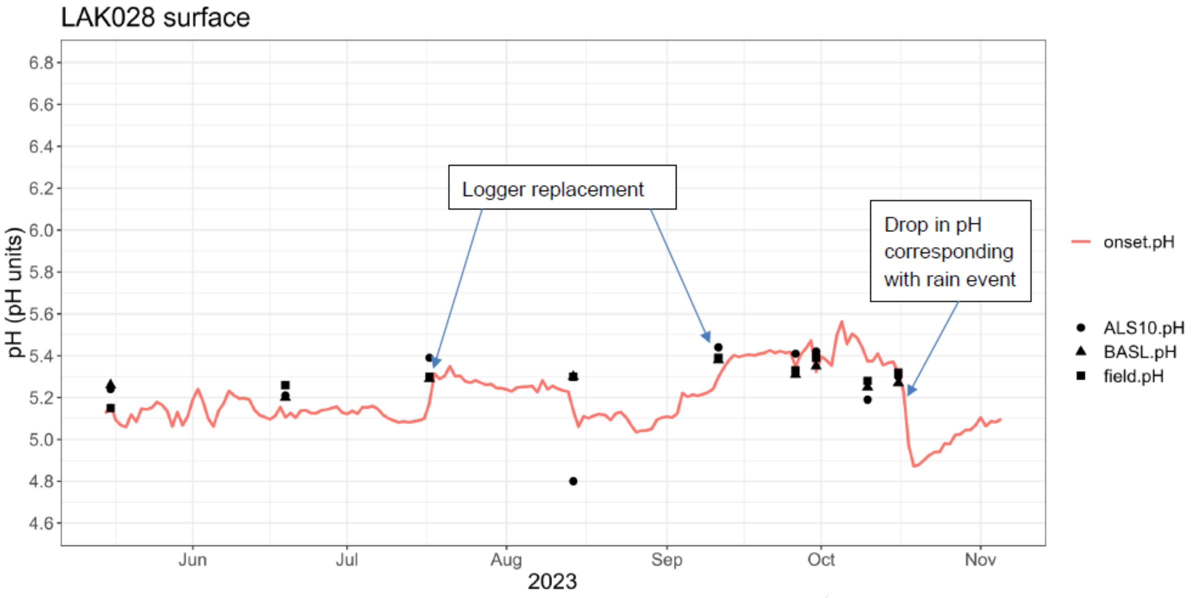


Figure 3-7. LAK028 pH measurements during the 2023 monitoring season, including continuous monitoring as well as field and laboratory measurements. Source: Limnotek 2024

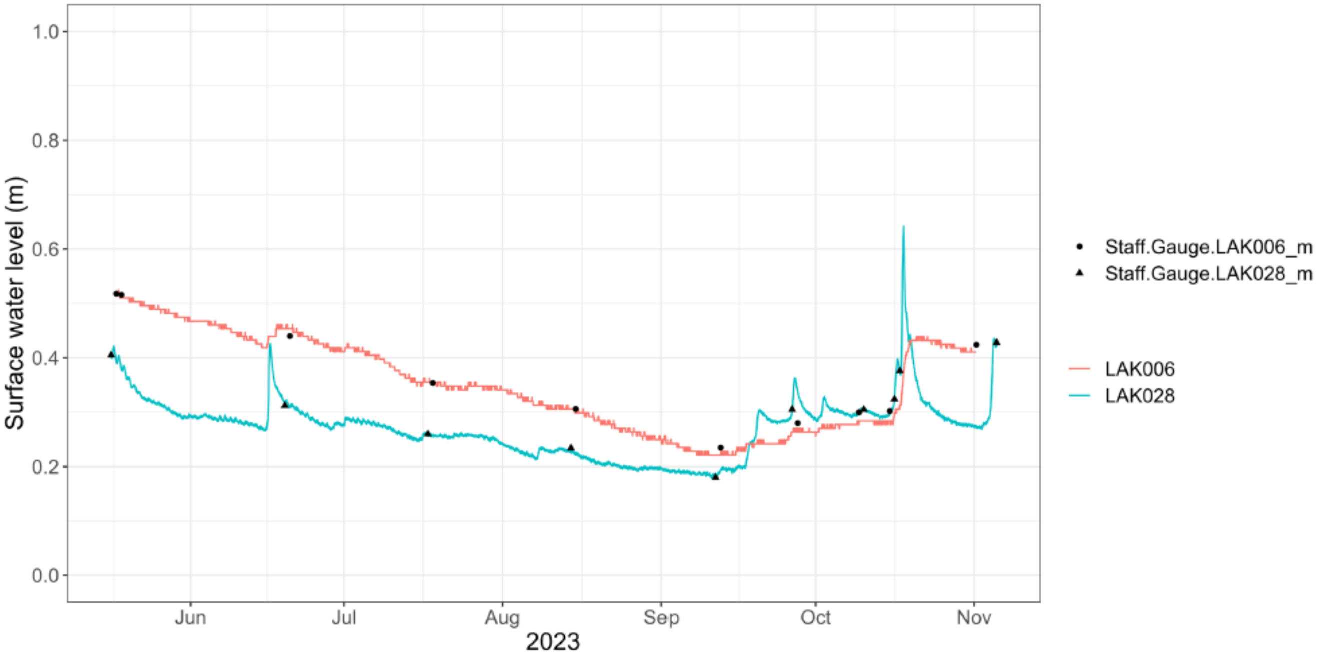


Figure 3-8. Water level during the 2023 monitoring season for LAK006 and LAK028. As per Limnotek (2024): ***Note that water level is relative to a benchmark at each lake, not to a common benchmark.*** **Source: Limnotek 2024**

4 Discussion

4.1 Separating Natural and Anthropogenic Factors: the Environmental Context

The SO_2 EEM Program has moved away from reporting and analyzing the annual changes between individual years (due to challenges in interpretability associated with the high degree of variability). However, it is still useful to look at the year-to-year changes to assess whether there are any widespread patterns of significance that may influence our analyses and interpretation of long-term changes in water chemistry.

As described in Section 2.4, the environmental conditions in August through mid-October were exceptionally dry, which would tend to result in increases CBANC, pH, Gran ANC, BCS, SO_4, and base cations through a concentration effect. However, the observed changes from the previous year might be lessened when the previous year was also a dry year and therefore the relative difference in hydrologic conditions is smaller. As described in Section 3.1, emissions (a proxy for deposition) in 2023 were significantly greater than the previous year (which were exceptionally low following the labour dispute). If hydrologic conditions in 2023 were unchanged from 2022, a return to higher emissions and presumably higher deposition (confirmed by deposition monitoring in Atmospheric component) would be expected to cause increased SO_4 and BC, and decreased pH and ANC. However, changing hydrologic conditions and changing deposition act concurrently to influence water chemistry. Table 4-1 compares the expected effects of drier conditions and increased emissions on major water chemistry parameters to the observed changes in the sensitive and less sensitive lakes, which shows that the changes do not strongly align with either factor. The control lakes (not shown) match the expectation of drier conditions – increased CBANC, Gran ANC, pH, and base cations – and should not be influenced by emissions at all.

Table 4-1. Observed changes in sensitive and less sensitive lakes compared to expected effects of drier conditions and increased emissions.

Parameter	Effect of drier conditions	Effect of increased emissions	Observed changes in sensitive & less sensitive lakes	Conclusion
SO4	Increase	Increase	7 increased 1 decreased	Both effects are in same direction; lakes align
CBANC	Increase	Decrease	4 decreased 3 increased 1 no change	Mixed results
pH	Increase	Decrease	8 "no change" (all within <0.08)	Mixed results (or limited effect)
Gran ANC	Increase	Decrease	4 decreased 4 no change	Mixed, but potentially stronger effect of emissions
BCS	Increase	Decrease	3 decreased 3 increased 2 no change	Mixed results
Base Cations	Increase	Increase	3 decreased 3 increased 2 no change	Both effects are in same direction; but less than half of lakes align

The graphs in Appendix 2 enable comparisons of the 2023 monitoring data to 2022. These graphs show (as also described in Section 3.1) that the patterns of annual change had a high level of consistency across the entire region in some of the primary metrics but not others. All of the sensitive and less sensitive lakes except one show a consistent pattern in SO_4 – a substantial drop in 2022 with a partial rebound in 2023, which is completely aligned the changes in emissions. The one exception is LAK028, which shows relatively little change in 2021 and then a decrease in 2022.

For CBANC, the changes in 2023 in the sensitive lakes are mixed – increases in 3 lakes, decrease in 3 lakes, and relatively little change in 1 lake. The lack of any dominant pattern suggests the combined influence of year-to-year changes in both hydrology and deposition together with spatial variation in how both factors were expressed across the region. CBANC increased in the three control lakes in both of the past two years, likely representing a "recovery" from the substantial drop observed in 2021. This pattern in the control lakes is consistent with the expected influence of dry conditions (and the lack of influence from changes in smelter emissions).

The changes in base cations follow a similar pattern to CBANC – mixed changes for the sensitive and less sensitive lakes, and consistent increases over two years in the control lakes. However, the mixed changes for the sensitive lakes are somewhat surprising given that both of the primary drivers should tend to increase base cations – dry conditions contributing to increasing concentrations of base cations through a concentration effect and increased deposition increasing the inputs of base cations into lakes both through increases in direct deposition of base cations in the watershed (likely minor) and by increasing the amount of hydrogen-driven cation-exchange in the watershed (likely more significant).

For pH, all lakes showed a big increase in 2022, broadly comparable to and occasionally greater than the substantial declines from 2019-2020 to 2021. For the sensitive and less sensitive lakes, the 2023 pH values are essentially unchanged from 2022 – i.e., a mix of increases and decreases but all within ±0.08 pH units. This could mean that the potentially opposing drivers of dry conditions and increased emissions either balanced each other out or both had limited effect on pH for the lakes within the plume. By contrast, the control lakes well outside of the influence of emissions all showed increases (0.1, 0.5, and 0.6 pH units), which is consistent with the expected effects of drier hydrologic conditions.

DOC declined in 10 of 11 lakes in 2023. For 8 of those lakes (4 sensitive, 1 less sensitive, and 3 controls), this is part of a two year decline in DOC associated with dry conditions. It is likely that in dry years lakes are less able to access shoreline vegetation (e.g., *Sphagnum* moss) that brings in organic acids. By contrast, we observed in 2020 (a relatively wet year) concurrent increases in DOC and decreases in pH in LAK042, associated with high lake levels that flooded the shoreline.

Although it is essentially impossible to completely disentangle the relative contributions of these two major drivers in 2023 – dry hydrologic conditions and increased emissions – there are some broad inferences that can potentially be made based on the observed patterns:

1. **SO_4 changes** in the sensitive lakes (other than LAK028) align with changing emissions but SO_4 changes in control lakes do not (as expected, since the control lakes were deliberately chosen to be well outside of the smelter's plume).
2. **CBANC changes** in sensitive lakes are mixed and appear to reflect varying degrees of contribution from the two major drivers.
3. **Gran ANC changes** in sensitive and less sensitive lakes may generally represent a balance of opposing influences with some lakes showing more influence from changes in emissions.
4. **pH changes** in sensitive lakes reflect a varying mixture of the two major drivers, whereas pH changes in the control lakes align with expectations under drier conditions (and should not be influenced by emissions, by design).

Overall, the observed patterns do not clearly indicate greater influence of emissions or hydrology.

4.2 Empirical Changes in Lake Chemistry with respect to the Aquatic Key Performance Indicator

This section only addresses the CBANC KPI and the pH informative indicator (of specific interest as the prior KPI), with respect to empirical changes. The statistical analyses represent the primary assessment of the KPI and informative indicators.

The mean values of CBANC indicate that there have been no exceedances of the KPI.

For the CBANC KPI, only 2 of the 7 sensitive lakes (LAK028 and LAK044) have values for the post-KMP averaging period below the *level of protection* threshold. Both of those lakes were already below that threshold in 2012 (and the alternate, transition period baseline) and neither of those lakes have exceeded the *change limit* threshold (LAK028 shows a decrease of -0.7 μeq/L; LAK044 shows an increase of +8.8 μeq/L). None of the 7 sensitive lakes exceeded the *change limit* threshold and only two lakes (LAK012 and LAK028) show long-term decreases in CBANC of any magnitude. In the sensitivity analyses with the alternate, transition period baseline (2012-2014), LAK012 is the only lake with an estimated long-term, albeit minor, decrease in CBANC (-2.0 μeq/L). The empirical data therefore indicate that none of the lakes exceeded the KPI.

For the pH informative indicator, 5 of the 7 sensitive lakes (LAK022, LAK023, LAK028, LAK042, and LAK044) have values for the post-KMP averaging period below the *level of protection* threshold (a pH of 6.0). As described in the STAR (section 9.4.1.2.4), all 7 sensitive lakes were already below pH 6.0 in 2012, reflecting primarily the influence of organic acids and in some cases the effects of historical smelter emissions (particularly in LAK028). Four of the lakes have been at or below pH 6.0 throughout the entire period of record. None of the sensitive lakes show any decrease in pH relative to 2012 and therefore none have exceeded the *change limit* threshold. In the sensitivity analyses with the alternate, transition period baseline (2012-2014), LAK022 shows a decrease of ~0.2 pH units, LAK028 shows a decrease of ~0.1 pH units, and the other 5 sensitive lakes show no change. The empirical data therefore indicate that none of the lakes have exceeded the pH informative indicator.

The following section (Section 4.3) applies the statistical analyses to the same data to assess the percent belief that CBANC KPI and the pH, Gran ANC and BCS informative indicators could have been exceeded.

LAK027 – Comparison with STAR Results

As discussed earlier, LAK027 was resampled again in 2023 because of anomalous effects in 2021 (very wet year) and 2022 (very dry year), thus confounding the original rationale for resampling LAK027 in 2021. We therefore focus on examining the changes between the values measured in the STAR in 2012 and those observed in 2023.

All of the lake chemistry metrics in Table 3-6 show increases, often substantial, from 2012 to 2023. CBANC, Gran ANC, BCS, SO_4, DOC, base cations, and Cl all roughly doubled from 2012 to 2023, and pH increased by 0.1 pH units.

However, as discussed earlier in this report, 2023 was again subject to anomalous conditions (i.e., exceptionally dry conditions and substantial increase in emissions from a greatly reduced level during 2022). Similar to last year's conclusions, it is again impossible to disentangle the potential long-term change in lake chemistry from the STAR from the short-term, regional effects experienced by all of the lakes. To obtain a more reliable assessment of the chemical status of LAK027, relative to the status observed in the STAR, it would be prudent to again resample this lake in 2024.

4.3 Statistical Analysis of Changes in Lake Chemistry

We evaluated the KPI and the informative indicators using the two-threshold structure (Table 4-2). None of the 11 EEM lakes have a high % belief in exceedance of either the KPI or any of the informative indicators. None of the 11 EEM lakes have even a moderate % belief in exceedance of the KPI – all lakes show a low % belief in exceedance of the CBANC KPI. However, two sensitive EEM lakes and one control lakes show moderate % belief of one or two of the informative indicators:

- LAK022 shows moderate % belief in exceedance of pH

- LAK028 shows moderate % belief in exceedance of BCS
- NC184 shows moderate % belief in exceedance of Gran ANC and pH

The results of the Bayesian statistical analyses are very similar to our previous report. The only changes in classification (across all lakes and metrics) from last year are the changes from moderate to low for Gran ANC in LAK022, BCS and pH in LAK042, and pH in NC194. All other results are the same as last year in terms of final classification. Overall, the list of lakes with moderate % belief in exceedance of one or more informative indicators decreased from 3 to 2 sensitive lakes and 2 to 1 control lakes.

Table 4-3 shows the results from 2023 compared to the results reported in the previous three annual reports and the 2019 comprehensive review, specifically for the evaluation of the *change limit*.

All 11 lakes have similar results to the last two years for CBANC, Gran ANC, and pH (i.e., same classification and similar percent belief values), except for 3 cases where the classification changed from moderate to low. The percent belief for these metrics decreased or remained the same for all but two cases. LAK012 increased from 23% to 40% for CBANC and LAK023 showed a negligible increase of 2% for pH. For SO_4, there was a more even mix of decreases and increases in the results over the past couple years, and the increases were generally larger than for the other metrics. LAK022, LAK016, DCAS14A, and NC194 increased by ≤5%, LAK023 and LAK028 increased by 7% and 10%, respectively, and the rest of the lakes decreased in percent belief.

This is now the fourth year that the Bayesian analyses were performed on CBANC. Despite the widespread changes in numerous water chemistry metrics observed in both 2021 and 2022, the CBANC results remain remarkably similar to the 2020 results for almost all of the lakes, suggesting that the CBANC metric may be robust to anomalous conditions.

This is the sixth year that the Bayesian analyses were performed for Gran ANC and pH. That length of time provides an opportunity to see how the results have changed since these analyses were first implemented in the 2019 Comprehensive Review. The results have remained very stable over these six years. For Gran ANC, there are only two of eleven lakes that have showed any change in category over the six years of repeating the analyses: LAK022 and NC194 changed from low to moderate, albeit still at the low end of the moderate range (~30% belief), and LAK022 has returned to low again in 2023. For pH, 2 sensitive lakes, 1 less sensitive lake, and all 3 control lakes changed categories – from low to moderate in all cases. In all cases, the shift occurred with the 2021 results (driven by high precipitation in September 2021) and the 2022 results remained quite similar[4]. LAK042 and LAK016, which were only in the low end of the moderate category, have returned to low in 2023. LAK022, DCAS14A, NC184, and NC194 are in the lower-mid-range of the moderate category for pH. Decreases in pH in the control lakes must be driven by factors other than the smelter because they are well outside the deposition plume, and all three control lakes have a low percent belief in any sulphate increase (Table 4-3).

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[4] Note: 4 out of these 5 lakes were not sampled in 2020, meaning the 2020 results were based only on 2018-2019, and therefore it is not actually possible to determine whether the shifts that show up in the 2021 results reflect changes in lake chemistry in 2020, 2021 or both

Table 4-2. Evaluation of the KPI and informative indicators based on the results for both the *change limit* and the *level of protection* thresholds. The first three sets of columns are the same as Table 3-7. The % belief values are derived from the Bayesian version of Method 1, as described in Aquatic Appendix F of the 2019 Comprehensive Review (ESSA et al. 2020b). Values of % belief < 20% are coloured green, 20-80% yellow, and >80% red. Both the Gran ANC and pH results are based on the integrated ("integ") time series (as per Section 2.1). Note: because NC194 does not have a lake-specific *change limit* threshold for CBANC / Gran ANC, it is not possible to evaluate these indicators).

	Changes in SO_4	Exceedance of *CHANGE LIMIT*				Exceedance of *LEVEL OF PROTECTION*				KPI and Informative Indicator Evaluation			
	(% belief that threshold exceeded; from Bayesian analysis method 1)	(% belief that metric value has decreased by more than the threshold; from Bayesian analysis method 1)				(% belief that metric value is below threshold; from Bayesian analysis method 1)				(Classification of % belief that both the *change limit* and *level of protection* thresholds are exceeded)			
Metric	**SO_4**	**CBANC**	**Gran ANC (integ)**	**BCS**	**pH (integ)**	**CBANC**	**Gran ANC (integ)**	**BCS**	**pH (integ)**	**CBANC**	**Gran ANC (integ)**	**BCS**	**pH (integ)**
Thresholds	Increase > 0	Lake-spec.	Lake-spec.	Δ 13 ueq/L	Δ 0.3 pH units	20 ueq/L	30.7 ueq/L	0 ueq/L	6.0 pH units	KPI	Inform. Indic.	Inform. Indic.	Inform. Indic.
LAK006	79%	0%	1%	2%	8%	0%	0%	0%	28%	LOW	LOW	LOW	LOW
LAK012	62%	40%	14%	62%	9%	0%	0%	0%	44%	LOW	LOW	LOW	LOW
LAK022	74%	7%	18%	8%	32%	0%	65%	0%	75%	LOW	LOW	LOW	MOD
LAK023	44%	0%	1%	2%	9%	0%	100%	0%	100%	LOW	LOW	LOW	LOW
LAK028	98%	6%	6%	43%	18%	100%	100%	100%	100%	LOW	LOW	MOD	LOW
LAK042	55%	1%	5%	12%	14%	0%	100%	21%	100%	LOW	LOW	LOW	LOW
LAK044	4%	0%	1%	0%	4%	99%	100%	0%	100%	LOW	LOW	LOW	LOW
LAK016	75%	3%	2%	25%	18%	0%	0%	0%	0%	LOW	LOW	LOW	LOW
DCAS14A	16%	2%	4%	9%	43%	0%	0%	0%	4%	LOW	LOW	LOW	LOW
NC184	6%	30%	26%	31%	34%	0%	48%	0%	82%	LOW	MOD	LOW	MOD
NC194	5%	▨	▨	6%	49%	0%	100%	0%	5%	noRel	noRel	LOW	LOW

Table 4-3. Comparison of the results of the updated statistical analyses of the changes relative to the *change limit* to the results in the previous two reporting periods (i.e., 2019 Annual Report and the 2019 comprehensive review (CR)). The 2023 results are the same as Table 3-7. The % belief values are derived from the Bayesian version of Method 1, as described in Aquatic Appendix F of the 2019 Comprehensive Review (ESSA et al. 2020b). Values of % belief < 20% are coloured green, 20-80% yellow, and >80% red.

LAKE	**Changes in CBANC** (% belief that CBANC *change limit* threshold exceeded)				**Changes in SO_4** (% belief in SO_4 increase > 0 µeq/L)						**Changes in Gran ANC** (% belief that Gran ANC *change limit* threshold exceeded)						**Changes in pH** (% belief that pH *change limit* threshold exceeded)					
Results from:	**2020**	**2021**	**2022**	**2023**	**CR**	**2019[1]**	**2020**	**2021**	**2022**	**2023**	**CR**	**2019[1]**	**2020**	**2021**	**2022**	**2023**	**CR**	**2019[1]**	**2020**	**2021**	**2022**	**2023**
Sensitive Lakes																						
LAK006	2%	1%	0%	0%	83%	85%	98%	97%	81%	79%	0%	0%	5%	2%	0%	1%	1%	0%	1%	5%	8%	8%
LAK012	40%	35%	23%	40%	91%	95%	99%	86%	70%	62%	1%	0%	19%	18%	14%	14%	1%	0%	1%	8%	10%	9%
LAK022 [2]	2%	11%	13%	7%	88%	89%	89%	87%	69%	74%	0%	0%	10%	31%	30%	18%	0%	0%	0%	39%	43%	32%
LAK023	2%	3%	6%	0%	5%	2%	0%	42%	37%	44%	0%	0%	3%	2%	2%	1%	1%	0%	3%	4%	7%	9%
LAK028	13%	15%	13%	6%	96%	97%	94%	92%	88%	98%	2%	1%	0%	4%	8%	6%	18%	6%	9%	18%	18%	18%
LAK042	9%	6%	6%	1%	36%	44%	81%	76%	60%	55%	0%	0%	2%	4%	6%	5%	2%	0%	13%	23%	21%	14%
LAK044	0%	1%	0%	0%	1%	0%	4%	6%	13%	4%	0%	0%	3%	3%	4%	1%	0%	0%	0%	1%	4%	4%
Less Sensitive Lakes																						
LAK016 [2]	7%	7%	2%	3%	97%	81%	81%	99%	70%	75%	0%	0%	1%	4%	7%	2%	1%	0%	6%	28%	32%	18%
Control Lakes																						
DCAS14A [2]	1%	10%	5%	2%	68%	75%	99%	56%	14%	16%	0%	0%	1%	11%	7%	4%	6%	0%	12%	50%	52%	43%
NC184 [2]	10%	43%	46%	30%	58%	69%	86%	50%	15%	6%	5%	4%	17%	28%	30%	26%	28%	14%	19%	48%	48%	34%
NC194 [2]	n/a	n/a	n/a		1%	1%	2%	12%	4%	5%	n/a	n/a	n/a	n/a	n/a	n/a	12%	4%	17%	62%	71%	49%

[1] The 2019 Annual Report applied a 4-year post-KMP averaging period (i.e., 2016-2019; adding the new year of observations to the post-KMP averaging period used in the CR), whereas the subsequent Annual Reports apply a 3-year post-KMP averaging period.

[2] For lakes not sampled in 2020, the post-KMP averaging periods applied in 2020 to 2022 are based on only two years of data.

4.4 Application of the Evidentiary Framework

We applied the evidentiary framework, as described in Section 2.6, using the updated results of the statistical analyses. The results are shown in Figure 4-1 and the underlying values are compiled in Table 4-4. A lake may appear in different parts of the evidentiary framework depending on whether we use CBANC or pH as criteria (CBANC is the KPI and pH is an informative indicator). To be precautionary, we consider the lake's appropriate assignment to be the furthest position into the evidentiary framework. Results show that: a) 1 sensitive lake (LAK044) and all 3 control lakes[5] land within the first box, "smelter not causally linked to changes in lake chemistry"; b) 1 sensitive lake (LAK012) and 1 less sensitive lake (LAK016) land within the second box, "lake is healthy, and not acidifying"; and c) 5 sensitive lakes (LAK006, LAK022, LAK023, LAK028 and LAK042) land within the third box, "some evidence of acidification; closely monitor". The situation for the lakes landing in the third box is expanded upon below.

For LAK028, this classification is based on: a) values for the post-KMP averaging period below the *level of protection* for both CBANC and pH, and b) moderate support for a decline in CBANC (56% belief) and pH (40% belief), but with low support for exceedance of either *change limit* threshold (6% belief for CBANC and 18% belief for pH). The overall result is the same as last year and the percent belief values are relatively similar.

For LAK006, LAK022, LAK023, and LAK042, this classification is based on pH only. All five lakes have 0% belief in CBANC being below the *level of protection.*

> LAK023 and LAK042 show: a) values for the post-KMP averaging period below the *level of protection* for pH only, and b) moderate support for declines in pH (24% and 23% belief, respectively), but with low support for exceedance of the *change limit* threshold for pH (9% and 14%, respectively).
>
> LAK022 shows: a) a moderate belief in exceeding the *level of protection* for pH (75% belief), and b) moderate support for declines in pH (50% belief), with moderate support for exceedance of the *change limit* threshold (32% belief).
>
> LAK006 shows: a) a moderate belief in exceeding the *level of protection* for pH (28% belief), and b) moderate to low support for declines in pH (21% belief), with low support for exceedance of the *change limit* threshold (8% belief).

There are no lakes that have acidification exceedances.

The only change in lake classification from last year's Annual Report is LAK012, due to the percent belief in a decrease in pH changing from 20% to 18% and thus being identified as a low

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[5] All of the control lakes are classified in the first box regardless of increases in sulphate because any such increases cannot be causally linked to the smelter due to their location well outside the smelter plume. In both 2022 and 2023, all three control lakes showed a low percent belief in SO_4 changes since 2013 (Table 4-3). In 2019-2021 two of the control lakes (DCAS14A and NC184) showed moderate to high beliefs in SO_4 change (Table 4-3), but the magnitude of changes over time were very small (see graphs for Control Lakes in Appendix 2).

level of support for such a change. This is an exact reversal of the change reported last year (having increased from 18% to 20%). This small change is within the range of variability from repeat runs of the Bayesian analyses. It is a negligible difference between years but happens to span the defined boundary between low and moderate classifications.

All of the other lakes have the same classification and generally very similar underlying results as last year. The only changes of >25% belief in the underlying results for the sensitive lakes were: a) the percent belief in exceeding the *level of protection* for pH for LAK006 and LAK012 decreased by 42% and 33%, respectively, while both still remaining within the range of “moderate”, and b) the percent belief for a decline in CBANC for LAK012 increased by 33%, while still remaining within the range “moderate”.

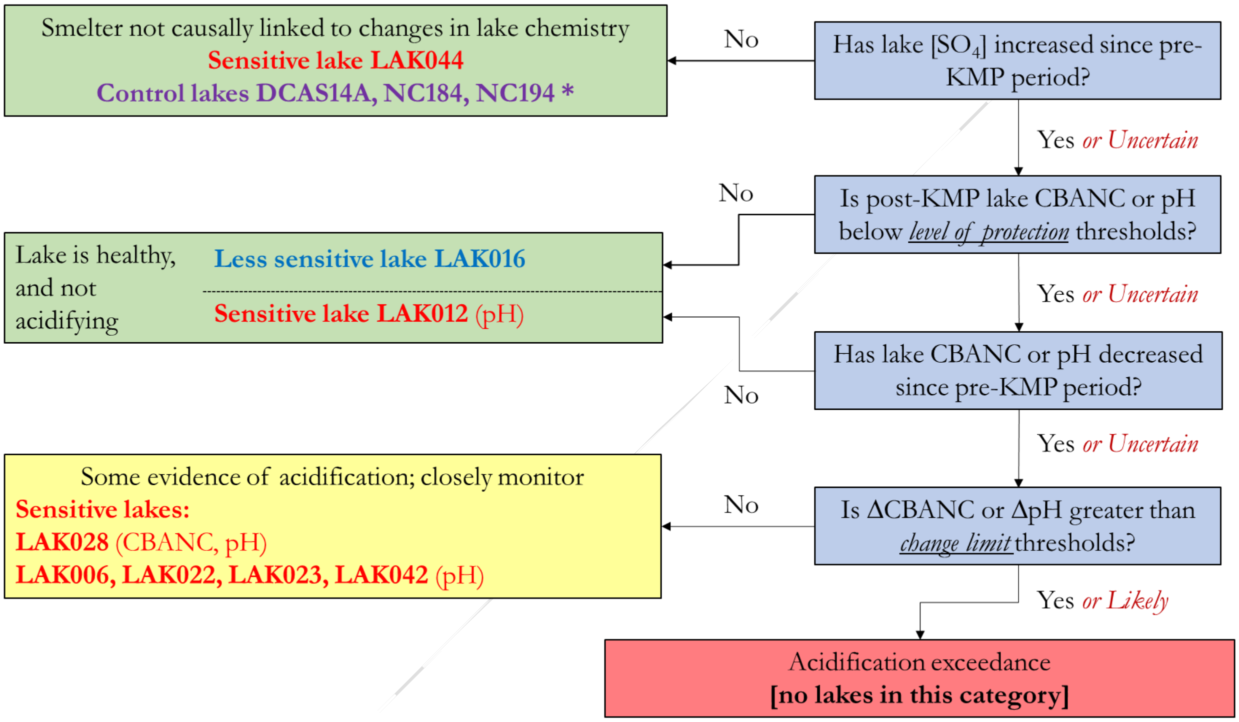

Figure 4-1. Classification of EEM lakes according to the simplified evidentiary framework. To be precautionary, we consider the lake’s appropriate assignment to be the furthest position into the evidentiary framework, based on CBANC or pH. LAK028 has moderate support for declines in CBANC and pH but low support for exceeding either *change limit* threshold. LAK006, LAK022, LAK023, and LAK042 have moderate support for declines in pH with low to low-moderate support for exceeding the *change limit* thresholds; however, they are all still above the CBANC *level of protection*. The control lakes (*) all show low support for increases in SO_4; however, they are classified in the first box regardless of potential increase in sulphate (as observed in some past years) because any such increases cannot be causally linked to the smelter due to their location well outside of the smelter plume.

Table 4-4. Results used in the application of the simple evidentiary framework. The first four columns are identical to Table 3-7 but the last two show the results for the % belief of *any* change in Gran ANC and pH. The % belief values are derived from the Bayesian version of Method 1, as described in Aquatic Appendix F of the 2019 Comprehensive Review (ESSA et al. 2020b). Values of % belief < 20% are coloured green, 20-80% yellow, and >80% red. "Post-KMP" refers to the post-KMP averaging period (2021-2023).

LAKE	**Changes in SO_4** (% belief in SO_4 increase / decrease)	**State of post-KMP CBANC** (% belief that CBANC *level of protection* threshold exceeded)	**State of post-KMP pH** (% belief that pH *level of protection* threshold exceeded)	**Changes in CBANC** (% belief that CBANC *change limit* threshold exceeded)	**Changes in pH** (% belief that pH *change limit* threshold exceeded)	**Change in CBANC (no threshold)** (% belief that CBANC decreased)	**Change in pH (no threshold)** (% belief that pH decreased)
Threshold type	**Any change (increase)**	**Level of Protection**	**Level of Protection**	**Change Limit**	**Change Limit**	**Any change (decrease)**	**Any change (decrease)**
Sensitive Lakes							
LAK006	79%	0%	28%	0%	8%	1%	21%
LAK012	62%	0%	44%	40%	9%	78%	18%
LAK022	74%	0%	75%	7%	32%	21%	50%
LAK023	44%	0%	100%	0%	9%	2%	24%
LAK028	98%	100%	100%	6%	18%	56%	40%
LAK042	55%	0%	100%	1%	14%	11%	23%
LAK044	4%	99%	100%	0%	4%	0%	16%
Less Sensitive Lakes							
LAK016	75%	0%	0%	3%	18%	18%	43%
Control Lakes							
DCAS14A	16%	0%	4%	2%	43%	14%	66%
NC184	6%	0%	82%	30%	34%	42%	49%
NC194	5%	0%	5%	n/a	49%	30%	64%

5 Recommendations

We recommend sampling LAK027 again in 2023. In 2021, the widely-observed storm-driven dilution event negated the ability of the sampling data to provide a meaningful comparison against the initial STAR data as intended. In 2022, the combination of exceptionally low deposition and particularly dry hydrologic conditions again negated the ability to provide the intended comparison. In 2023, the region was again subject to anomalous conditions (i.e., exceptionally dry conditions and substantial increase in emissions from a greatly reduced level during 2022). LAK027 does not show any evidence of acidification. With another year, we will have sampling across four different types of years and should be able to make a more robust confirmation of that conclusion.

We also recommend further consideration of sampling LAK028 and LAK006 near the end of October and again in mid-November to provide water chemistry samples that span the time period of likely rainstorms and episodic declines in pH. This information might help to distinguish hydrologically driven episodes (which would show decreases in CBANC, Gran ANC, BCS, pH, base cations, ***and*** SO_4) from smelter driven episodes (which would show similar declines but with an increase in SO_4). However, a decision by Rio Tinto to proceed with this sampling would need to consider the added safety risks of conducting the sampling in the late fall. Water chemistry can change rapidly during a rainstorm (Wiggington et al. 1996), so this added sampling may not be sufficient to clearly indicate the drivers of acidic episodes.

We do not recommend any other changes or adjustments to next year's program.

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Appendix 1: Water Chemistry Data from Annual Sampling, 2012-2023

The two tables below show the sample results for each of the EEM lakes and control lakes from annual monitoring conducted from 2012 to 2023, including charge balance ANC (CBANC), Gran ANC, base cation surplus (BCS), pH, dissolved organic carbon (DOC), and the concentration of major anions and cations, as well as the sum of all base cations (BC). The pH of the water samples has been measured by three different laboratories with (Trent University, 2012-2019; ALS, 2013-2022; BASL, 2019-2023). Gran ANC also transitioned from Trent University to BASL, overlapping in 2019.

The first table provides the mean annual value and standard error for each metric for lakes with multiple within-season samples, as calculated from all the within-season samples. Lakes with only a single annual sample will show the same value in both tables and no measure of variability. The second table presents the sampling data in its "raw" units, as measured, without converting concentration values to charge equivalents. Although acidification studies require converting measured concentrations to charge equivalents, these unconverted values may be more familiar and therefore easier to interpret for some audiences.

Mean Annual Values

The mean annual values and standard error have been calculated for all lakes with multiple within-season samples. Sample values with no standard error indicate that only a single annual sample was taken for that particular lake in that particular year.

Lake	Year	CBANC (μeq/L)	SE	Gran ANC (μeq/L) (Trent)	SE	Gran ANC (μeq/L) (BASL)	SE	BCS (μeq/L)	SE	pH (Trent)	SE	pH (ALS)	SE	pH (BASL)	SE	DOC (mg/L)	SE	SO_4 * (μeq/L)	SE	Cl (μeq/L)	SE	F (μeq/L)	SE	Ca * (μeq/L)	SE	Mg * (μeq/L)	SE	K * (μeq/L)	SE	Na * (μeq/L)	SE	∑ BC * (μeq/L)	∑ Anions (μeq/L)
Lak006	2012	49.2		25.7				34.6		5.8						3.6		11.4		5.8		4.5		30.3		12.5		2.9		14.9		60.6	66.2
LAK007	2012	1452.4		1437.6				1452.5		8.0						0.6		51.4		24.6		2.8		1272.2		157.0		19.3		55.4		1503.9	1552.5
LAK012	2012	114.5		57.0				94.5		5.6						4.6		6.1		4.2		5.0		74.5		20.8		5.2		20.0		120.6	115.9
LAK016	2012	127.2		68.7				112.0		6.3						3.7		39.0		6.3		7.8		117.7		20.5		7.3		20.8		166.3	166.4
LAK022	2012	67.9		27.8				44.5		5.9						5.3		30.2		6.9		6.1		58.1		16.0		3.2		20.8		98.1	99.4
LAK023	2012	46.9		19.8				29.3		5.7						4.2		19.0		4.5		5.6		39.4		12.0		3.7		10.8		65.9	72.2
LAK024	2012	315.4		299.5				311.7		7.1						1.4		24.8		27.3		1.6		273.2		33.0		4.2		29.6		340.0	376.5
LAK028	2012	16.0		-4.0				-5.1		5.0						4.9		56.9		6.1		20.7		47.5		9.5		3.1		12.8		72.9	95.7
LAK034	2012	177.6		99.4				158.1		6.7						4.5		24.1		5.8		5.8		119.3		31.6		5.8		44.9		201.7	221.4
LAK042	2012	47.2		-20.4				-15.4		4.7						13.2		6.2		6.1		3.2		7.4		22.7		3.1		20.3		53.4	73.4
LAK044	2012	8.0		1.3				2.5		5.4						1.7		6.2		5.6		2.9		6.8		3.2		4.1		0.0		14.2	27.7
Lak006	2013	43.1		29.0				30.3		6.2		6.1				3.2		14.4		8.7		5.6		27.1		13.0		5.3		12.2		57.6	80.1
LAK007	2013	1385.6		1462.1				1388.3		7.9		8.1				0.1		66.5		36.3		3.7		1226.0		156.5		21.9		47.6		1452.0	1598.9
LAK012	2013	97.5		63.5				79.5		6.3		6.1				4.2		11.3		14.7		8.2		64.8		20.3		9.2		14.6		108.9	168.1
LAK016	2013	108.7		96.9				90.9		6.7		7.2				4.2		56.9		12.3		11.5		114.4		23.9		11.2		17.6		167.1	206.6
LAK022	2013	62.0		36.4				33.9		6.2		6.1				6.2		47.1		12.4		8.7		65.1		19.2		6.0		18.8		109.1	145.9
LAK023	2013	37.7		23.8				20.7		6.0		6.0				4.0		24.1		7.5		7.4		37.1		13.3		5.1		8.3		63.9	89.7
LAK024	2013																																
LAK028	2013	-8.1		4.8				-40.2		5.2		5.5				7.1		128.1		17.7		32.0		85.1		18.3		5.0		13.0		121.3	184.0
LAK034	2013	219.5		210.4				199.4		6.9		7.4				4.7		38.1		8.2		10.0		152.7		41.7		9.2		54.1		257.7	287.0
LAK042	2013	55.1		21.0				10.0		5.5		5.4				9.7		5.7		7.7		3.2		16.0		22.3		3.4		19.3		61.0	87.4
LAK044	2013	8.9		8.6				4.5		5.7		6.0				1.5		6.2		8.9		3.8		7.8		3.6		5.9		-2.0		15.3	35.0
Lak006	2014	52.9	*2.0*	38.8	*0.6*			37.2	*2.6*	6.1	*0.1*	6.6	*0.2*			3.8	*0.3*	12.1	*0.6*	8.1	*1.2*	4.8	*0.1*	31.7	*0.5*	14.6	*0.4*	4.7	*0.3*	14.5	*1.2*	65.5	84.2
LAK007	2014	1484.8		1445.7				1484.5		8.1		8.0				0.7		30.7		19.2		1.9		1276.8		156.7		20.2		61.8		1515.5	1527.8
LAK012	2014	99.8	*3.1*	68.8	*6.8*			71.8	*7.9*	6.0	*0.1*	6.7	*0.2*			6.3	*1.0*	15.8	*5.2*	10.3	*2.2*	5.2	*0.2*	69.3	*1.6*	21.3	*0.6*	7.3	*0.5*	18.3	*1.6*	116.1	135.7
LAK016	2014	132.5		105.7				115.6		6.7		6.7				4.0		48.2		9.3		9.5		122.4		25.0		10.1		23.3		180.8	194.2
LAK022	2014	76.1		46.9				51.0		6.3		6.4				5.7		37.8		9.0		6.9		68.5		18.9		5.2		21.4		114.0	133.0
LAK023	2014	59.4	*3.3*	32.1	*1.1*			34.3	*2.1*	5.9	*0.1*	6.7	*0.3*			5.7	*0.4*	18.9	*1.0*	6.1	*0.3*	6.2	*0.2*	49.3	*3.9*	14.9	*0.4*	4.0	*0.1*	10.8	*0.3*	79.0	93.0
LAK024	2014	473.4		472.1				468.1		7.6		7.5				1.7		37.2		65.7		2.3		402.3		50.1		7.8		50.2		510.4	617.9

Lake	Year	CBANC (μeq/L)	SE	Gran ANC (μeq/L) (Trent)	SE	Gran ANC (μeq/L) (BASL)	SE	BCS (μeq/L)	SE	pH (Trent)	SE	pH (ALS)	SE	pH (BASL)	SE	DOC (mg/L)	SE	SO_4 * (μeq/L)	SE	Cl (μeq/L)	SE	F (μeq/L)	SE	Ca * (μeq/L)	SE	Mg * (μeq/L)	SE	K * (μeq/L)	SE	Na * (μeq/L)	SE	∑ BC * (μeq/L)	∑ Anions (μeq/L)
LAK028	2014	31.2		22.6				4.8		5.3		5.7				5.9		94.4		11.0		23.3		85.9		17.7		4.4		17.6		125.7	156.6
LAK034	2014	249.1		205.0				217.2		6.7		7.0				7.0		17.0		6.5		7.7		161.4		43.6		9.4		51.9		266.3	270.9
LAK042	2014	51.6		12.5				1.8		5.1		5.4				10.6		4.0		11.8		2.6		10.5		23.6		3.7		17.9		55.7	89.4
LAK044	2014	12.6		5.9				6.8		5.8		5.6				1.8		4.6		5.9		2.8		7.8		3.9		5.3		0.4		17.3	28.5
Lak006	2015	55.1	0.8	32.4	0.4			38.7	1.5	6.0	0.1	6.4	0.3			3.9	0.2	11.5	0.3	6.6	0.3	4.4	0.1	32.3	0.3	14.8	0.2	3.9	0.1	15.7	0.3	66.7	77.0
LAK007	2015	1461.9		1565.6				1463.9		8.0		7.9				0.3		45.6		24.0		2.6		1266.6		161.5		21.0		58.6		1507.7	1666.8
LAK012	2015	106.1	2.0	65.9	2.1			71.8	3.9	6.0	0.1	6.3	0.2			7.5	1.0	17.6	3.1	11.1	1.7	4.7	0.1	74.8	3.9	23.2	0.9	8.1	0.8	18.0	0.8	124.2	140.3
LAK016	2015	147.1		113.1				128.8		6.8		6.9				4.3		40.9		8.7		8.6		130.9		25.0		9.8		22.9		188.6	192.1
LAK022	2015	75.2		35.6				47.0		6.1		6.2				6.3		32.5		7.9		5.9		64.1		18.1		4.4		21.2		107.8	117.3
LAK023	2015	58.0	1.0	30.0	1.0			34.4	0.9	5.9	0.1	6.2	0.1			5.4	0.4	15.1	0.7	6.2	0.3	5.2	0.2	46.1	1.5	13.9	0.3	3.8	0.1	9.7	0.1	73.5	83.0
LAK024	2015	472.8		443.0				465.0		7.4		7.5				2.2		34.7		59.0		2.1		400.5		49.3		8.7		49.0		507.6	580.6
LAK028	2015	38.6		10.8				1.5		5.1		5.3				8.1		71.1		9.0		20.5		76.5		15.7		3.2		14.4		109.8	122.1
LAK034	2015	233.0		177.8				198.5		6.6		6.7				7.6		0.9		6.2		4.7		146.5		37.1		5.3		45.1		234.0	231.8
LAK042	2015	55.4		13.8				16.9		5.4		5.5				8.3		3.8		6.5		2.3		10.7		23.1		2.5		23.0		59.3	70.7
LAK044	2015	16.4		6.2				11.6		5.8		5.8				1.6		3.7		5.9		2.7		9.8		4.4		5.5		0.5		20.3	28.0
Lak006	2016	56.9	2.4	26.9	1.0			38.9	2.4	6.0	0.0	6.3	0.1			4.2	0.1	11.8	0.2	5.6	0.2	4.2	0.1	32.6	0.5	14.8	0.7	4.2	0.6	17.2	0.9	68.8	74.0
LAK007	2016	1495.8		1368.6				1495.2		8.0		8.1				0.8		46.7		25.4		2.6		1301.5		162.8		20.2		58.3		1542.8	1474.0
LAK012	2016	103.2	1.6	65.8	1.2			81.0	2.1	6.2	0.0	6.5	0.1			5.1	0.3	9.5	0.5	5.6	0.2	4.6	0.1	64.7	0.8	20.8	0.6	6.0	0.6	21.6	0.8	113.0	115.7
LAK016	2016	140.8		93.9				118.3		6.6		6.9				5.2		44.9		8.5		8.2		127.4		26.4		8.9		23.7		186.5	189.4
LAK022	2016	80.3		34.4				50.1		6.1		6.4				6.7		34.2		7.9		5.8		68.1		19.2		4.2		23.1		114.6	119.0
LAK023	2016	59.5	1.4	27.9	1.9			33.6	1.0	5.9	0.0	6.2	0.1			5.8	0.1	12.7	0.2	4.9	0.2	5.1	0.1	42.5	0.9	14.1	0.4	4.7	0.5	11.0	0.8	72.3	80.8
LAK024	2016	525.1		463.1				514.8		7.5		7.6				2.7		39.2		70.0		2.3		446.5		55.3		9.5		53.9		565.3	619.2
LAK028	2016	12.3	3.8	-4.9	6.2			-24.9	5.2	5.0	0.1	5.1	0.1			8.1	0.3	127.8	8.1	10.0	0.5	26.8	0.8	94.7	8.3	23.8	1.7	3.7	0.2	19.5	1.6	141.6	179.1
LAK034	2016	212.2		151.6				177.6		6.5		7.1				7.6		0.0		5.4		4.4		130.0		34.3		3.8		44.1		212.3	215.4
LAK042	2016	64.0	1.7	14.0	1.5			18.0	1.1	5.4	0.0	5.7	0.0			9.8	0.2	3.3	0.2	7.2	0.2	2.2	0.1	16.7	1.7	24.7	0.4	2.7	0.2	23.3	0.2	67.4	78.8
LAK044	2016	13.9	0.6	4.1	1.3			7.0	0.6	5.5	0.0	6.0	0.1			2.0	0.1	4.1	0.1	6.1	0.1	2.3	0.1	8.2	0.4	4.1	0.0	5.5	0.1	0.3	0.2	18.2	27.7
Lak006	2017	58.0	0.6	27.9	2.7			42.1	1.0	6.0	0.1	6.4	0.1			3.8	0.1	14.4	0.3	5.4	0.2	4.2	0.0	34.8	0.5	15.6	0.2	4.1	0.1	18.0	0.4	72.5	71.4
LAK007	2017	1402.3		1381.6				1404.3		8.0		8.0				0.3		47.1		25.9		2.4		1201.7		165.2		19.9		62.6		1449.4	1492.4
LAK012	2017	101.1	3.7	58.2	3.2			78.2	1.9	6.1	0.1	6.5	0.1			5.2	0.5	14.6	2.6	7.0	1.2	4.4	0.1	65.4	4.5	21.7	1.2	7.7	1.0	21.5	0.9	116.3	117.5
LAK016	2017	125.3		82.7				107.8		6.7		6.8				4.1		43.2		7.3		7.7		114.0		24.7		6.9		22.9		168.6	167.5
LAK022	2017	70.4		34.2				44.2		6.1		6.3				5.9		39.0		7.1		5.4		64.1		19.5		3.8		22.2		109.6	112.4
LAK023	2017	59.9	1.5	28.5	2.4			36.0	1.3	5.9	0.0	6.2	0.0			5.4	0.1	10.1	1.7	4.2	0.3	4.6	0.0	43.2	2.1	13.8	0.3	2.3	0.2	11.2	0.3	70.5	71.3
LAK024	2017	479.2		416.6				472.3		7.4		7.6				2.0		34.9		57.5		2.0		399.6		52.2		8.5		54.2		514.4	557.5
LAK028	2017	0.7	5.3	-9.9	4.5			-32.5	7.8	4.8	0.1	5.1	0.1			7.3	0.6	150.0	13.0	8.7	1.0	27.2	1.7	102.5	11.0	26.5	2.5	3.5	0.4	19.9	1.6	152.4	199.2
LAK034	2017	177.6		136.5				150.7		6.4		6.8				6.0		0.1		4.5		3.4		105.6		30.3		2.7		39.1		177.8	179.1
LAK042	2017	63.1	3.0	2.3	2.1			8.4	2.7	5.2	0.1	5.4	0.1			11.6	1.1	6.8	0.9	6.7	0.5	2.4	0.0	17.1	2.7	26.9	1.1	2.8	0.3	23.2	0.5	70.0	80.8
LAK044	2017	13.8	0.3	7.0	2.2			9.1	0.3	5.6	0.1	6.0	0.1			1.6	0.0	4.5	0.2	5.9	0.1	2.2	0.0	7.9	0.1	4.2	0.1	5.6	0.1	0.7	0.2	18.4	26.2
Lak006	2018	59.3	1.2	28.3	1.2			43.6	1.5	6.1	0.0	6.4	0.0			3.8	0.1	15.7	0.2	6.1	0.1	4.2	0.1	36.2	0.3	16.1	0.5	4.3	0.3	18.5	0.6	75.1	82.1
LAK007	2018	1443.8		1407.6				1445.7		8.1		8.1				0.3		47.1		27.9		2.6		1251.5		157.4		20.6		61.3		1490.8	1518.7
LAK012	2018	90.4	1.2	50.9	4.3			70.5	0.9	6.2	0.1	6.6	0.1			4.6	0.1	14.6	0.7	6.2	0.3	4.6	0.1	58.3	0.4	19.7	0.6	6.2	0.3	21.1	0.8	105.2	112.3
LAK016	2018	138.1		92.8				118.4		6.7		6.9				4.6		45.3		7.3		8.1		128.5		23.3		7.3		24.3		183.5	195.3

Lake	Year	CBANC (µeq/L)	SE	Gran ANC (µeq/L) (Trent)	SE	Gran ANC (µeq/L) (BASL)	SE	BCS (µeq/L)	SE	pH (Trent)	SE	pH (ALS)	SE	pH (BASL)	SE	DOC (mg/L)	SE	SO_4 * (µeq/L)	SE	Cl (µeq/L)	SE	F (µeq/L)	SE	Ca * (µeq/L)	SE	Mg * (µeq/L)	SE	K * (µeq/L)	SE	Na * (µeq/L)	SE	∑ BC * (µeq/L)	∑ Anions (µeq/L)
LAK022	2018	76.6		30.3				51.8		6.1		6.3				5.6		43.2		7.3		5.8		72.1		19.3		4.2		24.4		119.9	120.1
LAK023	2018	61.3	*0.7*	23.0	*0.7*			36.3	*1.6*	6.0	*0.1*	6.4	*0.1*			5.6	*0.2*	14.1	*0.9*	4.9	*0.2*	4.9	*0.1*	45.9	*0.3*	15.0	*0.3*	3.3	*0.2*	11.4	*0.4*	75.5	78.6
LAK024	2018	553.5		509.9				548.8		7.6		7.6				1.6		42.6		77.3		2.4		472.7		56.4		9.4		57.2		595.7	680.2
LAK028	2018	8.4	*1.8*	4.2	*1.6*			-10.2	*1.9*	5.3	*0.0*	5.5	*0.0*			4.4	*0.1*	107.5	*2.0*	6.6	*0.2*	20.9	*0.3*	76.4	*0.9*	19.0	*0.5*	2.8	*0.1*	17.9	*0.7*	116.0	147.4
LAK034	2018	183.4		130.6				161.0		6.5		6.6				5.1		0.1		3.7		3.7		113.1		27.7		2.1		40.8		183.7	176.3
LAK042	2018	50.4	*1.0*	0.6	*1.9*			0.7	*1.3*	5.1	*0.0*	5.3	*0.0*			10.6	*0.4*	6.3	*0.1*	6.1	*0.2*	2.3	*0.1*	8.8	*0.6*	23.9	*0.5*	2.3	*0.1*	21.8	*0.1*	56.8	74.4
LAK044	2018	13.2	*0.3*	3.9	*0.9*			7.0	*0.2*	5.5	*0.0*	5.9	*0.0*			1.9	*0.1*	4.5	*0.1*	6.4	*0.1*	2.2	*0.0*	8.3	*0.1*	4.1	*0.2*	5.5	*0.1*	-0.2	*0.3*	17.7	27.5
Lak006	2019	63.8	*2.2*	31.6	*2.7*	40.0	*1.1*	49.7	*1.8*	6.1	*0.0*	6.5	*0.1*	6.2	*0.0*	3.5	*0.2*	16.8	*0.6*	6.7	*0.6*	4.0	*0.2*	38.0	*0.6*	17.8	*0.4*	5.1	*0.2*	19.9	*0.9*	80.8	74.1
LAK007	2019	1443.5		1374.5		1496.3		1445.4		8.1		8.1		8.0		0.3		43.0		27.1		2.4		1246.6		158.4		20.4		61.2		1486.5	1469.6
LAK012	2019	96.5	*0.4*	55.3	*0.9*	64.1	*2.6*	74.8	*1.6*	6.1	*0.0*	6.6	*0.1*	6.2	*0.0*	5.0	*0.3*	13.5	*0.9*	7.1	*0.2*	4.4	*0.2*	59.7	*0.5*	21.3	*0.2*	6.5	*0.2*	22.6	*0.6*	110.1	121.4
LAK016	2019	129.8		90.8		100.9		111.2		6.6		7.1		6.6		4.4		58.6		9.0		7.9		127.9		26.5		9.7		24.4		188.6	219.5
LAK022	2019	74.8		35.9		44.4		47.8		6.1		6.4		6.2		6.0		49.3		8.7		5.6		71.5		22.4		5.0		25.3		124.2	123.4
LAK023	2019	59.4	*1.6*	20.7	*2.4*	26.8	*1.5*	33.4	*1.3*	5.8	*0.0*	6.3	*0.1*	6.0	*0.0*	5.9	*0.2*	13.5	*0.8*	5.4	*0.2*	4.8	*0.2*	42.2	*0.4*	15.4	*0.6*	3.3	*0.2*	12.1	*1.1*	73.1	79.4
LAK024	2019	570.7		496.9		548.7		566.0		7.7		7.7		7.3		1.6		40.8		75.3		2.1		478.3		58.1		8.7		66.3		611.4	652.5
LAK028	2019	4.5	*4.4*	3.3	*0.7*	4.0	*3.1*	-18.1	*6.0*	5.2	*0.0*	5.4	*0.0*	5.1	*0.0*	5.2	*0.3*	148.5	*4.0*	11.3	*0.6*	25.8	*1.1*	103.5	*1.2*	26.6	*0.5*	3.7	*0.2*	20.0	*0.9*	153.7	200.1
LAK034	2019	196.8		148.9		166.9		173.8		6.4		7.0		6.6		5.3		0.9		4.5		4.1		122.1		30.4		1.8		43.5		197.8	195.9
LAK042	2019	52.1	*2.1*	10.1	*0.6*	16.5	*1.0*	9.1	*1.4*	5.4	*0.0*	5.6	*0.1*	5.4	*0.0*	9.2	*0.5*	7.6	*0.6*	6.2	*0.3*	2.3	*0.1*	12.6	*1.8*	23.1	*0.6*	2.2	*0.3*	22.0	*0.3*	59.9	77.1
LAK044	2019	14.8	*0.6*	6.1	*0.4*	6.6	*0.3*	5.7	*1.2*	5.5	*0.0*	5.9	*0.1*	5.7	*0.0*	2.5	*0.3*	4.7	*0.3*	6.5	*0.3*	2.3	*0.1*	8.9	*0.2*	4.5	*0.2*	6.0	*0.2*	0.3	*0.2*	19.6	32.0
Lak006	2020	70.3	*1.5*			44.7	*1.3*	48.1	*3.8*			6.3	*0.0*	6.1	*0.0*	5.1	*0.5*	15.3	*0.5*	6.5	*0.6*	4.0	*0.1*	44.9	*1.3*	17.6	*0.7*	4.7	*0.4*	18.6	*0.4*	85.7	91.4
LAK012	2020	142.1	*6.4*			93.1	*9.0*	101.4	*4.9*			6.4		6.1	*0.0*	8.8		15.6		9.3		5.0		97.5		28.1		7.8		24.5		157.9	165.7
LAK016	2020																																
LAK022	2020																																
LAK023	2020	66.6	*0.5*			29.6	*1.6*	37.6	*2.8*			6.1		6.0	*0.0*	6.4		13.9		5.1		4.8		49.0		15.7		3.7		12.2		80.6	80.5
LAK028	2020	8.0	*1.4*			0.5	*0.6*	-26.7	*1.5*			5.0	*0.0*	5.0	*0.0*	7.6	*0.2*	149.1	*4.2*	9.8	*0.2*	24.3	*0.9*	110.6	*3.2*	24.5	*0.6*	3.4	*0.2*	20.3	*0.9*	158.8	193.3
LAK042	2020	79.5	*0.4*			-10.0	*3.6*	-13.2	*0.9*			4.8		4.7	*0.1*	19.2		7.6		6.5		2.5		23.6		33.2		2.9		27.5		87.2	102.9
LAK044	2020	14.5	*0.9*			2.4	*1.6*	8.1	*1.1*			5.7	*0.1*	5.6	*0.0*	1.9	*0.0*	5.2	*0.2*	6.9	*0.1*	2.1	*0.1*	8.4	*0.2*	4.6	*0.1*	6.6	*0.0*	0.3	*0.5*	19.9	21.8
Lak006	2021	67.8	*3.6*			39.1	*0.8*	46.0	*3.8*			6.3	*0.1*	5.9	*0.0*	5.0	*0.5*	17.5	*0.5*	6.8	*0.5*	4.0	*0.2*	45.0	*1.8*	17.2	*0.7*	4.9	*0.2*	18.3	*0.8*	85.4	91.3
LAK012	2021	101.2	*2.6*			58.7	*6.9*	68.1	*4.1*			6.3	*0.0*	5.8	*0.0*	7.3	*0.7*	28.7	*2.6*	6.5	*0.9*	4.2	*0.2*	79.4	*2.7*	23.9	*0.6*	6.0	*0.2*	21.6	*0.8*	130.8	133.3
LAK016	2021	138.1				95.9		97.9				6.7		6.2		8.7		59.5		8.2		8.7		139.4		28.0		8.2		23.3		198.8	213.4
LAK022	2021	68.8				20.6		44.2				5.4		5.5		5.6		41.9		7.6		5.6		65.1		20.1		3.9		21.8		110.8	104.5
LAK023	2021	56.2	*3.9*			24.9	*1.0*	32.4	*3.9*			6.1	*0.1*	5.7	*0.0*	5.4	*0.3*	24.5	*1.1*	4.7	*0.3*	4.6	*0.3*	51.9	*2.8*	15.1	*0.6*	3.5	*0.2*	11.5	*0.5*	81.9	82.0
LAK028	2021	11.7	*1.9*			-5.7	*0.9*	-31.9	*2.5*			4.9	*0.1*	4.8	*0.0*	9.4	*0.3*	96.9	*6.8*	10.2	*0.5*	19.4	*0.3*	76.5	*3.7*	17.9	*1.4*	2.7	*0.1*	12.9	*1.2*	110.0	141.1
LAK042	2021	62.4	*4.3*			-11.8	*3.8*	-16.5	*4.3*			4.7	*0.1*	4.7	*0.1*	16.5	*0.6*	13.5	*1.1*	5.6	*0.3*	2.3	*0.2*	20.9	*1.8*	28.2	*0.6*	2.7	*0.1*	24.3	*0.8*	76.1	100.5
LAK044	2021	17.1	*1.4*			5.4	*1.9*	9.5	*1.6*			5.5	*0.1*	5.5	*0.0*	2.2	*0.2*	4.2	*0.3*	5.6	*0.1*	1.8	*0.1*	9.4	*1.4*	4.4	*0.3*	6.5	*0.2*	1.1	*0.3*	21.5	25.6
Lak006	2022	70.1	*1.3*			44.1	*1.7*	52.2	*1.7*			6.5	*0.0*	6.3	*0.0*	4.2	*0.3*	12.1	*0.4*	5.9	*0.3*	3.7	*0.0*	42.0	*0.7*	17.2	*0.2*	4.2	*0.1*	18.9	*0.5*	82.3	84.7
LAK012	2022	112.4	*1.1*			81.9	*1.6*	90.2	*2.2*			6.7	*0.0*	6.3	*0.0*	5.1	*0.2*	1.0	*0.5*	5.8	*0.1*	4.1	*0.0*	67.7	*1.1*	22.0	*0.2*	3.2	*0.1*	20.7	*0.5*	113.6	115.9
LAK016	2022	141.4				113.1		123.2				7.0		6.6		4.3		41.7		7.3		7.3		128.5		24.8		8.6		21.8		183.6	188.4
LAK022	2022	75.4				39.4		47.8				6.3		6.2		6.2		31.6		6.8		5.1		62.6		18.7		4.0		21.7		107.1	107.0
LAK023	2022	54.0	*0.5*			26.3	*5.8*	29.6	*1.3*			6.2	*0.0*	6.1	*0.0*	5.5	*0.2*	12.7	*0.3*	4.6	*0.1*	4.2	*0.0*	39.4	*0.4*	13.3	*0.1*	3.9	*0.1*	10.2	*0.3*	66.8	72.0
LAK028	2022	19.3	*4.0*			10.4	*1.9*	-10.6	*3.6*			5.3	*0.1*	5.2	*0.1*	6.6	*0.4*	100.4	*1.8*	7.1	*0.1*	16.4	*0.8*	80.7	*2.2*	18.7	*0.3*	3.2	*0.1*	17.3	*0.5*	119.9	139.4
LAK042	2022	52.8	*1.3*			15.4	*1.7*	15.6	*2.2*			5.6	*0.0*	5.5	*0.0*	8.1	*0.3*	3.4	*0.3*	4.8	*0.4*	1.7	*0.1*	11.0	*0.3*	20.6	*0.3*	2.2	*0.2*	22.5	*0.7*	56.3	65.7

Lake	Year	CBANC (µeq/L)	SE	Gran ANC (µeq/L) (Trent)	SE	Gran ANC (µeq/L) (BASL)	SE	BCS (µeq/L)	SE	pH (Trent)	SE	pH (ALS)	SE	pH (BASL)	SE	DOC (mg/L)	SE	SO_4 * (µeq/L)	SE	Cl (µeq/L)	SE	F (µeq/L)	SE	Ca * (µeq/L)	SE	Mg * (µeq/L)	SE	K * (µeq/L)	SE	Na * (µeq/L)	SE	∑ BC * (µeq/L)	∑ Anions (µeq/L)
LAK044	2022	16.8	0.4			7.3	0.5	10.9	1.6			5.8	0.1	5.8	0.0	1.8	0.3	3.0	0.1	5.7	0.2	1.7	0.1	8.2	0.2	4.2	0.1	6.7	0.3	0.8	0.2	19.9	22.1
LAK006	2023	66.6	1.3			41.8	1.3	52.7	1.5			6.4	0.0	6.3	0.0	3.4	0.1	14.7	0.8	5.8	0.4	4.0	0.1	40.6	0.1	17.1	0.2	4.1	0.1	19.6	0.3	81.4	78.3
LAK012	2023	92.2	0.8			62.4	1.1	75.2	0.5			6.4	0.1	6.3	0.0	4.0	0.1	7.3	0.6	5.0	0.1	4.2	0.1	55.1	0.3	19.0	0.2	3.9	0.3	21.7	0.2	99.7	95.4
LAK016	2023	128.1				93.9		112.2				6.6		6.6		3.8		42.8		6.8		7.3		116.5		23.8		8.4		22.4		171.1	162.6
LAK022	2023	81.4				40.0		57.6				6.2		6.2		5.4		32.3		7.3		5.1		66.1		19.4		4.4		23.9		113.8	106.5
LAK023	2023	57.0	1.0			27.3	0.8	36.3	0.8			6.1	0.0	6.1	0.0	4.8	0.0	16.2	0.9	4.8	0.2	4.9	0.1	43.5	0.5	14.2	0.1	3.8	0.1	11.9	0.2	73.4	71.0
LAK028	2023	14.7	2.5			5.1	3.2	-2.5	1.5			5.3	0.0	5.3	0.0	4.1	0.3	86.8	3.1	6.6	0.1	17.6	0.3	66.8	1.1	16.9	0.4	3.0	0.1	14.9	0.8	101.6	116.3
LAK042	2023	57.2	0.5			15.9	2.5	13.4	2.5			5.5	0.0	5.4	0.0	9.4	0.5	5.8	0.2	6.4	0.2	2.4	0.2	10.8	0.2	24.1	0.4	2.6	0.1	25.6	0.4	63.1	75.1
LAK044	2023	16.7	0.4			7.4	0.8	11.2	0.6			5.8	0.0	5.7	0.0	1.7	0.1	3.1	0.2	6.3	0.2	2.0	0.1	8.2	0.1	4.0	0.1	7.0	0.2	0.7	0.1	19.9	20.0
NC184	2012																																
NC194	2012																																
DCAS14A	2012																																
NC184	2013	80.4		16.2				25.6		5.7						11.6		5.7		24.0		0.3		50.5		17.5		4.4		13.8		86.2	132.0
NC194	2013	35.6		28.0				35.3		6.6						0.7		3.6		7.6		0.3		23.2		3.4		5.2		7.4		39.2	59.3
DCAS14A	2013	53.5		50.6				49.9		6.5						1.4		33.4		9.2		0.6		63.9		10.3		10.3		6.1		90.6	115.6
NC184	2014																																
NC194	2014																																
DCAS14A	2014																																
NC184	2015	73.0		18.4				27.2		5.5		5.6				9.8		5.7		21.7		0.5		48.8		16.1		2.9		10.8		78.7	104.6
NC194	2015	40.9		33.0				40.2		6.5		6.5				0.8		2.3		7.3		0.5		26.9		4.4		4.3		7.9		43.4	56.3
DCAS14A	2015	74.9						73.6		6.6		6.7				0.9		35.7		7.3		0.5		77.6		12.4		11.2		9.9		111.0	49.0
NC184	2016	94.6		27.3				44.9		5.8		6.2				10.6		5.5		21.2		0.5		62.6		19.3		2.7		15.5		100.1	120.5
NC194	2016	40.0		28.7				35.1		6.4		6.6				1.6		2.3		7.9		0.5		26.4		4.3		3.8		7.9		42.4	55.4
DCAS14A	2016	72.7		57.5				68.3		6.6		6.8				1.5		36.8		8.5		0.5		77.5		11.8		10.5		9.7		109.6	116.1
NC184	2017	76.3		9.8				13.0		5.4		6.0				13.3		4.7		14.7		0.5		45.2		17.4		2.5		15.9		81.0	104.6
NC194	2017	46.5		12.4				44.8		6.4		6.4				1.0		2.5		4.8		0.5		29.9		5.7		3.6		9.9		49.1	39.4
DCAS14A	2017	67.8		51.0				63.3		6.6		6.7				1.5		31.1		5.6		0.5		68.2		11.8		9.1		9.9		99.0	99.0
NC184	2018	95.0		44.0				63.1		6.2		6.4				7.0		8.3		16.6		0.5		67.8		17.3		3.1		15.3		103.4	113.3
NC194	2018	43.1		26.1				45.0		6.5		6.7				0.3		2.6		5.1		0.5		28.3		4.3		4.1		9.1		45.8	45.6
DCAS14A	2018	79.0		59.3				77.3		6.8		6.8				1.0		41.3		7.3		0.5		85.6		12.6		11.5		10.7		120.4	124.2
NC184	2019	86.1	1.7	24.9	1.5	47.3	14.2	42.9	2.2	5.7	0.0	6.1	0.1	5.9	0.0	9.3	0.3	7.1	0.2	23.2	1.0	0.5	0.0	58.3	0.3	19.0	0.6	2.6	0.1	13.5	1.1	93.3	114.5
NC194	2019	46.7	0.6	30.4	5.3	41.4	0.2	44.7	0.4	6.4	0.0	6.6	0.1	6.5	0.0	1.0	0.2	2.7	0.3	9.2	0.4	0.5	0.0	31.4	0.6	4.8	0.1	4.7	0.2	8.5	0.3	49.4	50.0
DCAS14A	2019	81.1	1.5	58.6	5.9	73.0	0.3	78.3	1.4	6.6	0.1	6.8	0.0	6.6	0.0	1.2	0.0	41.0	0.9	8.8	1.0	0.5	0.0	85.3	1.2	13.7	0.2	11.9	0.3	11.9	0.3	122.8	138.6
NC184	2020																																
NC194	2020																																
DCAS14A	2020																																
NC184	2021	61.2				9.2		6.4				5.1		5.2		11.6		3.5		18.9		0.3		37.3		13.5		2.0		11.8		64.7	100.8
NC194	2021	35.6				27.4		33.1				6.2		6.0		1.1		2.1		5.9		0.3		22.4		3.9		3.8		7.7		37.8	54.9
DCAS14A	2021	63.8				55.6		55.0				6.6		6.0		2.4		28.5		7.9		0.6		63.6		11.9		10.2		9.4		95.1	101.0
NC184	2022	85.3				25.2		35.5				6.1		5.9		10.6		4.5		15.2		0.3		54.3		18.0		2.8		14.7		89.8	110.1
NC194	2022	36.3				28.6		35.1				6.5		6.4		0.9		1.9		5.1		0.3		22.7		4.0		3.8		7.7		38.3	40.8
DCAS14A	2022	70.9				62.7		68.1				6.8		6.5		1.2		30.7		5.4		0.3		71.2		11.4		10.1		9.1		101.7	98.5

Lake	Year	CBANC (µeq/L) SE	Gran ANC (µeq/L) (Trent) SE	Gran ANC (µeq/L) (BASL) SE	BCS (µeq/L) SE	pH (Trent) SE	pH (ALS) SE	pH (BASL) SE	DOC (mg/L) SE	SO_4 * (µeq/L) SE	Cl (µeq/L) SE	F (µeq/L) SE	Ca * (µeq/L) SE	Mg * (µeq/L) SE	K * (µeq/L) SE	Na * (µeq/L) SE	∑ BC * (µeq/L)	∑ Anions (µeq/L)
NC184	2023	111.5	▨	67.1	80.4	▨	6.5	6.5	6.9	4.2	23.7	0.3	80.0	18.6	4.0	13.2	115.7	131.1
NC194	2023	43.1	▨	34.2	42.4	▨	6.5	7.0	0.8	1.2	7.1	0.3	27.6	4.3	4.2	8.3	44.4	47.1
DCAS14A	2023	84.2	▨	68.7	81.4	▨	6.8	6.6	1.2	32.2	7.1	0.3	82.1	12.8	10.9	10.7	116.5	109.1

[1] SE = standard error

Sampling Data in "Raw" Units

The annual or mean annual values (depending on whether the lake had multiple within-season samples) are presented in their "raw" units, as measured, without converting concentration values to charge equivalents.

Lake	Year	Gran Alkalinity (mg/L) (Trent)	Gran Alkalinity (mg/L) (BASL)	pH (Trent)	pH (ALS)	pH (BASL)	DOC (mg/L)	Conductivity (µS/s)	SO$_4$ (mg/L)	Cl (mg/L)	F (mg/L)	NO3 (µg/L)	NH4 (µg/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	Fe (mg/L)	Al (mg/L)	Mn (mg/L)
Lak006	2012	1.3		5.8			3.6	6.7	0.6	0.2	0.1	0.1	3.0	0.6	0.2	0.1	0.5	0.0	0.1	0.0
Lak007	2012	71.9		8.0			0.6	148.9	2.6	0.9	0.1	4.7	1.8	25.5	2.0	0.8	1.8	0.0	0.0	0.0
LAK012	2012	2.9		5.6			4.6	12.7	0.3	0.1	0.1	0.7	3.4	1.5	0.3	0.2	0.5	0.7	0.1	0.2
LAK016	2012	3.4		6.3			3.7	17.9	1.9	0.2	0.1	0.8	3.9	2.4	0.3	0.3	0.6	0.0	0.1	0.0
LAK022	2012	1.4		5.9			5.3	10.7	1.5	0.2	0.1	0.7	3.7	1.2	0.2	0.1	0.6	0.0	0.1	0.0
LAK023	2012	1.0		5.7			4.2	7.5	0.9	0.2	0.1	0.3	3.3	0.8	0.2	0.1	0.3	0.0	0.1	0.0
LAK024	2012	15.0		7.1			1.4	40.0	1.3	1.0	0.0	0.4	2.4	5.5	0.5	0.2	1.2	0.0	0.0	0.0
LAK028	2012	-0.2		5.0			4.9	12.2	2.8	0.2	0.4	1.5	3.4	1.0	0.1	0.1	0.4	0.1	0.4	0.0
LAK034	2012	5.0		6.7			4.5	22.4	1.2	0.2	0.1	1.6	4.9	2.4	0.4	0.2	1.1	0.0	0.0	0.0
LAK042	2012	-1.0		4.7			13.2	11.9	0.3	0.2	0.1	0.7	8.5	0.2	0.3	0.1	0.6	0.6	0.4	0.0
LAK044	2012	0.1		5.4			1.7	3.1	0.3	0.2	0.1	0.4	3.0	0.1	0.1	0.2	0.1	0.0	0.0	0.0
Lak006	2013	1.5		6.2	6.1		3.2	7.0	0.7	0.3	0.1	2.5	2.5	0.5	0.2	0.2	0.5	0.0	0.0	0.0
Lak007	2013	73.2		7.9	8.1		0.1	147.0	3.4	1.3	0.1	2.5	2.5	24.6	2.0	0.9	1.8	0.0	0.0	0.0
LAK012	2013	3.2		6.3	6.1		4.2	12.8	0.6	0.5	0.2	2.5	2.5	1.3	0.3	0.4	0.6	0.4	0.1	0.0
LAK016	2013	4.9		6.7	7.2		4.2	20.3	2.8	0.4	0.2	22.7	7.1	2.3	0.3	0.4	0.6	0.0	0.0	0.0
LAK022	2013	1.8		6.2	6.1		6.2	13.8	2.3	0.4	0.2	2.5	2.5	1.3	0.3	0.2	0.7	0.1	0.1	0.0
LAK023	2013	1.2		6.0	6.0		4.0	9.6	1.2	0.3	0.1	30.1	2.5	0.7	0.2	0.2	0.3	0.0	0.1	0.0
LAK024	2013																			
LAK028	2013	0.2		5.2	5.5		7.1	20.3	6.2	0.6	0.6	20.4	2.5	1.7	0.3	0.2	0.6	0.2	0.6	0.0
LAK034	2013	10.5		6.9	7.4		4.7	28.3	1.9	0.3	0.2	2.5	2.5	3.1	0.5	0.4	1.4	0.0	0.0	0.0
LAK042	2013	1.1		5.5	5.4		9.7	8.0	0.3	0.3	0.1	2.5	2.5	0.3	0.3	0.1	0.6	0.3	0.3	0.0
LAK044	2013	0.4		5.7	6.0		1.5	3.3	0.3	0.3	0.1	2.5	2.5	0.2	0.1	0.2	0.1	0.0	0.0	0.0
Lak006	2014	1.9		6.1	6.6		3.8	8.5	0.6	0.3	0.1	7.7	40.5	0.6	0.2	0.2	0.5	0.0	0.1	0.0
Lak007	2014	72.4		8.1	8.0		0.7	154.2	1.6	0.7	0.0	2.5	2.5	25.6	2.0	0.8	1.8	0.0	0.0	0.0
LAK012	2014	3.4		6.0	6.7		6.3	13.9	0.8	0.4	0.1	7.6	5.3	1.4	0.3	0.3	0.6	0.3	0.1	0.0
LAK016	2014	5.3		6.7	6.7		4.0	21.5	2.4	0.3	0.2	2.5	6.7	2.5	0.3	0.4	0.7	0.0	0.1	0.0
LAK022	2014	2.3		6.3	6.4		5.7	14.4	1.9	0.3	0.1	2.5	2.5	1.4	0.3	0.2	0.7	0.1	0.1	0.0
LAK023	2014	1.6		5.9	6.7		5.7	9.3	0.9	0.2	0.1	10.9	5.3	1.0	0.2	0.2	0.4	0.0	0.1	0.0
LAK024	2014	23.6		7.6	7.5		1.7	63.1	2.1	2.3	0.0	5.1	2.5	8.1	0.8	0.4	2.5	0.0	0.0	0.0
LAK028	2014	1.1		5.3	5.7		5.9	20.2	4.6	0.4	0.4	2.5	2.5	1.7	0.2	0.2	0.6	0.1	0.5	0.0
LAK034	2014	10.3		6.7	7.0		7.0	27.5	0.9	0.2	0.1	2.5	2.5	3.2	0.5	0.4	1.3	0.1	0.0	0.0
LAK042	2014	0.6		5.1	5.4		10.6	10.8	0.3	0.4	0.1	2.5	2.5	0.2	0.3	0.2	0.6	0.4	0.3	0.0
LAK044	2014	0.3		5.8	5.6		1.8	3.6	0.3	0.2	0.1	2.5	2.5	0.2	0.1	0.2	0.1	0.0	0.0	0.0
Lak006	2015	1.6		6.0	6.4		3.9	5.6	0.6	0.2	0.1	3.4	5.4	0.7	0.2	0.2	0.5	0.1	0.1	0.0
Lak007	2015	78.4		8.0	7.9		0.3	151.2	2.3	0.9	0.0	5.6	2.5	25.4	2.0	0.8	1.8	0.0	0.0	0.0
LAK012	2015	3.3		6.0	6.3		7.5	10.1	0.9	0.4	0.1	8.3	8.0	1.5	0.3	0.3	0.6	0.3	0.1	0.0
LAK016	2015	5.7		6.8	6.9		4.3	20.7	2.0	0.3	0.2	7.9	2.5	2.6	0.3	0.4	0.7	0.0	0.1	0.0
LAK022	2015	1.8		6.1	6.2		6.3	12.8	1.6	0.3	0.1	2.5	2.5	1.3	0.2	0.2	0.6	0.1	0.1	0.0
LAK023	2015	1.5		5.9	6.2		5.4	5.9	0.8	0.2	0.1	6.3	2.5	0.9	0.2	0.2	0.3	0.0	0.1	0.0

Lake	Year	Gran Alkalinity (mg/L) (Trent)	Gran Alkalinity (mg/L) (BASL)	pH (Trent)	pH (ALS)	pH (BASL)	DOC (mg/L)	Conductivity (µS/s)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	NO3 (µg/L)	NH4 (µg/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	Fe (mg/L)	Al (mg/L)	Mn (mg/L)
LAK024	2015	22.2		7.4	7.5		2.2	58.7	2.0	2.1	0.0	8.1	2.5	8.1	0.7	0.4	2.3	0.1	0.0	0.0
LAK028	2015	0.5		5.1	5.3		8.1	17.8	3.5	0.3	0.4	2.5	2.5	1.5	0.2	0.1	0.5	0.2	0.6	0.0
LAK034	2015	8.9		6.6	6.7		7.6	22.3	0.1	0.2	0.1	2.5	2.5	2.9	0.5	0.2	1.2	0.1	0.0	0.0
LAK042	2015	0.7		5.4	5.5		8.3	8.1	0.2	0.2	0.0	2.5	2.5	0.2	0.3	0.1	0.7	0.2	0.3	0.0
LAK044	2015	0.3		5.8	5.8		1.6	3.5	0.2	0.2	0.1	2.5	2.5	0.2	0.1	0.2	0.1	0.0	0.0	0.0
Lak006	2016	1.3		6.0	6.3		4.2	7.8	0.6	0.2	0.1	2.5	2.5	0.7	0.2	0.2	0.5	0.0	0.1	0.0
Lak007	2016	68.5		8.0	8.1		0.8	153.7	2.4	0.9	0.1	6.5	2.5	26.1	2.0	0.8	1.8	0.0	0.0	0.0
LAK012	2016	3.3		6.2	6.5		5.1	12.4	0.5	0.2	0.1	5.0	4.7	1.3	0.3	0.2	0.6	0.3	0.1	0.0
LAK016	2016	4.7		6.6	6.9		5.2	20.8	2.2	0.3	0.2	10.9	2.5	2.6	0.3	0.4	0.7	0.0	0.1	0.0
LAK022	2016	1.7		6.1	6.4		6.7	13.7	1.7	0.3	0.1	2.5	2.5	1.4	0.3	0.2	0.7	0.1	0.1	0.0
LAK023	2016	1.4		5.9	6.2		5.8	9.1	0.6	0.2	0.1	2.5	5.1	0.9	0.2	0.2	0.4	0.0	0.1	0.0
LAK024	2016	23.2		7.5	7.6		2.7	66.3	2.2	2.5	0.0	20.7	2.5	9.0	0.8	0.4	2.6	0.1	0.0	0.0
LAK028	2016	-0.2		5.0	5.1		8.1	23.7	6.2	0.4	0.5	21.5	2.5	1.9	0.3	0.2	0.6	0.1	0.7	0.0
LAK034	2016	7.6		6.5	7.1		7.6	22.1	0.0	0.2	0.1	2.5	2.5	2.6	0.4	0.2	1.1	0.1	0.0	0.0
LAK042	2016	0.7		5.4	5.7		9.8	8.8	0.2	0.3	0.0	2.5	3.7	0.3	0.3	0.1	0.7	0.2	0.3	0.0
LAK044	2016	0.2		5.5	6.0		2.0	3.9	0.2	0.2	0.0	2.5	2.5	0.2	0.1	0.2	0.1	0.0	0.0	0.0
Lak006	2017	1.4		6.0	6.4		3.8	8.8	0.7	0.2	0.1	2.5	2.5	0.7	0.2	0.2	0.5	0.0	0.1	0.0
Lak007	2017	69.1		8.0	8.0		0.3	149.0	2.4	0.9	0.0	2.5	2.5	24.1	2.1	0.8	2.0	0.0	0.0	0.0
LAK012	2017	2.9		6.1	6.5		5.2	12.9	0.7	0.2	0.1	9.7	5.6	1.3	0.3	0.3	0.6	0.3	0.1	0.0
LAK016	2017	4.1		6.7	6.8		4.1	18.5	2.1	0.3	0.1	2.5	2.5	2.3	0.3	0.3	0.7	0.0	0.1	0.0
LAK022	2017	1.7		6.1	6.3		5.9	12.8	1.9	0.3	0.1	2.5	2.5	1.3	0.3	0.2	0.6	0.0	0.1	0.0
LAK023	2017	1.4		5.9	6.2		5.4	7.9	0.5	0.2	0.1	7.7	2.5	0.9	0.2	0.1	0.3	0.0	0.1	0.0
LAK024	2017	20.9		7.4	7.6		2.0	57.4	2.0	2.0	0.0	11.2	2.5	8.1	0.8	0.4	2.4	0.1	0.0	0.0
LAK028	2017	-0.5		4.8	5.1		7.3	26.9	7.2	0.3	0.5	25.3	3.3	2.1	0.3	0.1	0.6	0.1	0.7	0.0
LAK034	2017	6.8		6.4	6.8		6.0	17.6	0.0	0.2	0.1	2.5	2.5	2.1	0.4	0.1	1.0	0.1	0.0	0.0
LAK042	2017	0.1		5.2	5.4		11.6	9.8	0.4	0.2	0.0	2.5	5.4	0.3	0.3	0.1	0.7	0.3	0.4	0.0
LAK044	2017	0.4		5.6	6.0		1.6	4.4	0.2	0.2	0.0	2.5	2.5	0.2	0.1	0.2	0.1	0.0	0.0	0.0
Lak006	2018	1.4		6.1	6.4		3.8	8.8	0.8	0.2	0.1	2.5	2.5	0.7	0.2	0.2	0.5	0.0	0.1	0.0
Lak007	2018	70.4		8.1	8.1		0.3	147.4	2.4	1.0	0.0	2.5	2.5	25.1	2.0	0.8	2.0	0.0	0.0	0.0
LAK012	2018	2.5		6.2	6.6		4.6	11.5	0.7	0.2	0.1	2.5	2.5	1.2	0.3	0.2	0.6	0.3	0.1	0.0
LAK016	2018	4.6		6.7	6.9		4.6	20.0	2.2	0.3	0.2	2.5	2.5	2.6	0.3	0.3	0.7	0.0	0.1	0.0
LAK022	2018	1.5		6.1	6.3		5.6	13.4	2.1	0.3	0.1	2.5	2.5	1.5	0.3	0.2	0.7	0.0	0.1	0.0
LAK023	2018	1.1		6.0	6.4		5.6	9.4	0.7	0.2	0.1	2.5	2.5	0.9	0.2	0.1	0.4	0.0	0.1	0.0
LAK024	2018	25.5		7.6	7.6		1.6	70.2	2.4	2.7	0.0	2.5	2.5	9.5	0.9	0.4	2.8	0.0	0.0	0.0
LAK028	2018	0.2		5.3	5.5		4.4	17.7	5.2	0.2	0.4	2.5	3.3	1.5	0.2	0.1	0.5	0.1	0.5	0.0
LAK034	2018	6.5		6.5	6.6		5.1	17.8	0.0	0.1	0.1	2.5	2.5	2.3	0.3	0.1	1.0	0.0	0.0	0.0
LAK042	2018	0.0		5.1	5.3		10.6	8.6	0.3	0.2	0.0	2.5	2.5	0.2	0.3	0.1	0.6	0.3	0.4	0.0
LAK044	2018	0.2		5.5	5.9		1.9	3.6	0.2	0.2	0.0	2.5	2.5	0.2	0.1	0.2	0.1	0.0	0.0	0.0
Lak006	2019	1.6	2.0	6.1	6.5	6.2	1.1	8.3	0.8	0.2	0.1	2.5	2.5	0.8	0.2	0.2	0.6	0.0	0.0	0.0
Lak007	2019	68.8	74.9	8.1	8.1	8.0	0.3	147.2	2.2	1.0	0.0	2.5	2.5	25.0	2.0	0.8	1.9	0.0	0.0	0.0
LAK012	2019	2.8	3.2	6.1	6.6	6.2	1.8	11.0	0.7	0.3	0.1	3.2	2.5	1.2	0.3	0.3	0.7	0.2	0.0	0.0

Lake	Year	Gran Alkalinity (mg/L) (Trent)	Gran Alkalinity (mg/L) (BASL)	pH (Trent)	pH (ALS)	pH (BASL)	DOC (mg/L)	Conductivity (µS/s)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	NO3 (µg/L)	NH4 (µg/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	Fe (mg/L)	Al (mg/L)	Mn (mg/L)
LAK016	2019	4.5	5.1	6.6	7.1	6.6	2.5	19.8	2.9	0.3	0.2	2.5	6.2	2.6	0.3	0.4	0.7	0.0	0.1	0.0
LAK022	2019	1.8	2.2	6.1	6.4	6.2	1.3	13.6	2.4	0.3	0.1	2.5	2.5	1.4	0.3	0.2	0.8	0.1	0.1	0.0
LAK023	2019	1.0	1.3	5.8	6.3	6.0	1.0	7.1	0.7	0.2	0.1	2.5	3.6	0.9	0.2	0.1	0.4	0.0	0.1	0.0
LAK024	2019	24.9	27.5	7.7	7.7	7.3	6.9	66.8	2.3	2.7	0.0	8.0	2.5	9.6	0.9	0.4	3.0	0.0	0.0	0.0
LAK028	2019	0.2	0.2	5.2	5.4	5.1	5.4	24.0	7.2	0.4	0.5	11.9	5.2	2.1	0.4	0.2	0.7	0.1	0.6	0.0
LAK034	2019	7.5	8.4	6.4	7.0	6.6	3.0	17.8	0.1	0.2	0.1	2.5	2.5	2.5	0.4	0.1	1.1	0.0	0.0	0.0
LAK042	2019	0.5	0.8	5.4	5.6	5.4	1.5	6.6	0.4	0.2	0.0	4.3	2.5	0.3	0.3	0.1	0.6	0.2	0.3	0.0
LAK044	2019	0.3	0.3	5.5	5.9	5.7	1.5	2.4	0.3	0.2	0.0	2.5	2.5	0.2	0.1	0.2	0.1	0.0	0.0	0.0
Lak006	2020		2.2		6.3	6.1	5.1	8.5	0.8	0.2	0.1	2.5	2.5	0.9	0.2	0.2	0.6	0.1	0.1	0.0
LAK012	2020		4.7		6.4	6.1	8.8	15.1	0.8	0.3	0.1	2.5	2.5	2.0	0.4	0.3	0.7	0.5	0.1	0.1
LAK016	2020																			
LAK022	2020																			
LAK023	2020		1.5		6.1	6.0	6.4	7.3	0.7	0.2	0.1	2.5	2.5	1.0	0.2	0.1	0.4	0.0	0.1	0.0
LAK028	2020		0.0		5.0	5.0	7.6	25.0	7.2	0.3	0.5	25.4	3.8	2.2	0.3	0.1	0.7	0.1	0.7	0.0
LAK042	2020		-0.5		4.8	4.7	19.2	14.2	0.4	0.2	0.0	2.5	2.5	0.5	0.4	0.1	0.8	0.6	0.6	0.0
LAK044	2020		0.2		5.6	5.6	1.9	2.5	0.1	0.1	0.0	2.5	2.5	0.2	0.1	0.2	0.1	0.0	0.0	0.0
Lak006	2021		2.0		6.3	5.9	5.0	8.3	0.9	0.2	0.1	2.5	5.3	0.9	0.2	0.2	0.6	0.1	0.1	0.0
LAK012	2021		2.9		6.3	5.8	7.3	13.1	1.4	0.2	0.1	12.9	4.8	1.6	0.3	0.2	0.6	0.4	0.1	0.0
LAK016	2021		4.8		6.7	6.2	8.7	20.5	2.9	0.3	0.2	18.1	2.5	2.8	0.4	0.3	0.7	0.1	0.2	0.0
LAK022	2021		1.0		5.4	5.5	5.6	12.6	2.1	0.3	0.1	2.5	2.5	1.3	0.3	0.2	0.7	0.1	0.2	0.0
LAK023	2021		1.2		6.1	5.7	5.4	8.3	1.2	0.2	0.1	18.7	3.3	1.0	0.2	0.1	0.4	0.0	0.1	0.0
LAK028	2021		-0.3		4.9	4.8	9.4	20.4	4.7	0.4	0.4	20.5	3.2	1.5	0.2	0.1	0.5	0.2	0.7	0.0
LAK042	2021		-0.6		4.7	4.7	16.5	14.5	0.7	0.2	0.0	2.5	4.1	0.4	0.4	0.1	0.7	0.5	0.5	0.0
LAK044	2021		0.3		5.5	5.5	2.2	2.7	0.2	0.2	0.0	2.5	2.5	0.2	0.1	0.3	0.1	0.0	0.0	0.0
Lak006	2022		1.8		5.2	5.0	3.4	9.4	0.5	0.2	0.1	2.0	2.5	0.7	0.2	0.1	0.4	0.1	0.0	0.0
LAK012	2022		4.1		6.7	6.3	5.1	11.9	0.1	0.2	0.1	2.5	2.5	1.4	0.3	0.1	0.6	0.2	0.0	0.0
LAK016	2022		5.7		7.0	6.6	4.3	20.7	2.0	0.3	0.1	7.2	6.0	2.6	0.3	0.3	0.6	0.0	0.1	0.0
LAK022	2022		2.0		6.3	6.2	6.2	12.1	1.6	0.2	0.1	2.5	2.5	1.3	0.2	0.2	0.6	0.1	0.1	0.0
LAK023	2022		1.3		6.2	6.1	5.5	7.6	0.6	0.2	0.1	2.5	2.5	0.8	0.2	0.2	0.3	0.0	0.1	0.0
LAK028	2022		0.4		4.3	4.2	5.3	18.6	3.9	0.2	0.2	2.6	2.0	1.3	0.2	0.1	0.4	0.1	0.4	0.0
LAK042	2022		0.8		5.6	5.5	8.1	7.0	0.2	0.2	0.0	2.5	3.1	0.2	0.3	0.1	0.6	0.2	0.2	0.0
LAK044	2022		0.4		5.8	5.8	1.8	3.4	0.2	0.2	0.0	2.5	2.5	0.2	0.1	0.3	0.1	0.0	0.0	0.0
LAK006	2023		2.1		6.4	6.3	3.4	9.3	0.7	0.2	0.1	2.5	5.8	0.8	0.2	0.2	0.6	0.0	0.0	0.0
LAK012	2023		3.1		6.4	6.3	4.0	10.6	0.4	0.2	0.1	2.5	2.5	1.1	0.2	0.2	0.6	0.1	0.0	0.0
LAK016	2023		4.7		6.6	6.6	3.8	19.3	2.1	0.2	0.1	2.5	8.5	2.3	0.3	0.3	0.6	0.0	0.0	0.0
LAK022	2023		2.0		6.2	6.2	5.4	13.1	1.6	0.3	0.1	2.5	2.5	1.3	0.3	0.2	0.7	0.1	0.1	0.0
LAK023	2023		1.4		6.1	6.1	4.8	8.0	0.8	0.2	0.1	2.5	2.5	0.9	0.2	0.2	0.4	0.0	0.1	0.0
LAK028	2023		0.3		5.3	5.3	4.1	16.3	4.2	0.2	0.3	2.5	4.7	1.3	0.2	0.1	0.5	0.1	0.4	0.0
LAK042	2023		0.8		5.5	5.4	9.4	8.0	0.3	0.2	0.0	2.5	2.5	0.2	0.3	0.1	0.7	0.2	0.3	0.0
LAK044	2023		0.4		5.8	5.7	1.7	3.6	0.2	0.2	0.0	2.5	3.5	0.2	0.1	0.3	0.1	0.0	0.0	0.0

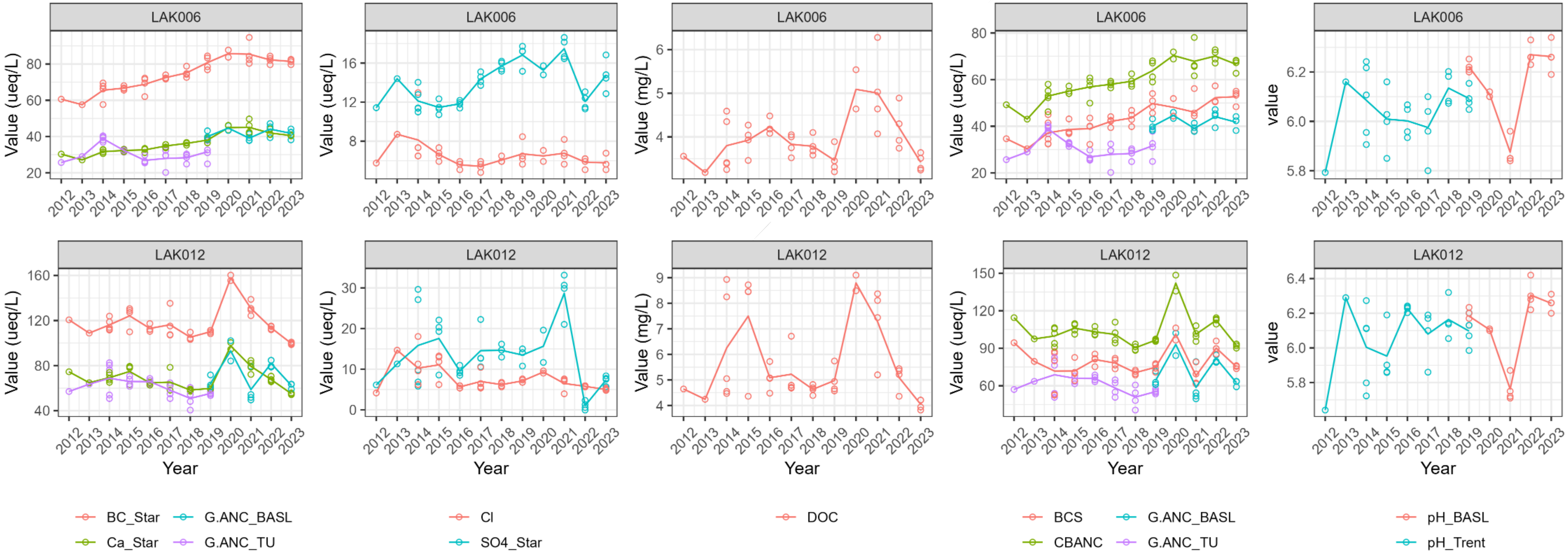
Lake	Year	Gran Alkalinity (mg/L) (Trent)	Gran Alkalinity (mg/L) (BASL)	pH (Trent)	pH (ALS)	pH (BASL)	DOC (mg/L)	Conductivity (µS/s)	SO_4 (mg/L)	Cl (mg/L)	F (mg/L)	NO3 (µg/L)	NH4 (µg/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	Na (mg/L)	Fe (mg/L)	Al (mg/L)	Mn (mg/L)
NC184	2012																			
NC194	2012																			
DCAS14A	2012																			
NC184	2013	0.8		5.7			11.6	10.0	0.4	0.9	0.0	5.0	1.0	1.0	0.3	0.2	0.8			
NC194	2013	1.4		6.6			0.7	3.9	0.2	0.3	0.0	1.0	1.0	0.5	0.1	0.2	0.3			
DCAS14A	2013	2.5		6.5			1.4	10.6	1.7	0.3	0.0	52.6	2.5	1.3	0.1	0.4	0.3	0.0	0.0	0.0
NC184	2014																			
NC194	2014																			
DCAS14A	2014																			
NC184	2015	0.9		5.5	5.6		9.8	11.6	0.4	0.8	0.0	2.5	2.5	1.0	0.2	0.1	0.7	0.2	0.3	0.0
NC194	2015	1.7		6.5	6.5		0.8	5.4	0.1	0.3	0.0	2.5	2.5	0.5	0.1	0.2	0.3	0.0	0.0	0.0
DCAS14A	2015			6.6	6.7		0.9	14.0	1.8	0.3	0.0	6.8	2.5	1.6	0.2	0.4	0.4	0.0	0.0	0.0
NC184	2016	1.4		5.8	6.2		10.6	12.8	0.4	0.8	0.0	2.5	2.5	1.3	0.3	0.1	0.8	0.1	0.3	0.0
NC194	2016	1.4		6.4	6.6		1.6	5.9	0.1	0.3	0.0	2.5	2.5	0.5	0.1	0.2	0.3	0.0	0.0	0.0
DCAS14A	2016	2.9		6.6	6.8		1.5	14.8	1.8	0.3	0.0	2.5	2.5	1.6	0.2	0.4	0.4	0.0	0.0	0.0
NC184	2017	0.5		5.4	6.0		13.3	11.4	0.3	0.5	0.0	2.5	2.5	0.9	0.2	0.1	0.7	0.2	0.3	0.0
NC194	2017	0.6		6.4	6.4		1.0	4.9	0.1	0.2	0.0	2.5	2.5	0.6	0.1	0.1	0.3	0.0	0.0	0.0
DCAS14A	2017	2.6		6.6	6.7		1.5	11.7	1.5	0.2	0.0	2.5	2.5	1.4	0.2	0.4	0.3	0.0	0.0	0.0
NC184	2018	2.2		6.2	6.4		7.0	12.3	0.5	0.6	0.0	2.5	2.5	1.4	0.3	0.1	0.7	0.1	0.2	0.0
NC194	2018	1.3		6.5	6.7		0.3	5.4	0.2	0.2	0.0	2.5	2.5	0.6	0.1	0.2	0.3	0.0	0.0	0.0
DCAS14A	2018	3.0		6.8	6.8		1.0	14.7	2.0	0.3	0.0	2.5	2.5	1.7	0.2	0.5	0.4	0.0	0.0	0.0
NC184	2019	1.2	2.4	5.7	6.1	5.9	1.1	11.1	0.5	0.8	0.0	3.7	2.5	1.2	0.3	0.1	0.8	0.1	0.3	0.0
NC194	2019	1.5	2.1	6.4	6.6	6.5	0.9	5.3	0.2	0.3	0.0	2.5	2.5	0.6	0.1	0.2	0.4	0.0	0.0	0.0
DCAS14A	2019	2.9	3.7	6.6	6.8	6.6	1.4	13.7	2.0	0.3	0.0	10.3	2.5	1.7	0.2	0.5	0.4	0.0	0.0	0.0
NC184	2020																			
NC194	2020																			
DCAS14A	2020																			
NC184	2021		0.5		5.1	5.2	11.6	9.5	0.3	0.7	0.0	2.5	2.5	0.8	0.2	0.1	0.6	0.2	0.3	0.0
NC194	2021		1.4		6.2	6.0	1.1	3.3	0.1	0.2	0.0	2.5	2.5	0.5	0.1	0.2	0.3	0.0	0.0	0.0
DCAS14A	2021		2.8		6.6	6.0	2.4	10.8	1.4	0.3	0.0	39.8	2.5	1.3	0.2	0.4	0.4	0.0	0.0	0.0
NC184	2022		1.3		6.1	5.9	10.6	10.9	0.3	0.5	0.0	2.5	2.5	1.1	0.3	0.1	0.6	0.1	0.3	0.0
NC194	2022		1.4		6.5	6.4	0.9	4.6	0.1	0.2	0.0	2.5	2.5	0.5	0.1	0.2	0.3		0.0	0.0
DCAS14A	2022		3.1		6.8	6.5	1.2	12.1	1.5	0.2	0.0	2.5	2.5	1.4	0.2	0.4	0.3	0.0	0.0	0.0
NC184	2023		3.4		6.5	6.5	6.9	13.9	0.3	0.8	0.0	2.5	2.5	1.6	0.3	0.2	0.8	0.1	0.2	0.0
NC194	2023		1.7		6.5	7.0	0.8	5.3	0.1	0.3	0.0	2.5	2.5	0.6	0.1	0.2	0.3	0.0	0.0	0.0
DCAS14A	2023		3.4		6.8	6.6	1.2	13.6	1.6	0.3	0.0	2.5	2.5	1.7	0.2	0.4	0.4	0.0	0.0	0.0

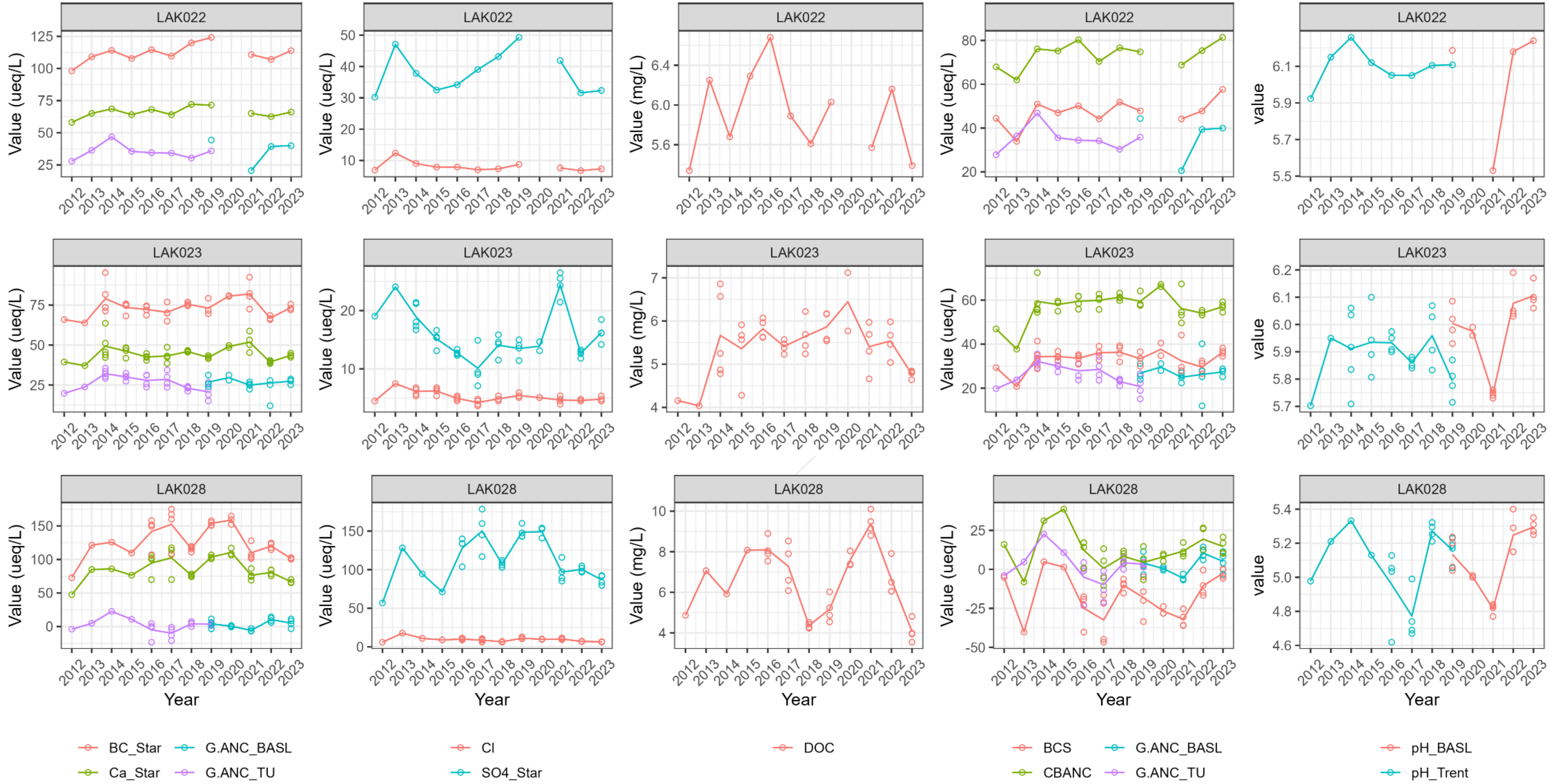
Appendix 2: Changes in Ion Concentrations from 2012 to 2023

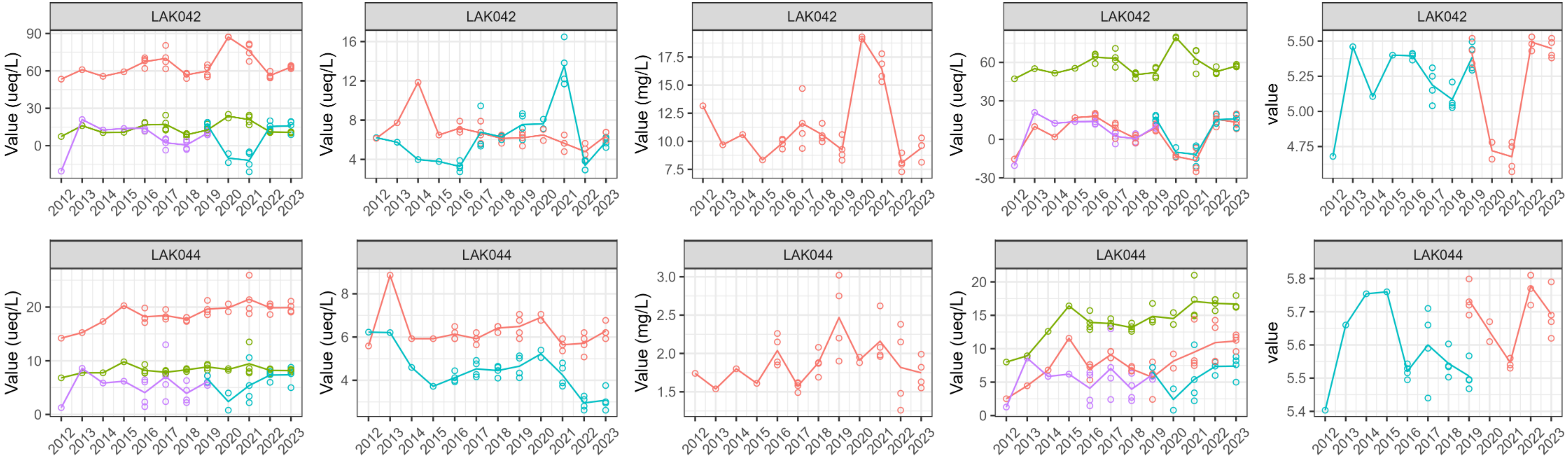
For each of the EEM lakes, the figures in this appendix show the inter-annual changes in six major water chemistry metrics from 2012 to 2023: Gran ANC, base cations and calcium (left panel), sulfate and chloride (centre-left panel), dissolved organic carbon (centre panel), CBANC, Gran ANC, and BCS (centre-right panel), and pH (right panel). The selection of each set of metrics is solely based on optimizing graphical representation across all metrics and lakes (i.e., metrics with somewhat similar numeric ranges are shown together). The axis for pH does not start at zero – be aware that this can make relatively minor changes appear to be much more substantial than they are. Due to large variation among the lakes for some of the metrics, the Y-axis is not consistent across the lakes, therefore extra caution is required for making comparisons among lakes with respect to the magnitude of changes. However, these graphs are especially useful for looking at the patterns of changes for individual lakes across the sampling record and determining whether similar patterns are observed across lakes and/or metrics.

These figures show the results for all of the sampling events for each lake in each year that were taken within the fall index period. The points represent the values for individual sampling events. The solid lines represent the annual trend, based on either the single annual sample or the average of all the within-season samples, as appropriate for the lake and year.

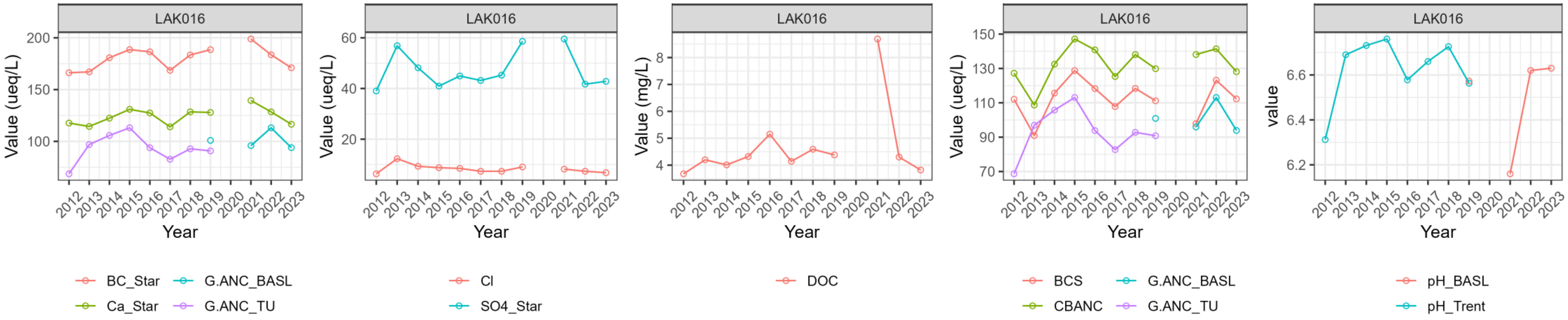
Sensitive Lakes



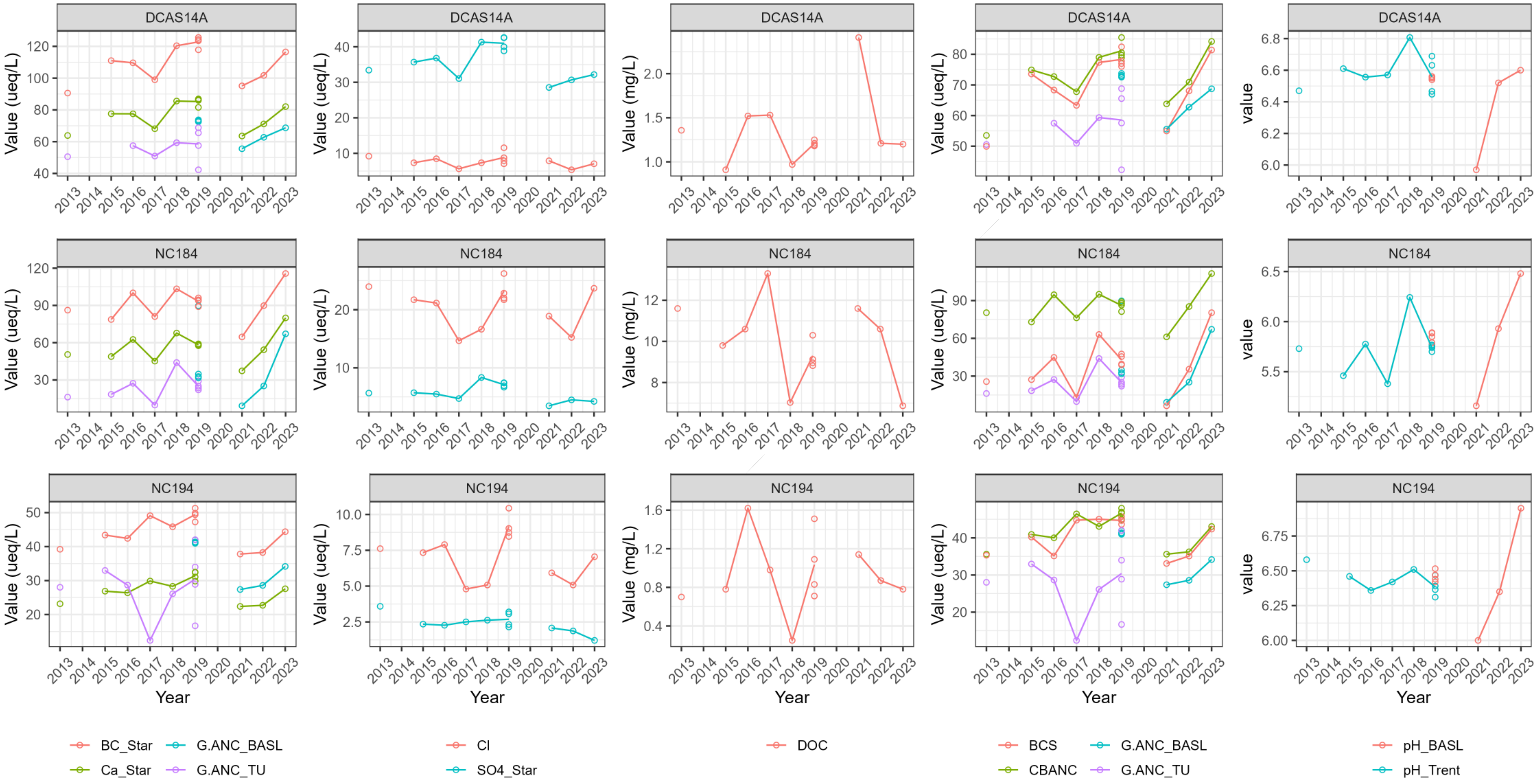

LAK022
LAK023
LAK028
Value (ueq/L)
Value (mg/L)
value
Year
2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
BC_Star
Ca_Star
G.ANC_BASL
G.ANC_TU
Cl
SO4_Star
DOC
BCS
CBANC
pH_BASL
pH_Trent



Less Sensitive Lakes



Control Lakes

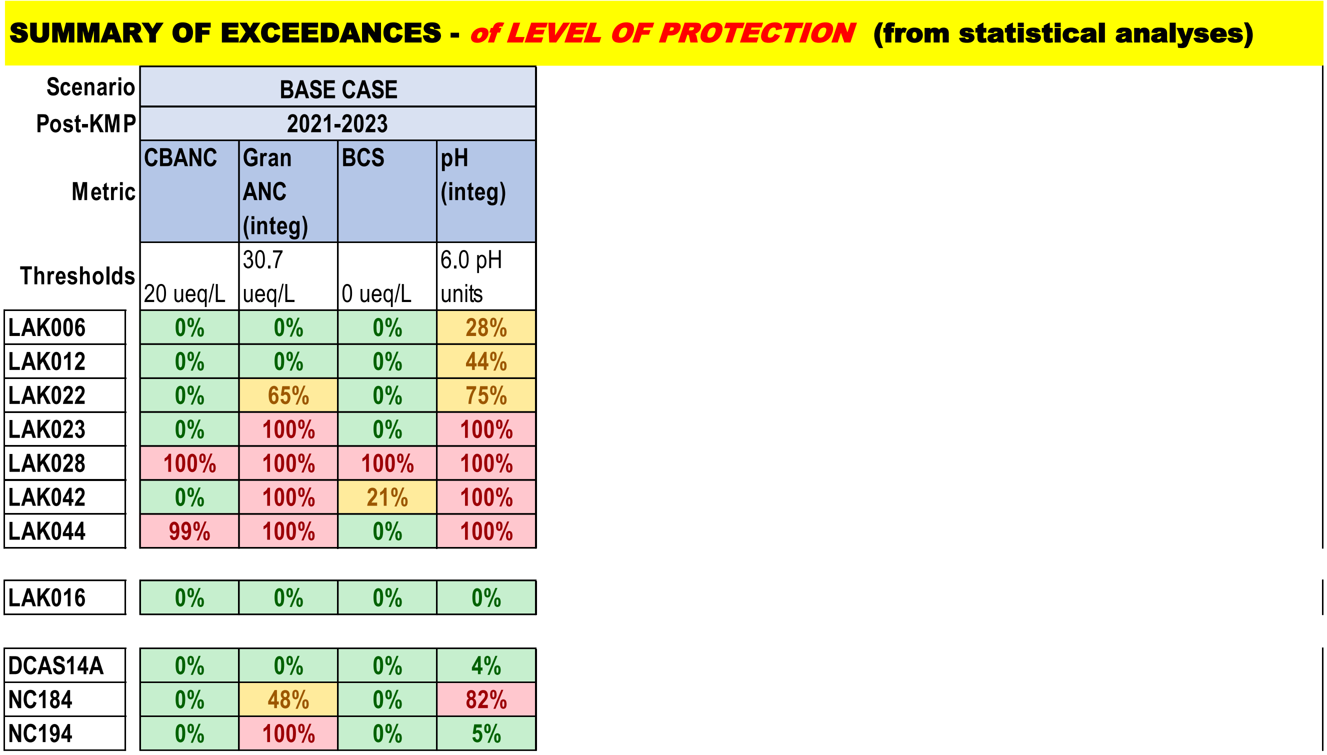


Appendix 3: Sensitivity Analyses for Statistical Analyses of Post-KMP Changes in Lake Chemistry

This appendix includes the results of the primary statistical analyses presented in Section 3.3 alongside the results of the sensitivity analyses performed using the alternate transition period baseline (2012-2014, as compared to the 2012 pre-KMP baseline applied in the base case). The upper panel shows the % belief in an exceedance of the *change limit*, the middle panel shows the % belief in an exceedance of the *level of protection*, and the bottom panel indicates the level of support for an overall exceedance of each indicator (based on the approach described in the main text).

SUMMARY OF EXCEEDANCES - *of CHANGE LIMIT* (from statistical analyses)

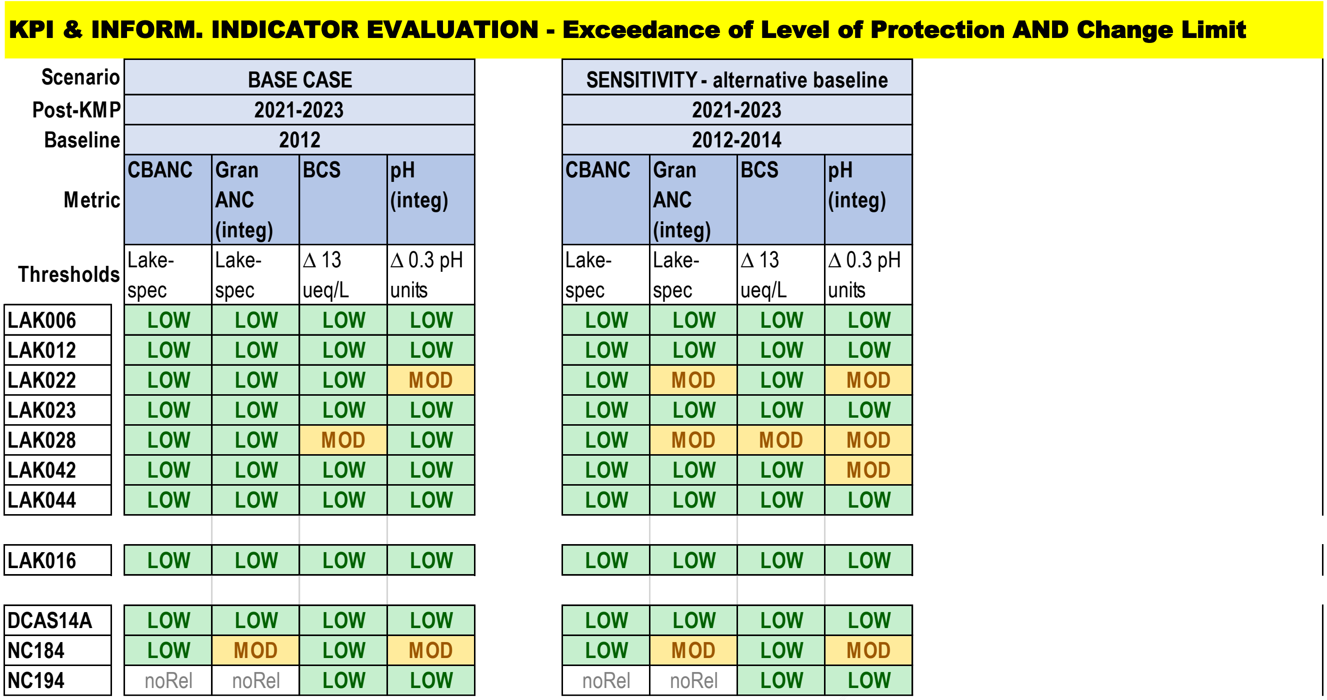
Scenario	**BASE CASE**				**SENSITIVITY - alternative baseline**			
Post-KMP	**2021-2023**				**2021-2023**			
Baseline	**2012**				**2012-2014**			
Metric	**CBANC**	**Gran ANC (integ)**	**BCS**	**pH (integ)**	**CBANC**	**Gran ANC (integ)**	**BCS**	**pH (integ)**
Thresholds	Lake-spec	Lake-spec	Δ 13 ueq/L	Δ 0.3 pH units	Lake-spec	Lake-spec	Δ 13 ueq/L	Δ 0.3 pH units
LAK006	0%	1%	2%	8%	0%	1%	0%	6%
LAK012	40%	14%	62%	9%	8%	8%	20%	13%
LAK022	7%	18%	8%	32%	1%	33%	2%	39%
LAK023	0%	1%	2%	9%	2%	5%	1%	2%
LAK028	6%	6%	43%	18%	12%	20%	28%	21%
LAK042	1%	5%	12%	14%	0%	9%	10%	20%
LAK044	0%	1%	0%	4%	0%	3%	0%	4%
LAK016	3%	2%	25%	18%	0%	8%	8%	32%
DCAS14A	2%	4%	9%	43%	4%	3%	9%	40%
NC184	30%	26%	31%	34%	30%	22%	29%	36%
NC194	▨	▨	6%	49%	▨	▨	6%	48%



SUMMARY OF EXCEEDANCES - *of LEVEL OF PROTECTION* (from statistical analyses)

Scenario	BASE CASE			
Post-KMP	2021-2023			
Metric	CBANC	Gran ANC (integ)	BCS	pH (integ)
Thresholds	20 ueq/L	30.7 ueq/L	0 ueq/L	6.0 pH units
LAK006	0%	0%	0%	28%
LAK012	0%	0%	0%	44%
LAK022	0%	65%	0%	75%
LAK023	0%	100%	0%	100%
LAK028	100%	100%	100%	100%
LAK042	0%	100%	21%	100%
LAK044	99%	100%	0%	100%
LAK016	0%	0%	0%	0%
DCAS14A	0%	0%	0%	4%
NC184	0%	48%	0%	82%
NC194	0%	100%	0%	5%

<u>Note</u>: This row of tables (i.e., *level of protection*) is not missing a table – there is no “alternative baseline” scenario because the *level of protection* is solely based on the post-KMP status. Therefore, the overall assessment under the alternative baseline scenario (i.e., middle table in last row of tables) is based on the alternative baseline scenario the *change limit* assessment and the base case scenario for the *level of protection* assessment.



KPI & INFORM. INDICATOR EVALUATION - Exceedance of Level of Protection AND Change Limit

Scenario	BASE CASE				SENSITIVITY - alternative baseline			
Post-KMP	2021-2023				2021-2023			
Baseline	2012				2012-2014			
Metric	CBANC	Gran ANC (integ)	BCS	pH (integ)	CBANC	Gran ANC (integ)	BCS	pH (integ)
Thresholds	Lake-spec	Lake-spec	∆ 13 ueq/L	∆ 0.3 pH units	Lake-spec	Lake-spec	∆ 13 ueq/L	∆ 0.3 pH units
LAK006	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW
LAK012	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW
LAK022	LOW	LOW	LOW	MOD	LOW	MOD	LOW	MOD
LAK023	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW
LAK028	LOW	LOW	MOD	LOW	LOW	MOD	MOD	MOD
LAK042	LOW	LOW	LOW	LOW	LOW	LOW	LOW	MOD
LAK044	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW
LAK016	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW
DCAS14A	LOW	LOW	LOW	LOW	LOW	LOW	LOW	LOW
NC184	LOW	MOD	LOW	MOD	LOW	MOD	LOW	MOD
NC194	noRel	noRel	LOW	LOW	noRel	noRel	LOW	LOW

Appendix 4: Sensitivity Analyses on Imputation of Gran ANC and pH Values for Integrated Time Series

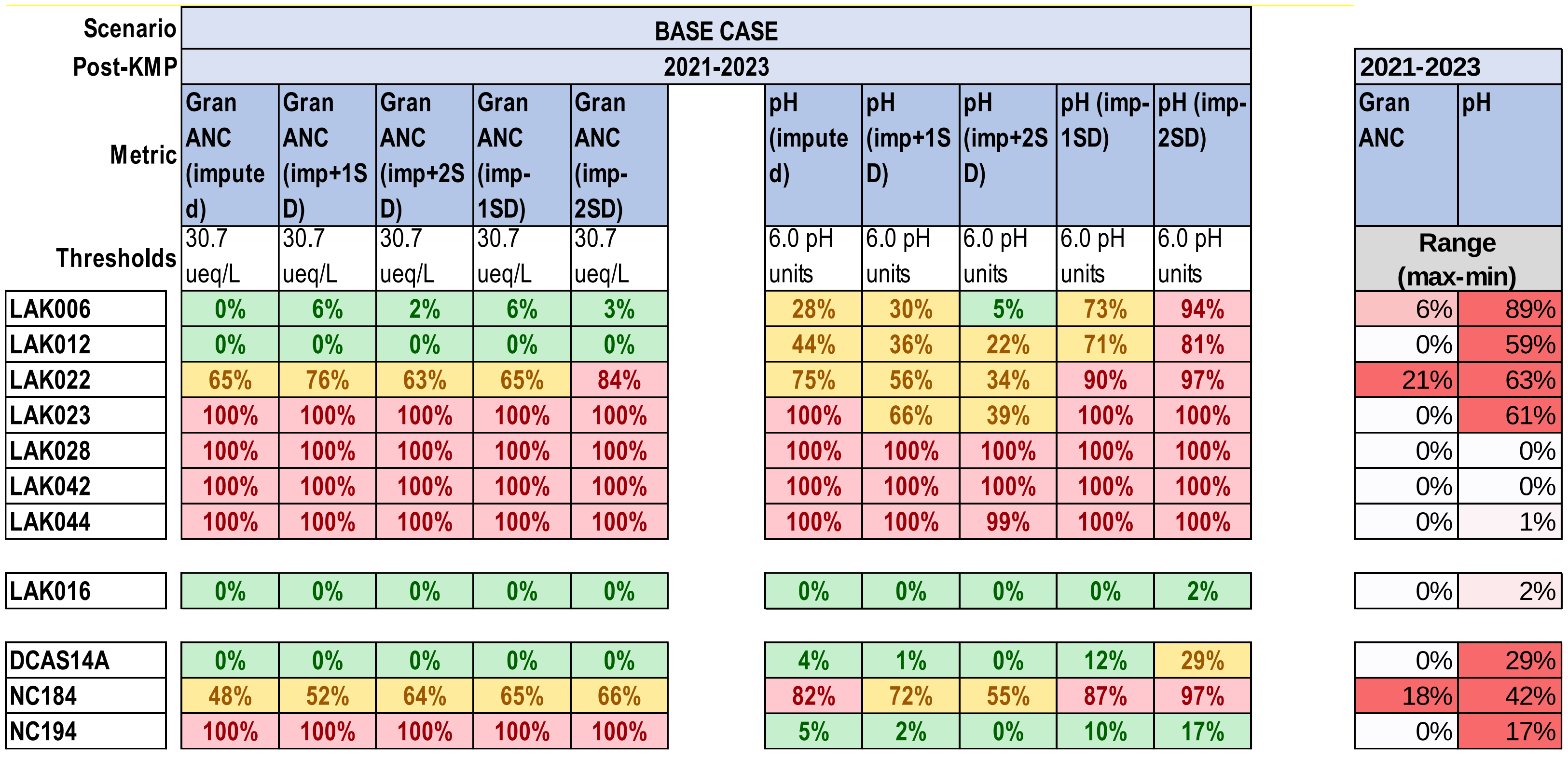
This appendix includes the results of the Bayesian statistical analyses for Gran ANC and pH using alternate values for the imputed 2020, 2021, 2022, and 2023 values in order to explore the sensitivity of the results to the uncertainty in the imputation process (see description in Section 2.1 of the SO_2 EEM Program 2020 Aquatic Technical Memo W09 for full details). Results are shown for the range of data series for Gran ANC and pH across the base case scenario and the alternative baseline scenario. For each scenario, the tables below show the results across all lakes for each data series and the range of results across all of the permutations of a particular metric for each lake. *Note: "Gran ANC (imputed)" is the same metric that is referenced as "Gran ANC (integ)" in the main text; same for pH as well.*

SUMMARY OF EXCEEDANCES - *of CHANGE LIMIT* (from statistical analyses)

Scenario	BASE CASE											
Post-KMP	2021-2023										2021-2023	
Baseline	2012										2012	
Metric	Gran ANC (imputed)	Gran ANC (imp+1SD)	Gran ANC (imp+2SD)	Gran ANC (imp-1SD)	Gran ANC (imp-2SD)	pH (imputed)	pH (imp+1SD)	pH (imp+2SD)	pH (imp-1SD)	pH (imp-2SD)	Gran ANC	pH
Thresholds	Lake-spec	Lake-spec	Lake-spec	Lake-spec	Lake-spec	∆ 0.3 pH units	∆ 0.3 pH units	∆ 0.3 pH units	∆ 0.3 pH units	∆ 0.3 pH units	Range (max-min)	
LAK006	1%	1%	1%	1%	0%	8%	9%	4%	12%	15%	1%	11%
LAK012	14%	13%	12%	14%	18%	9%	9%	6%	11%	14%	6%	8%
LAK022	18%	18%	18%	18%	19%	32%	26%	20%	38%	43%	1%	23%
LAK023	1%	0%	0%	0%	1%	9%	7%	4%	12%	16%	1%	12%
LAK028	6%	6%	6%	7%	7%	18%	14%	8%	25%	32%	1%	24%
LAK042	5%	4%	5%	4%	3%	14%	11%	12%	20%	21%	2%	10%
LAK044	1%	1%	0%	1%	1%	4%	3%	2%	5%	8%	1%	6%
LAK016	2%	2%	2%	3%	4%	18%	14%	12%	24%	29%	2%	17%
DCAS14A	4%	4%	3%	3%	4%	43%	35%	28%	51%	59%	1%	31%
NC184	26%	25%	24%	27%	23%	34%	33%	32%	37%	40%	4%	8%
NC194	▨	▨	▨	▨	▨	49%	40%	34%	50%	60%	0%	26%

Scenario	SENSITIVITY - alternative baseline											
Post-KMP	2021-2023										2021-2023	
Baseline	2012-2014										2012-2014	
Metric	Gran ANC (imputed)	Gran ANC (imp+1SD)	Gran ANC (imp+2SD)	Gran ANC (imp-1SD)	Gran ANC (imp-2SD)	pH (imputed)	pH (imp+1SD)	pH (imp+2SD)	pH (imp-1SD)	pH (imp-2SD)	Gran ANC	pH
Thresholds	Lake-spec	Lake-spec	Lake-spec	Lake-spec	Lake-spec	∆ 0.3 pH units	∆ 0.3 pH units	∆ 0.3 pH units	∆ 0.3 pH units	∆ 0.3 pH units	Range (max-min)	
LAK006	1%	1%	1%	0%	1%	6%	3%	2%	11%	23%	1%	21%
LAK012	8%	5%	7%	10%	12%	13%	9%	4%	20%	30%	7%	26%
LAK022	33%	33%	31%	37%	35%	39%	26%	17%	53%	66%	6%	49%
LAK023	5%	4%	4%	5%	6%	2%	2%	1%	8%	17%	2%	16%
LAK028	20%	20%	17%	20%	22%	21%	12%	6%	36%	54%	5%	48%
LAK042	9%	6%	9%	8%	9%	20%	14%	9%	28%	35%	3%	26%
LAK044	3%	2%	1%	2%	2%	4%	3%	1%	11%	22%	2%	21%
LAK016	8%	6%	6%	8%	11%	32%	18%	13%	46%	66%	5%	53%
DCAS14A	3%	2%	4%	4%	4%	40%	32%	28%	48%	59%	2%	31%
NC184	22%	25%	24%	25%	26%	36%	32%	27%	40%	42%	4%	15%
NC194	▨	▨	▨	▨	▨	48%	40%	38%	54%	57%	0%	19%

SUMMARY OF EXCEEDANCES - *of LEVEL OF PROTECTION* (from statistical analyses)



Scenario	BASE CASE											
Post-KMP	2021-2023										2021-2023	
Metric	Gran ANC (imputed)	Gran ANC (imp+1SD)	Gran ANC (imp+2SD)	Gran ANC (imp-1SD)	Gran ANC (imp-2SD)	pH (imputed)	pH (imp+1SD)	pH (imp+2SD)	pH (imp-1SD)	pH (imp-2SD)	Gran ANC	pH
Thresholds	30.7 ueq/L	30.7 ueq/L	30.7 ueq/L	30.7 ueq/L	30.7 ueq/L	6.0 pH units	6.0 pH units	6.0 pH units	6.0 pH units	6.0 pH units	Range (max-min)	
LAK006	0%	6%	2%	6%	3%	28%	30%	5%	73%	94%	6%	89%
LAK012	0%	0%	0%	0%	0%	44%	36%	22%	71%	81%	0%	59%
LAK022	65%	76%	63%	65%	84%	75%	56%	34%	90%	97%	21%	63%
LAK023	100%	100%	100%	100%	100%	100%	66%	39%	100%	100%	0%	61%
LAK028	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%
LAK042	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%
LAK044	100%	100%	100%	100%	100%	100%	100%	99%	100%	100%	0%	1%
LAK016	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	2%
DCAS14A	0%	0%	0%	0%	0%	4%	1%	0%	12%	29%	0%	29%
NC184	48%	52%	64%	65%	66%	82%	72%	55%	87%	97%	18%	42%
NC194	100%	100%	100%	100%	100%	5%	2%	0%	10%	17%	0%	17%

Appendix 5: Lake-specific thresholds for *change limits* for CBANC

The lake-specific CBANC thresholds for the *change limit* are shown in the table below. The table and caption below are directly copied from Table 14 of the SO_2 EEM Program Phase III Plan.

Lake-specific thresholds for *change limits* in CBANC. Values calculated from analyses of the titration data, showing the change in CBANC associated with a pH decline of 0.3 pH units from the 2012 (or 2013 for control lakes) pH value for each lake. A lake-specific threshold cannot be estimated for control lake NC194 given limited data.

	EEM Group	Lake-specific CBANC threshold (μeq/L)
LAK006	Sensitive Lake	-10.8
LAK012	Sensitive Lake	-16.3
LAK022	Sensitive Lake	-11.5
LAK023	Sensitive Lake	-10.5
LAK028	Sensitive Lake	-13.4
LAK042	Sensitive Lake	-24.4
LAK044	Sensitive Lake	-6.2
LAK016	Less Sensitive Lake	-25.6
DCAS14A	Control Lake	-21.7
NC184	Control Lake	-10.8
NC194	Control Lake	n.a.

Appendix D: Technical Report of Lake Monitoring in 2023

The following pages contain the full **Rio Tinto BC Works SO$_2$ Environmental Effects Program: Monitoring of Lakes in 2023, Final Report**, in PDF format.

Citation: Limnotek. 2024. Rio Tinto SO$_2$ Environmental Effects Program: Monitoring of Lakes in 2023. Report prepared by Limnotek Research and Development Inc. for Rio Tinto Ltd. 62 pp.

Rio Tinto BC Works SO_2 Environmental Effects Program: Monitoring of Lakes in 2023

Draft Report

March 12, 2024

LIMNOTEK

Rio Tinto BC Works SO_2 Environmental Effects Program: Monitoring of Lakes in 2023

Draft Report

Submitted to

Rio Tinto BC Works Ltd.
Kitimat, B.C.

Prepared by

S. Bennett, MSc., RPBio. and C.J. Perrin, MSc., RPBio

March 12, 2024

Citation: Limnotek. 2024. Rio Tinto SO_2 Environmental Effects Program: Monitoring of lakes in 2023. Report prepared by Limnotek Research and Development Inc. for Rio Tinto Ltd. 62pp.

Cover photo: Allistair Lake (control lake DCAS14A) on September 30, 2023. Photo credit, Chris Perrin.

EXECUTIVE SUMMARY

Chemical measurements among selected lakes near Kitimat and Terrace, British Columbia were completed in 2023 as part of ongoing environmental effects monitoring (EEM) of SO_2 emissions from the Rio Tinto smelter in Kitimat . This lake sampling and analysis is the aquatic component of a larger EEM that also includes atmospheric SO_2 and acidic deposition, human health, vegetation, and soils. This report presents quality control measurements and selected limnological interpretations in support of the continued EEM program. Detailed analysis of the EEM data is presented in a separate report by ESSA Technologies Ltd. In addition to the on-going tasks, tasks were started in 2023 to characterize the trophic state of lakes that are potentially exposed to emissions as part of an initiative by Rio Tinto to consider cumulative effects of smelter emissions with expected emissions from the LNG Canada refrigeration plant that is under construction in Kitimat.

Quality assurance testing showed acceptable accuracy and precision among analytes, indicating continued excellent repeatability of sample handling and analysis procedures in 2023.

Positive blanks were found on two dates: sodium and total zinc in the October 10 blank, and dissolved copper, lead, and zinc in the September 27 blank. Concentrations of these analytes exceeded those in corresponding lake water samples, which has never happened before in the Rio Tinto EEM. Possible sources of contamination included metals on lab gloves used for water processing and/or cross contamination of preservative used in sulfide bottles affecting handling of the metals bottles. Arguments are presented to show these sources of error are remote but cannot be ignored. Recommendations are presented to reduce or eliminate these sources of error.

Two factors affect pH measurement among instruments that are operating correctly with new electrodes and sample bottles are filled without air space after capping. First is duration that a water sample is exposed to air before pH is measured and second is duration of electrode immersion in a water sample before pH is measured. Testing in 2023 along with evidence from earlier years showed that most accurate pH in north coast lakes is measured using an electrode immersion time of close to 10 minutes and use of the shortest duration possible between the time a water sample is exposed to air after uncapping and a stable pH value is recorded. Longer periods of exposure to air results in upward bias in pH due to degassing. Using these criteria, a ranking of pH instruments/lab methods from shortest time sample was exposed to air before measurement and longest time of electrode immersion to longest time sample was exposed to air before measurement and shortest time of electrode immersion in 2023 was in situ pH logger (Onset) > WTW field pH meter > pH measured at a lab at the University of Alberta (called BASL) > ALS Environmental in Burnaby, B.C. using a 10-minute electrode immersion time > ALS using a 3-minute electrode immersion time. At ALS the exposure time was greater using the 3-minute exposure period due to delays in large numbers of samples held in cues for automated analysis compared to a 10-minute electrode immersion time that is a manual method using shorter air exposure periods. Those ALS data are not considered useful for tracking long term change in pH because of the upward bias. In contrast, pH among the other instruments/labs was often not significantly different and are all considered reliable for long term trend analysis. BASL data has been used by ESSA for this purpose in past years and can continue to be used based on tests using the 2023 data. The WTW field instrument data has the longest

record in the EEM and can also be used for analysis of temporal and spatial change in pH among the EEM lakes with confidence that the data are reliable and accurate.

New measurements and analytes were introduced in 2023 to track meromixis in LAK028, a condition originally detected in 2017. Meromictic lakes contain strata that do not mix. A bottom layer, called the monimolimnion, has little to no oxygen and high solute content. LAK028 does not have a complete monimolimnion but rather a chemocline having characteristics of a monimolimnion (high conductivity, anoxic, reduced sulfur, high nutrient concentrations). While meromixis infers inherent stability, detection of what might be rare endogenic mixing is needed to prevent confounding in data from surface water that is used by ESSA in analysis of time course change in acid loading. Expanded measurements in 2023 compared to 2022 included year-long high frequency conductivity and temperature logging (including under ice in winter) using a mult-sensor mooring. Wet chemistry measurements of key analytes from the surface and at a depth of 13 m continued in 2023 as was done in earlier years. Results showed continued meromixis (stable and continuous chemical stratification) with overlaid dimictic mixing of the mixolimnion (layer above the chemocline). The chemocline was confined closer to the sediments in 2023 compared to earlier years. The cause of this change is unknown. Findings showed that data describing surface water chemistry for the EEM in 2023 was not confounded by mixing of chemically different water associated with meromixis in LAK028.

A new measurement called “trophic state” was added to the lake data in 2023 to begin collating background evidence of sensitivity of lakes to change in nitrogen loading that is expected following startup of the LNG Canada refrigeration plant in Kitimat in 2025. Trophic state is an indicator of water quality in lakes and an overall measure of biological production. It can be quantified in an index called a trophic state index (TSI) that is scaled from 0 to 100 where 0 is high water quality and called oligotrophic to 100 that is very poor water quality and is called eutrophic. It is based on concentrations of chlorophyll-a (a direct measure of algal biomass) and nutrients. Trophic state data are needed for analysis of cumulative effects in lakes in relation to Rio Tinto smelter and LNG Canada emissions. Cumulative effects are being examined in a separate project. Preliminary TSI values based on data from only part of the biological growing season showed that lakes being sampled for the EEM are oligotrophic to mesotrophic (a moderate condition between oligotrophic and eutrophic), which shows high water quality. TSI’s from once per year sampling of lakes (end of September or early October) since the beginning of the EEM 10 years ago showed no time course change in trophic state. These TSI values cannot be compared to other published values because they are not from the complete eutrophic zone (surface layer where photosynthetic biological production occurs) over a complete growing season, which is standard in trophic state measurements. They can, however, be used within the EEM to examine relative change over time and space as long as methods are consistent.

Eleven recommendations emerged from the 2023 EEM to be considered in future monitoring. They are highlighted in boxes in the discussion and recommendations section following text that develops a rationale for each point. Application of these recommendations will ensure continued high-quality data for the Rio Tinto EEM of lakes in relation to SO_2 emissions and for analysis of cumulative effects in relation to the pending emissions from the LNG Canada refrigeration plant, both located in Kitimat, British Columbia.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

At the end of March 2016, Rio Tinto completed modernization of its smelter in Kitimat, British Columbia to increase production of aluminum. The modernization, hereafter called the Kitimat Modernization Project or KMP, increased emissions of SO_2 , which could potentially change the acidity of precipitation affecting downwind watersheds and communities, including Terrace, Kitimat, and Kitamaat Village (village of the Haisla Nation). ESSA et al. (2013a) estimated that the acidic deposition may exceed the critical load of acidity for some lakes. Critical load (CL) is defined as “a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge” (Nilsson and Grennfelt 1988). An environmental effects monitoring program (EEM) was developed by ESSA et al. (2013b) in consultation with representatives of Rio Tinto, the Haisla Nation, and the BC Ministry of Environment. The monitoring plan was implemented and has been ongoing annually. It included indicators of atmospheric SO_2 and acidic deposition, SO_2 thresholds for human health, vegetation, soils, water chemistry, and aquatic biota. In the water and aquatic biota component, indicators included charge balance ANC (CBANC) as a Key Performance Indicator (KPI), and a set of informative indicators (Gran ANC, base cation surplus (BCS), pH). Additional indicators (dissolved organic carbon (DOC), and the concentration of major anions and cations) are used to perform QA/QC checks and evaluate year on year changes (ESSA 2022). The focus of annual water monitoring has been on lakes potentially exposed to acid deposition. Chemical measurements in streams downstream of a lake closest to the smelter have also been conducted, but less frequently than the lake sampling. In 2015, the annual water sampling expanded to include three control lakes (called DCAS14A, NC184 and NC194) that are not within the smelter-influenced airshed. A comprehensive review of the EEM data collected during 2013 – 2018 showed no evidence of exceedances of pH or ANC thresholds (ESSA et al. 2019). This outcome showed that ambient base cation supply was sufficient to offset acid loading among lakes and streams of local drainages affected by smelter emissions, thus limiting change in ANC and pH.

This report presents measurements collected from lakes that were sampled in 2023 in support of the continued EEM program. In addition to the on-going tasks, sampling was added to begin to characterize the trophic state of lakes that are potentially exposed to emissions as part of an initiative by Rio Tinto to consider cumulative effects of smelter emissions with expected emissions from the LNG Canada refrigeration plant that is under construction in Kitimat (ESSA 2024) . The LNG plant emissions are expected to include nitrogen oxides thus increasing loading of nitrogen to downwind lakes and streams. Nitrogen loading can contribute to biological production in lakes and streams, leading to poor water quality where other nutrients are abundant (Wetzel 2001). Ten tasks were as follows:

1. Annual water sampling of 12 lakes completed on September 30, 2023 followed by analytical chemistry. The sampling was completed , using helicopter sampling

techniques that were developed in early years of the EEM by Limnotek. The lakes included seven *acid-sensitive* lakes (LAK006 (End Lake), LAK012 (Little End Lake), LAK022, LAK023 (West Lake), LAK028, LAK042, and LAK044), one *less acid-sensitive* lake (LAK016), three *control* lakes (DCAS14A, NC184, NC194) and one non-EEM lake (LAK027 Bowbyes Lake, added at the request of BC Environment).

2. Monthly sampling in May through September 2023 to provide data for later analysis of spring and summer variability among chemical analytes in LAK006 (End Lake) and LAK028 and to describe their basic limnology. These two selected lakes were representative of acid – sensitive lakes in the study area.
3. Addition of three sampling episodes in late September through late October for later analysis of variability among chemical analytes during the fall sampling period in LAK006, LAK012, LAK023, LAK028, LAK042, and LAK044. This sampling supplemented the annual EEM sampling in Task 1.
4. Quality assurance testing of the 2023 water chemistry results.
5. Time course monitoring of pH and water level using data loggers in LAK006 and LAK028 in May through October 2023 to supplement Task 2.
6. Full year temperature monitoring at several depths in LAK028 from October 15, 2022 through to the end of October 2023. This sampling started in 2018 to examine physical differences between surface and bottom layers in LAK028 that are associated with meromixis that was detected in 2017.
7. Operation of a pH logger at the surface and bottom of LAK028 and a pH logger near the surface in LAK006 to examine seasonal variation in pH and provide insight into meromixis in LAK028.
8. Full year conductivity monitoring at several depths in LAK028 from October 15, 2022 through to October 15, 2023 to examine and interpret long term physical stability of the chemocline.
9. Maintenance of an instrument raft on LAK028 (Figure 1). The raft supported temperature and pH moorings. Tripods that were secured to the raft deck hosted air samplers that were part of the SO_2 sampler network in the Terrace-Kitimat valley (ESSA et al. 2022).
10. Sampling of chlorophyll-*a* in the eutrophic zone of lakes was added for use in characterizing the trophic status of lakes. Measurement of chlorophyll-*a* concentration was included during late September and early October sampling episodes in LAK006, LAK012, LAK023, LAK028, LAK042 and LAK044 (Task 3) and during the annual sampling of all lakes on September 30, 2023 (Task 1).

All data were supplied to ESSA Technologies Ltd. to update analyses needed for the EEM program.

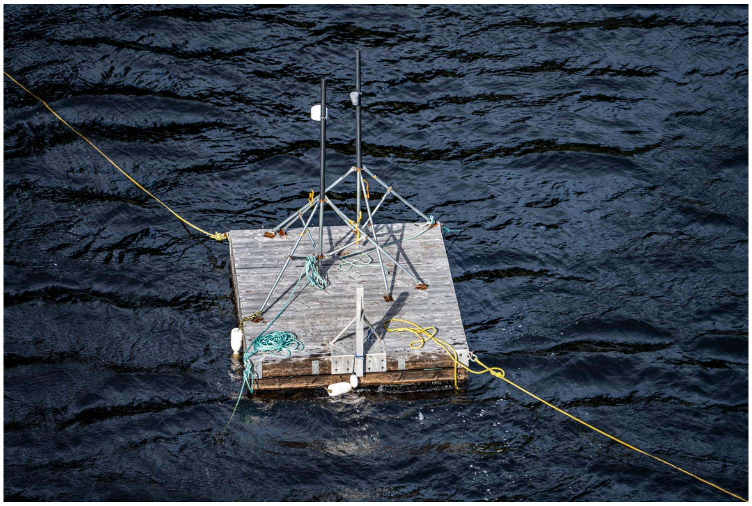

Figure 1. Image of the instrument raft on LAK028 in 2022. The raft did not change in 2023. The temperature and conductivity moorings and pH loggers (surface and bottom) were suspended from the raft. The tripods supported air sampling equipment that is reported by ESSA et al. (2022).

2 METHODS

2.1 Sampling sites

Twelve lakes were included in 2023 EEM following recommendations by ESSA et al. (2020a) and BC Environment (Table 1). The lakes included seven *acid-sensitive* lakes (LAK006 (End Lake), LAK012 (Little End Lake), LAK022, LAK023 (West Lake), LAK028, LAK042, and LAK044), one *less acid-sensitive* lake (LAK016), three *control* lakes (DCAS14A, NC184, NC194) and one non-EEM lake (LAK027 Bowbyes Lake) (Figure 2). Bowbyes Lake (LAK027) was added in 2021 following a request from BC Environment to sample another lake in the high SO_2 deposition zone.

Table 1. List of 11 EEM lakes and one non-EEM lake sampled in 2023.

Number of water body	Lake or stream name	Lake area (ha)		Lake designation[a]	UTM zone	Easting	Northing	Sampling activity in the EEM program[b]
LAK006	End Lake	10.25		Sensitive	9U	524155	6020661	SWC, F
LAK012	Little End Lake	2.30		Sensitive	9U	524145	6021028	SWC, F
LAK022		5.74		Sensitive	9U	524185	6022796	SWC
LAK023	West Lake	6.77		Sensitive	9U	522750	6018850	SWC, F
LAK028		1.02		Sensitive	9U	519139	5993425	SWC[c]
LAK042		1.46		Sensitive	9U	520911	6048362	SWC
LAK044		2.01		Sensitive	9U	522541	6050321	SWC, F
LAK016		2.58		Less sensitive	9U	523347	6018243	SWC, F
DCAS14A	Allistair Lake	717.2		Control	9U	488170	5994898	SWC
NC184		6.8		Control	9U	512321	5933333	SWC
NC194		35.6		Control	9U	522119	5949616	SWC
LAK027	Bowbyes Lake	19.5		Non-EEM lake	9U	518232	5995394	N/A

a. There are three sets of lakes in ESSA et al (2020a) defined as: **“*Less sensitive lakes”***. *These lakes were expected to show changes in lake SO_4^{2-} if exposed to increased deposition of S, but no biologically significant changes in pH of Gran ANC due to their greater ability to neutralize acidic deposition,* ***Sensitive lakes:*** *seven lakes that were predicted in the STAR to decrease in pH >0.1 units under maximum future emission levels, and* ***Control lakes****: three sensitive lakes located well outside of the deposition plume from Rio Tinto. The control lakes were added in 2015 but had sampling data from 2013 KAEEA program[1].”*

b. EEM sampling activities have included surface water chemistry (SWC) and fish (F)

c. Fish sampling was conducted in LAK028 in 2017 but it was not part of the original EEM program.

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[1] ESSA et al 2014

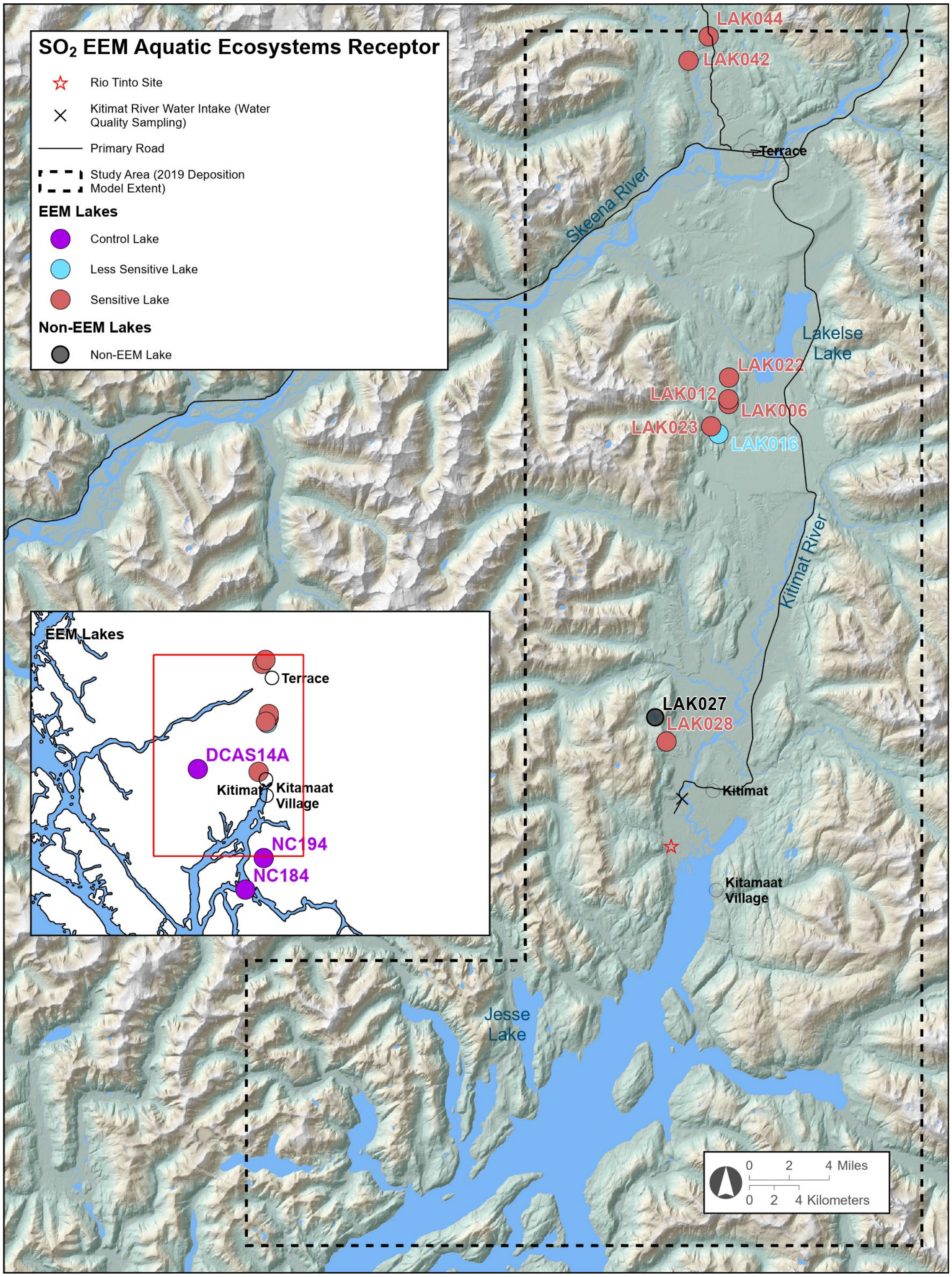

Figure 2. Layout of 12 lakes sampled in 2023.

2.2 Single date annual lake water sampling, 2023

The one – day annual sampling of the EEM lakes was completed on September 30, 2023. At each lake, instruments were deployed, and water was collected from a Twinstar helicopter in a hover position approximately 4 m above the water surface using a crew of three people plus the pilot. The crew leader in the front seat recorded data on a standard field sheet, took site photos, double-checked the global positioning system (GPS) waypoint location, and provided overall direction of sampling activities. The other two crew members worked together in the back seat to take instrument readings and collect the water samples. The pilot made all decisions related to safety. Crew members and the pilot were always in communication via headsets. Lab-supplied nitrile gloves were worn by crew members handling the instruments and water bottles.

The following sampling procedure was followed at each lake. As the helicopter approached a lake, the crew leader (front seat) provided the pilot with general guidelines about where the sampling station should be located, which was usually at an expected deep point, based on lake morphometry. The pilot decided on the actual location. Station coordinates from the helicopter GPS were logged on the field form. Once on station in a stable hover, the sliding back door of the helicopter was opened, a weighted transducer was lowered into the lake just under the water surface and the water depth and temperature was measured using a Lowrance Mark-5X portable depth sounder. The sounder transducer was retrieved. The data were recorded on a field sheet (Table 2). A 5 L VanDorn water bottle (Wildlife Supply Co. Yulee, FL) was lowered to a depth of 1 m, triggered with a messenger to collect a water sample and retrieved.

At LAK028, a second water sample from a depth of 13 m was also collected by helicopter in three steps. A 13 m depth mark was placed on the haul line. The Van Dorn water bottle was lowered to the point where the 13 m mark on the haul line was at the water surface. The messenger for the Van Dorn was then released to trigger the closing mechanism on the Van Dorn, which was then hauled back into the helicopter. This method resulted in the collection of a sample from a depth of approximately 13 m based on the haul line mark. Due to movement of the helicopter in a hover position, that sampling depth may have been plus or minus 1m.

Samples at all lakes were dispensed from the VanDorn bottle into the following bottles on board the helicopter:

- two 250 mL pre-cleaned polyethylene bottles,
- one 125 mL precleaned amber glass bottle precharged with sulfuric acid preservative (H_2SO_4),
- two precleaned 125 mL polyethylene bottles,
- one 1 L precleaned polyethylene bottle,
- one 500 mL precleaned polyethylene bottle, and

- At LAK028 only, an additional 60 mL polyethylene bottle pre-charged with preservative (sodium hydroxide and zinc acetate) was filled.

After filling all bottles at a given lake, the sample bottles were placed in a plastic bag labelled with the lake number and packed on ice in a cooler that was carried in the helicopter skid basket. At the end of the day of sample collections, water samples from each site were handled as follows:

- H_2SO_4 preserved sample in the 125 mL amber glass bottle was packed on ice, and shipped to ALS Environmental in Burnaby, B.C. for fluorometric analysis of NH_4-N concentration, total phosphorus (TP), and total nitrogen (TN) by standard methods (APHA 2011).
- Sample in one of the 125 mL polyethylene bottles was preserved with HNO_3 by dispensing the HNO_3 contents of a plastic vial prepared by the lab into the sample bottle. The sample bottle was packed on ice with other samples from the day of sampling and shipped to ALS for analysis of total base cation (Ca, K, Mg, Na, Sr, Al, Mn, Fe) concentrations using inductively coupled plasma – mass spectrometry (ICPMS).
- From the second 125 mL polyethylene bottle, ALS analyzed pH using a revised method for low ionic strength waters, as requested by Limnotek in 2020. This method was identical to the standard pH method (see below) with the exception that the instrument did not time out after 3-minutes but was allowed to stabilize for up to 10-minutes before a pH value was recorded. Field tests in 2019 showed that immersion of the electrode for 10-minutes provided stable pH readings (Limnotek 2020).
- Sample in the 60 mL polyethylene bottle that was pre-charged with sodium hydroxide and zinc acetate preservative (collected at LAK028 only) was packed on ice and shipped to ALS for analysis of total sulfide (as H_2S and S) by colourimetry (APHA 2011).
- The first 250 mL polyethylene bottle was packed on ice and shipped to Biogeochemical Analytical Service Laboratory (BASL) at the University of Alberta in Edmonton, Alberta, for analysis of pH and Gran ANC by titration on a PC-titration Plus system (https://mantech-inc.com/analysis-systems/automated-titration-analysis/). Detailed methods for this procedure are available upon request. Note that prior to 2020, these samples were shipped to Trent University in Ontario. After a cross-lab comparison using paired samples collected in October 2019 (Limnotek 2020), this transition from Trent to BASL was implemented in 2020. The change in labs was due to Trent not having the capacity to provide lab services beyond 2019.
- The second 250 mL poly bottle was packed on ice and shipped to ALS for analysis of anion (HCO_3, Cl, SO_4, F, NO_3-N) concentrations by ion chromatography, total dissolved solids by gravimetric analyses, specific

conductivity using an automated bench top conductivity meter, soluble reactive phosphorus (SRP) by standard methods (APHA 2011), and pH using a Skalar Sp2000 auto-titrator system (https://www.skalar.com/analyzers/sp2000-robotic-analyzers-turnkey-or-custom-made-automation-solutions/) or a Metrohm 848 Titrino Plus system (https://www.metrohm.com/en/products/titration/titrino-plus/28480010). The Metrohm system included stirring of the sample during pH measurement. These instruments recorded a stable signal if the pH changed less than 0.05 pH units in five consecutive readings that were five seconds apart. The instruments timed out after 3-minutes, which means that even if a stable signal was not found before 3-minutes of electrode immersion, a pH value was recorded.

- A 250 mL aliquot was measured into a graduated cylinder from the 500 mL polyethlylene bottle. In 50 mL aliquots, the water was filtered through a 0.45 µm nitrocellulose filter using a vacuum hand pump and a Swinnex apparatus to collect phytoplankton biomass for analysis of chlorophyll-a concentration. Care was taken to limit light exposure of the chlorophyll-a samples during storage and handling of water samples. The filter was removed with tweezers, folded twice and placed into a labelled opaque centrifuge tube, capped and placed on ice for shipping to ALS for measurement of chlorophyll-a concentration by fluorometry (EPA Method 445.0; Arar and Collins 1997).
- Aliquots from the 1 L polyethylene bottle were handled as follows:
    - At the field lab in Terrace, B.C. a 40 mL aliquot was dispensed in smooth flow without bubbles to a 50 mL polyethylene flask pre-rinsed with sample water for immediate pH measurement using a WTW ProfiLine 3210 Portable pH meter equipped with a Sentix 41 pH combination electrode (Xylem Analytics, Weilheim, Germany) prior to any other aliquots being dispensed to avoid degassing of CO_2 from the sample prior to pH measurement. This field pH measurement followed procedures in EPA method 150.3 (EPA 2017) that is followed by the Canadian federal agencies (*e.g.* https://www.canada.ca/en/health-canada/services/publications/healthy-living/guidelines-canadian-drinking-water-quality-guideline-technical-document-ph.html#a42 , CCME 2011). No stirring of the sample was done during electrode stabilization to avoid degassing of CO_2 from the samples as recommended by Busenberg and Plummer (1987) for measurement of pH in very low conductivity waters. The field pH meter was equipped with a new electrode on May 27, 2023, before the start of field sampling.
    - A 125 mL aliquot was filtered (0.45 µm) and preserved with HNO_3, packed on ice, and shipped to ALS for analysis of dissolved base cation (Ca, K, Mg, Na, Sr, Al, Mn, Fe) concentrations using ICPMS.

- A 125 mL aliquot was filtered (0.45 µm) and shipped to ALS for analysis of dissolved inorganic carbon (DIC) by combustion (APHA 2011).
- A 125 mL aliquot was filtered into a pre-charged glass amber bottle (H_2SO_4), packed on ice, and shipped to ALS for analysis of total dissolved phosphorus (TDP) and dissolved organic carbon (DOC) concentration by standard methods (APHA 2011).
- All filtrations were done using a Sartorius Minisart® syringe filter (28 mm, 0.45 µm Hydrophilic Teflon DIGIFilter) in a filtration stand (Figure 3).

Figure 3. Example of a filtration stand for use in minimizing user contact with the syringe plunger during water filtrations in the field. Image source: “ALS EnviroMail 06 December 2017. Best practices to prevent false positives and negatives for dissolved metals”. Note that vinyl gloves are preferred over nitrile gloves that may host metals contamination.

Measurements of descriptive variables were compiled on a field data at each lake. The listing of these variables and how they were measured is provided in Table 2. These data provided supportive evidence of lake conditions that could later assist with interpretation of lake water chemistry.

Table 2. List of descriptive variables and associated methods of calculation that were recorded on the field data sheet.

Habitat or other descriptive variable	Units	Description and method
Lake name	No units	Station label
Site ID	No units	Preassigned site identification number
Date	No units	Date of sampling
Time on station	24-hour clock	Time of arrival at station
Time off station	24-hour clock	Time of departure from station
Field Crew	No units	Names of field crew
Northing	UTM	UTM northing recorded with a Garmin GPSmap 76CSx GPS receiver
Easting	UTM	UTM easting recorded with a Garmin GPSmap 76CSx GPS receiver
Weather	No units	Coding for present conditions and conditions in past 24 hours and past week
Riparian Vegetation	%	Estimate (%) of each type, totaling 100% including: unvegetated, grasses/ferns/herbs, shrubs, deciduous forest, coniferous forest, and wetland
Water depth at sampling station	m	Water depth at the sampling station measured using the Lowrance Mark-5XDSI portable depth sounder.
Water sample depth	m	Depth of sample collection recorded from the calibrated line used to deploy the VanDorn water bottle.
Temperature	ºC	Instantaneous surface temperature in all lakes measured with the Lowrance Marck 5XSDI portable depth sounder.
pH	Relative units	Measurement taken with the WTW ProfiLine 3210 Portable pH meter in a field lab on the day of sample collection from each lake. The WTW meter was calibrated with fresh pH buffers on the day of measurement.
Secchi depth[a]	m	A black and white disc (Secchi disc) is lowered on the shaded side of the boat until it is no longer visible. The depth is on the haul line is noted. The disc is then slowly raised until it is visible again. The depth on the haul line is noted. The average of the two depths is the Secchi depth.

a. Secchi depth was added to the field sheet on September 25th, 2023. It was measured during work conducted from the boat, not during work conducted from the helicopter.

2.3 Time course lake water sampling, 2023

2.3.1 Overview

Time course sampling of selected lakes (specified in following sections) was done during spring through fall, 2023 to provide data for later analysis by ESSA Technologies. The lakes included LAK006, LAK012, LAK023 LAK028, LAK042, and LAK044. All lakes were sampled at the surface except LAK028 where samples were collected from both surface and 2 m off bottom. The added sampling at LAK028 was done to describe meromixis that was not present in the other lakes.

Chlorophyll-a analysis was added to lake water sampling on or after September 25th, 2023, following decisions by Rio Tinto to engage in sampling to address uncertainties about algal biomass (measured as chlorophyll-a concentration) as needed for a forthcoming assessment of cumulative emissions from Rio Tinto and pending emissions from LNG Canada. Chlorophyll-a samples were collected from the top, bottom, and midpoint depth of a lake euphotic zone where euphotic depth was approximated as twice the Secchi depth, a standard measure of water transparancy (Wetzel 2001). Secchi depth was the average depth at which a standard 20 cm white and black Secchi disc dissappeared upon lowering and reappeared upon raising from the shaded side of the boat. Aliquots of 150mL were collected from each depth using the VanDorn bottle. The three aliquots were mixed and 200 mL was filtered through a 0.45 µm, 47 mm diameter membrane filter using a vacuum pressure differential of <100 mm of Hg. The filter with retained biomass was placed into a labelled 15 mL opaque centrifuge tube with screw top closure, packed on ice, and delivered to the lab for analysis of chlorophyll-*a* concentration by extraction in acetone followed by measurement of fluorescence as described by Arar and Collins (1997). This analytical procedure was the same as used for the chlorophyll-a samples that were collected from the surface of all lakes during the single date annual sampling described in Section 2.2.

An Onset (Bourne, MA) MX2501 pH and temperature logger (hereafter referred to as an “Onset”) was installed at a water depth of 2 m in LAK006 and at depths of 2 m and 13 m in LAK028 during 2023 to continuously record pH. Data from the deep Onset in LAK028 assisted with continued interpretation of meromixis that was detected in 2017. Prior to 2021, electrodes were changed every 2-3 months in the field. However, field replacements of electrodes during rainy or damp weather may allow moisture into electronics of the instrument. In 2023, two new instruments were ordered at the beginning of the year for each station along with multiple replacement electrodes. Brand new instruments were installed in each lake at the beginning of the year and every two months, new electrodes were installed on spare instruments the day prior to the field visit, and the whole instrument was replaced on the field day. All loggers had an anti-biofouling ring on the pH electrode, which prevented growth of a biofilm on the electrodes. Methods for the water sampling at all lakes and lab procedures are described in the following sub-sections.

2.3.2 LAK028

Time course water sampling of LAK028 occurred on May 16, June 19, July 17, Aug. 18, Sept. 11, Sept. 26, Oct. 10, and Oct. 16, 2023. Access was by truck off the Wedeene forest service road (FSR) for 2 km until the Mt. Claque trailhead. From there, the field crew hiked 750 m up the steep Mt. Claque trail and then another 550 m from the Mt. Claque trail to the edge of LAK028. Once at the lake, the crew unlocked and launched a 12 foot aluminum Marlon jon boat from the lake edge (which had been slung into LAK028 via helicopter and received by the Limnotek field crew in October 2016) and paddled to the centre of the lake where the raft was anchored. The boat was tied to the raft for water sampling and servicing of instruments. On all samping dates, water samples were collected from the surface and 13 m (roughly 2 m off bottom) using a Van Dorn sampler. Sampling depth was exact using this method. On all dates, the water samples were analyzed for all parameters described in Section 2.2.

On the last 3 sampling dates, three equidistant euphotic zone aliquots of water were collected, mixed, shipped, and analyzed for chlorophyll-a concentration using procedures described in Section 2.3.1

On each sampling date, temperature, specific conductivity, turbidity and dissolved oxygen concentration profiles were completed using a YSI ProDSS multiparameter water quality meter that was calibrated on the day of use. After a 10-minute electrode stabilization period at the surface, the instrument was lowered at a rate of 20 $cm \cdot s^{-1}$ from the raft until it reached the lake bottom, while logging readings once every 1 second to instrument memory. Logged data were uploaded to a computer on the day of sampling.

Scripts in R (www.**r**-project.org) were used to produce colour filled three dimensional plots of the temperature, conductivity, dissolved oxygen and turbidity profiles over time from those profiling data. Depth of the thermocline during stratification and chemocline was captured from these images as the range of depths where water temperature or other physical attributes changed more rapidly with depth than it did in stable layers above and below.

After each day of water sampling, the boat was pulled out of the water and locked to a tree. The crew hiked out with the water samples, which were packed on ice in a soft cooler nested in a backpack. The total return trip time from the parking area on the Wedeene FSR was 5 hours. After the final sampling event in 2023, the boat was chained and locked to a tree in an upright, inverted position to shed snowfall.

A temperature mooring was installed in LAK028 in 2019 to examine mixing patterns needed to interpret potential interaction between meromixis and surface water chemistry that was used for interpretation of time course change in pH and Gran ANC. Ten Onset TidBit temperature loggers were distributed from surface to bottom on a vertical line that was attached to the raft and weighted with a 10 lb. dumbbell. Logger depths (m) were 1, 3, 6, 8, 9, 10, 11, 12, 13, and 14 m. The mooring and loggers were installed on June 13, 2019. Data were recorded in 30-minute intervals. Temperature loggers were replaced with new loggers in July, 2022. In 2023, data were uploaded from the temperature loggers on May 15, Sept. 26 and on Nov 5 before the line was reset for the winter. Each winter since 2019, the temperature mooring has been set up independent from the raft using a weighted line and floats to overwinter in the centre of the lake.

On May 15, 2023 an Onset pH logger was clipped onto the mooring at a depth of 2 m and another at 13 m. Pre-and post-calibration checks were performed and calibrations were conducted on each sampling date using a two point calibration with standard buffers of pH 4 and 7 via a bluetooth application on a cell phone. The loggers were removed at the end of sampling on November 5, 2023, and data were uploaded to computer. The logger electrodes were cleaned using a Q-tip at the time of calibration if needed. Battery replacement on the Onsets was not required.

A conductivity mooring consisting of one logger situated at each of 1, 8, 10, 12, and 14 m on a vertical line was installed in July, 2022. Logger data were downloaded and loggers reinstalled on October 17, 2022 to overwinter on the same mooring as the temperature loggers. The conductivity loggers were removed on May 15, 2023, data were uploaded at the field lab, and loggers were reinstalled on May 16, 2023 with logging interval set to once every 30 minutes on all loggers. The loggers were removed for downloading a second time on Oct. 16 and reinstalled on Oct. 17, 2023. The conductivity loggers shared the same vertical line as the temperature loggers which was set up independent from the raft using a weighted line and floats to overwinter in the centre of the lake.

2.3.3 LAK006 (End Lake)

Time course water sampling of End Lake (Figure 4) occurred on May 17, June 20, July 18, Aug. 15, Sept. 12, Sept. 27, Oct. 9, and Oct. 15. Access was by truck and sampling was done from a 10 foot long inflatable boat equipped with 2.2hp outboard engine. Water samples were collected from the surface using a Van Dorn bottle and were analyzed for all parameters described in Section 2.2. On the last 3 sampling dates, three equidistant euphotic zone aliquots of water were collected, mixed, shipped, and analyzed for chlorophyll-a concentration using procedures described in Section 2.3.1

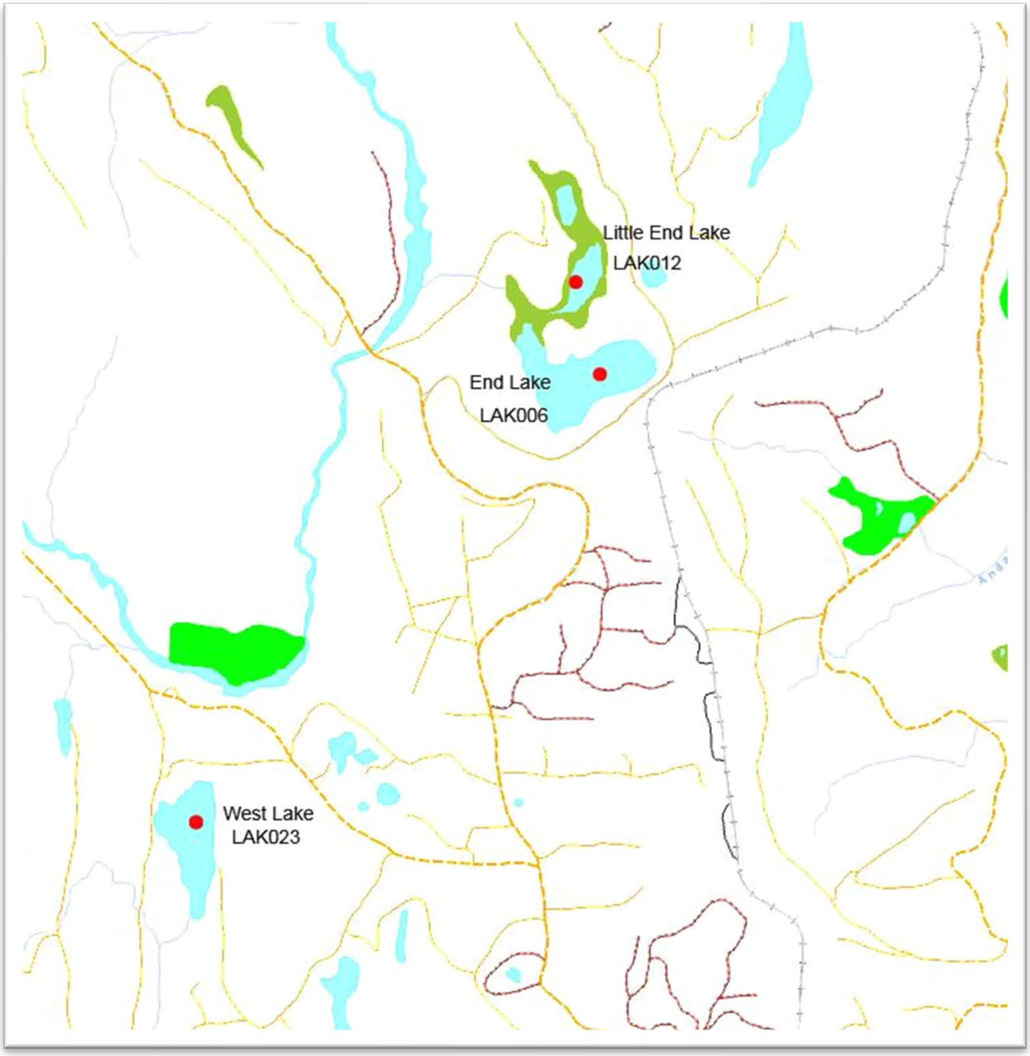

Figure 4. Location of End Lake (LAK006), Little End Lake (LAK012) and West lake (LAK023) with water sampling locations shown as red solid circles. General location of the lakes is shown in Figure 2. The yellow dotted lines represent roads or ATV trails.

An Onset pH logger was installed on a submerged mooring line in LAK006. Weights anchored the mooring. The line length was 1 m less than water depth at the chosen site. The line was held vertical through the water column with submerged floats. The Onset was attached to the line 1 m beneath the floats using a locking carribiner. During instrument calibrations that occurred on each of the water sampling dates, the submerged floats were captured using a boat hook, pulled to the surface, and another float was clipped onto the vertical mooring using a tag line. This arrangement allowed easy access to the mooring for redeployment of the instruments after calibration on the boat.

For servicing on each visit, the Onset logger was clipped off the mooring line, pre- and post-calibration checks were run using solutions of known pH, data were downloaded, and a two point calibration was run using standard buffers of pH 4 and 7 via a bluetooth application on a cell phone as was done in LAK028 (2.3.2). All this was done on the boat.

On each sampling day, temperature, specific conductivity, turbidity and concentration of dissolved oxygen was measured over the water profile using a YSI ProDSS handheld multiparameter water quality meter, as was done in LAK028 (section 2.3.2). Again, scripts in R (www.**r**-project.org) were used to produce colour filled three dimensional plots of the temperature, conductivity, dissolved oxygen and turbidity profiles over time from those profiling data. Depth of the thermocline during stratification was captured from these images as the range of depths where water temperature or other physical attributes changed more rapidly with depth than it did in stable layers above and below.

2.3.4 LAK012, LAK023, LAK042, and LAK044

Time course water sampling of LAK012 and LAK023 occurred on Sept. 27, Oct. 9 and Oct. 15 and at LAK042 and LAK044 it occurred on Sept. 25, Oct. 11 and Oct. 18, 2023 (Figure 4). Access to LAK042 was via a spur road to a wood waste dump off the Kalum West FSR approximately 7 kilometers north of Hwy 16. A small inflatable boat, paddles and PFD's were carried down to the lake along with the water sample bottles and sampling equipment (roughly 300 m). The boat was launched from the edge of the lake and paddled out to the centre, where water samples were collected. Following collection of the samples, the gear and boat were packed back to the truck. Access to LAK044 was by truck and then by hiking 40 meters with the inflatable boat. The crew paddled the boat to the centre of the lake, where water samples were collected. Access to LAK012 and LAK023 was by truck close to the lake shore. Sampling was done from a depth of 2 m using the VanDorn water bottle and all water samples were analyzed of the full suite of analytes described in Section 2.2. On the last 3 sampling dates, three equidistant euphotic zone aliquots of water were collected, mixed, shipped, and analyzed for chlorophyll-a concentration using procedures described in Section 2.3.1

2.4 Quality of chemical data

2.4.1 Blanks and duplicates

A blank and blind duplicate water sample were collected on each sampling date for calculation of precision and accuracy. Blanks were deionized water provided by ALS Environmental and handled the same way as all test samples including water transfers to sample bottles, filtrations, storage, and shipping. Duplicates were water samples collected from a randomly selected station on each sampling date and again handled the same way as test samples. The presence of cations and anions in the blank samples indicated contamination during sample processing and the chemical concentration showed the amount of contamination.

2.4.2 Precision

Precision (D_f) was calculated as relative percent difference of an analyte concentration between a sample and its corresponding duplicate using the following equation recommended by the BC Field Sampling Manual (2013):

$$D_f = \left(\frac{A-B}{(A+B)/2}\right) * 100 \qquad \text{Equation 1}$$

where A is the concentration of an analyte in sample A and B is the concentration of the same analyte in the duplicate sample. The measurement of precision was associated with field and lab processes because it integrated sample collection, processing in the field, transport to the lab, and processing of samples in the labs.

2.4.3 Accuracy

Lab accuracy was tested by calculating percent recovery on solutions of known concentrations. Accuracy was determined as percent recovery (R_p) according to the following equation:

$$R_p = \left(\frac{B}{A}\right) * 100 \qquad \text{Equation 2}$$

where B is the recovered concentration and A is the known concentration of a given analyte in a solution. A solution containing the known analyte concentration was prepared in each lab using inorganic standards. The average value from up to 9 separate spiked samples was used to show average percent recovery from known standards of each cation and anion. Tests of percent recovery were limited to analytical values that were more than five times greater than the method detection limit, where the method detection limit was the concentration above which there was a high probability that a substance could be detected, following procedures reported by the BC Field Sampling Manual (2013).

2.5 Handling effects on pH measurement

2.5.1 Effect of electrode immersion time on pH at the ALS lab

Paired water samples were collected from all sites and dates to continue analysis of the effect of electrode immersion time on pH at ALS. Each sample pair was dispensed from the same water sample collected with the VanDorn into two separate bottles. Both bottles were shipped to ALS, where each of two methods were used to measure pH. First was the standard automated method in which the instrument timed out after 3 minutes whether a stable pH reading was attained or not. The second method forced a 10-minute electrode stabilization period. The 10-minute period was based on results by Limnotek (2020) with the field pH meter that showed that up to 9 minutes was needed for electrode stabilization in low ionic strength sample waters. The Shapiro-Wilk test was run to test for normality of the sample distribution. If significant (*p*<0.05), the non-parametric Wilcoxon test was used to test for significance of paired differences. If the Shapiro-Wilk test was not significant, a paired t-test was run to test for significance of paired differences. There was no control for this test (no known values of pH for each pair). Therefore, if the test showed a method effect on pH, the assumption was that the pH values using the new method allowing a longer time for electrode stabilization would be more accurate than the standard method. If the test for paired differences was not significant ($p<0.05$), there would be no evidence to support use of the longer electrode immersion times for measurement of pH at ALS. If the P value for a paired t-test or Wilcoxin test was less than 0.05, the mean difference between paired values reported by the two methods that were contrasted was considered significantly different from zero. The statistical analyses were run in R (R Core Team 2022).

2.5.2 Onset pH electrode drift

Output drift of a pH electrode was examined on each of the Onsets. Drift was the difference between observed and expected pH values following a period of operation. The expected value was the pH in a standard buffer solution of pH 4.0 and 7.0. The observed value was the pH in that buffer solution before calibration to the buffer value. Electrode drift is caused by the slow passage of hydrogen ions across the glass bulb which leads to dilution of the reference solution.

2.5.3 Test of instrument effects on pH during sampling of lakes on Sept. 30, 2023

Following sampling of the 12 lakes (Table 1) on Sept. 30, 2023, the following instruments and sample handling procedures were used to measure pH:

- The WTW ProfilLine 3210 portable pH meter (described in Section 2.2). There was no air space in the sample bottle used for measurement of pH using this meter, thus minimizing effects of CO_2 degassing on pH. The instrument was set up and calibrated before opening a sample bottle. A sample bottle was then opened, an aliquot was gently poured into a measurement vial that was rinsed with sample water. The sample bottle was recapped and pH measurment was made, in that order. A measurement was recorded following pH stabilization shown on the instrument.
- Bench top automated pH meter at ALS Environmental located in Burnaby within 9 days after sampling. There was no air space in the sample bottle thus minimizing effects of CO_2 degassing on pH. Two measurements were made: one using a standard 3-minute electrode immersion period and another using a 10-minute electrode immersion period for methods testing that is described in Section 2.5.1.
- Mantech PC automatic titrator (Mantech Inc. Guelph, Ontario) at the BASL located in Edmonton, Alberta within 15 days after sampling. The difference in time between sampling and measurement at BASL and ALS was due to shipping

and not time for processing in each lab. There was no air space in the sample bottle thus minimizing effects of CO_2 degassing on pH.

Resulting data supported a test of an instrument effect on pH. A series of paired t-tests were run as a batch analysis wherein the pairs were WTW versus ALS, WTW versus BASL, and BASL versus ALS. The null hypothesis was that pH measurement in a lake sample by a given instrument was more similar to its corresponding measurement by one of the other instruments than to samples from the other lakes. The significance level for a single contrast of $p=0.05$ was adjusted using the Bonferroni correction to account for random effects, resulting in conservative control over Type I error (probability of rejecting the null hypothesis of no difference in pH between a pair of instruments when the null hypothesis is actually true). The Bonferroni correction was α/c where α was the nominal significance level (*e.g.*, 0.05) and c was the number of paired contrasts, which in this case was three, resulting in the corrected significance level of 0.017.

The equation for calculating the t value for each paired test was as follows:

$$t = \frac{Mean\ differences}{SE\ of\ differences} \qquad \textit{Eq}\text{uation 3}$$

If the P value for a paired t-test was less than 0.017, the mean difference between paired values reported by the two instruments that were contrasted was considered significantly different from zero.

The statistical analyses were run in R (R Core Team 2022).

2.5.4 Time course pH in LAK006 (End Lake) and LAK028

During the time course sampling of End Lake (2.3.3) and LAK028 (2.3.2), the following instruments and sample handling procedures were used to measure pH:

- Onset pH logger installed at a depth of 2 m in each lake and another one installed at a depth of 2 m off bottom (13 m from the surface) in LAK028 with a new Onset instrument and pH electrode at the start of the season. A new electrode was installed in a spare instrument (also new in spring 2023) that replaced the existing instrument at the lake station every two months. The purpose of replacing the entire instrument was to avoid electrode replacements in the field which may result in moisture entering the instrument electronics during inclement weather. The two to three month period for electrode replacement was based on monitoring the electrode offset value during calibrations to avoid logging and calibration errors associated with the end of electrode life. In the low conductivity waters of LAK006 and surface water of LAK028, the electrode life is less than the manufacturer’s recommendation.
- The WTW ProfilLine 3210 portable pH meter (described in Section 2.2). Measurements were made in the field laboratory within 5 hours of water sample

collection. There was no air space in sample bottles thus minimizing effects of $_{CO2}$ degassing on pH between the time of sample collection and pH measurement.

- Two samples were shipped to the lab at ALS Environmental located in Burnaby for analyses using a bench top automated pH meter in the lab. On average, there were 3 days between sampling and analyses. The pH in one sample was measured using a 3-minute electrode stabilization period and the other was measured with up to 10-minute electrode stabilization (See Section 2.5.1). There was no air space in the sample bottle thus minimizing effects CO_2CO_2 degassing on pH. If tests showed that the effect of electrode immersion time on pH was statistically significant, the pH value from the longer immersion period was used in describing pH over time in End Lake and LAK028.
- Bench top automated pH meter in the lab at BASL in Edmonton within 16 days after sampling. Measurement was done on a Mantech PC automatic titrator (Mantech Inc. Guelph, Ontario).

For both LAK006 and LAK028 there were 9 dates of measurement for each instrument corresponding with the 9 sampling dates during May 15 – October 16, 2023 (see dates in Section 2.3.2 for LAK028 and Section 2.3.3 for End Lake).

A repeated measures design was used to test the hypothesis that a pH measurement by a given instrument at a lake was more similar to its corresponding measurement by one of the other instruments than to samples from other dates. Measurements from the four instruments were compared using a repeated measures one-way ANOVA run on data from each lake. There were four levels (Onset, WTW, ALS lab, BASL) followed by post hoc tests between the instrument pairs. The significance level for the overall test of instrument effect was 0.05 adjusted using the Bonferroni correction for multiple comparisons to avoid the influence of random effects on those comparisons. The statistical analyses were run in R (R Core Team 2022).

2.6 Water surface elevation in End Lake and LAK028

Water surface elevation was monitored during May 17 through November 1, 2023 in End Lake and during May 16 through November 5, 2023 in LAK028. The measurement interval was 30 minutes at both lakes. Instrumentation included a standard staff gauge for manual water level readings and a Onset Hobo water level logger. The logger in End Lake was model MX2001-04 equiped with automatic compensation for atmospheric pressure (new in 2022). The model in LAK028 was U20-001-04 coupled with a Hobo barometric logger used for atmospheric barometric pressure compensation that was suspended from the top of the angle iron directly above the water level logger at the shoreline. Each logger was suspended using a 1 m length of aircraft cable inside a 2 inch PVC stand-pipe. The pipe was fitted with a grated cover on the lower end, and had holes drillld in it to allow free water movement. The staff gauge and logger assembly was secured to a 2.7 m length of angle iron that was bolted into a shoreline tree (Figure 5, Figure 6), thus providing a fixed station for readings of water level at each lake. A simple 3-point survey with a rod and level was completed on the day of logger installation and day of removal to fix the monitoring location and determine if position of the staff gauge and logger housing shifted or was moved during the period of data logging. In 2023, there was no shift in position between May and November.

During water sampling visits to each lake, water depth on the staff gauge was recorded on the field notes and the logger installations were checked for signs of tampering or vandalism. There were no signs of tampering or vandalism of the staff gauges or water level loggers during 2023.

Figure 5. Photo showing the installed water level staff gauge and 2-inch PVC pipe that housed the water level logger in End Lake.

Figure 6. Photo showing the installed water level staff gauge and 2-inch PVC pipe that housed the Hobo water level logger in LAK028.

2.7 Trophic State of Lakes

Trophic state is a classification of lake productivity and water quality wherein oligotrophy implies low biological production and high water quality, eutrophy shows high biological production that can lead to low water quality, and mesotrophy is in between (Wetzel 2001). Each of these states is commonly defined by mean annual concentrations and ranges of TP, TN, and chlorophyll-a. Secchi depth may also be used but only where there is no confounding by inorganic turbidity affecting water column transparency (*e.g.* Carlson 1980, Carlson 1992, Wetzel 2001).

A trophic state index (TSI) is a numerical scale ranging from 1 to 100 where 1 is extreme oligotrophy and 10 is extreme eutrophy, using TP concentration or chlorophyll-a concentration as inputs to equations reported by Carlson (1977) and updated by Wetzel (2001). A TSI using either variable relates to phytoplankton biomass to some extent. TP concentration can be positively related to biomass and chlorophyll-a concentration is a direct measure of biomass. Phosphorus is used in index calculations rather than nitrogen, another macronutrient that can play a role in limiting algal growth, because it can theoretically generate 500 times its own weight in algae while nitrogen can only produce 71 times its own weight, meaning that algae are much more reactive to change in P supply than to change in N supply when growth is limited by either nutrient (Wetzel 2001). This difference is why TP rather than TN is used in trophic state equations related to nutrient supply. Wetzel (2001) suggested that TSI values <30 showed oligotrophy, values of 30 – 50 showed mesotrophy, and values >50 showed some degree of eutrophy.

A TSI is based on mean concentrations of TP or chlorophyll-a concentrations or both at multiple depths in the euphotic zone of a lake over a year. For practical purposes, the time period is commonly the phytoplankton growing season (*e.g.* April – November or thereabouts). For preliminary insight in the present data, separate TSI's were calculated for lakes in each of four different time categories:

1. Chlorophyll-a based TSI for the surface of each lake sampled on September 30, 2023 (only one depth on one date),
2. A TSI based on TP for LAK028 and LAK006 sampled monthly during May through October, 2023
3. Chlorophyll-a and TP based TSI's for LAK028, LAK006, LAK012, LAK023, LAK042, LAK044 sampled from the lake surface on four dates during late September through late October, 2023.
4. TP based TSI for all lakes from the single sampling date in each year, where data were available for 2013 to 2023. This calculation used a single TP concentration from the surface water collected on the annual fall sampling date (Section 2.2). This category of TSI values can be used to track change in trophic state over time, standardized to the annual EEM layout.

With the possible exception of TSI's for LAK028 and LAK006 that were sampled over most of the growing season (albeit at only one depth in the euphotic zone), TSI's in these four categories are not comparable to standard measures of trophic state in the published literature because they do not cover a complete growing season and for chlorophyll-a, they did not cover complete euphotic zones. They are not reliable values for use in making environmental management decisions. Present values do, however, provide a rough idea and initial insight into trophic state over selected time periods until more precise data are collected in the future.

The TSI equations were from Wetzel (2001). The TSI based on chlorophyll-a concentration was :

$$TSI[Chl] = 30.6 + 9.81\ln{(Chl)} \qquad \text{Equation 1}$$

Where TSI is a trophic state index based on chlorophyll-a concentration measured in units of $mg{\cdot}m^{-3}$.

The total phosphorus (TP) based TSI was

$$TSI[TP] = 4.15 + 14.42\ln{(TP)} \qquad \text{Equation 2}$$

Where TSI is a trophic state index based on TP concentration (Chl) measured in units of $mg{\cdot}m^{-3}$.

3 RESULTS

3.1 Overview

All water sampling and measurements were completed as planned. There were no safety incidents, and all work was completed on time within the planned schedule. All field and laboratory data were compiled into csv files ready for import into R data analysis software (R Core Team 2022). Those files were sent to ESSA Technologies for further analysis.

3.2 Quality of chemical data

3.2.1 Blanks and duplicates

A total of 20 blank and 20 duplicate samples were collected in 2023. One duplicate sample collected on May 16, 2023 from the 13 m depth (called LAK028D; "D" means deep) was discarded due to large difference in colour, conductivity, pH and total alkalinity between it and the main sample. These differences were related to a deeper depth of the top of the chemocline in 2023 than in earlier years (Section 3.6) affecting chemistry of samples between the two hauls collected from the standard 13 m depth. The 13 m sampling depth was exactly where there was large change between reduced and oxidized conditions with a very small change in depth. The chemistry differences between the two samples were attributed to small differences in depth of the Van Dorn haul between the two samples. It amounted to a few cm that can be expected in hand hauls, particularly when using a vertically oriented Van Dorn bottle directly intersecting a steep chemical gradient.

Positive dissolved Cu, Pb and Zn were found in the September 27th filtered blank, and positive Na and total Zn was found in the October 10th unfiltered blank (Table 3). NH_4-N was also detected in a blank but its concentration was 2% of that in lake water samples, which was within margins of error at the lab and not a concern. In contrast, the concentration of dissolved Cu, dissolved Pb, and dissolved and total Zn in the positive blanks exceeded concentrations of those analytes in corresponding lake water samples. Furthermore, the TN concentration in its one positive blank was 20% of the average concentration in lake water samples and the Na concentration in its one unfiltered positive blank was about half of that in lake water samples. These are high concentrations all occurring in two blank bottles (Table 3). On October 10th, there was no contamination of the filtered blank but there was contamination in the unfiltered blank (Table 4). Given more handling when processing filtered samples, this difference points to contamination of the bottle receiving the unfiltered sample. A blank unfiltered sample is simply deionized water decanted from a central supply into a sample bottle. Absence of the same anomalies in the lake water samples shows contamination was limited to the blank. Since sample handling procedures were the same between lake water samples and blanks and that deionized water for blanks on other dates that were not contaminated came from the same source, only the single bottles used for blanks on September 27th and October 10th were contaminated.

Table 3. Incidence of positive blanks (deionized water having an analyte concentration above the method detection limit) and comparison of analyte concentrations in positive blanks with analyte concentrations in lake water samples, 2023.

Analyte	Method detection limit ($mg \cdot L^{-1}$)	Number of positive blanks (maximum possible is 20)	Average concentration in positive blanks ($mg \cdot L^{-1}$) (range in brackets if applicable)	Average concentration in lake samples in 2023 ($mg \cdot L^{-1}$)
Ammonium, (NH_4-N)	0.005	2	0.0061 (0.0053 - 0.0069)	0.331
Copper, dissolved	0.0002	1*	0.0137	0.00033
Lead, dissolved	0.00005	1*	0.00052	0.00006
Nitrogen, Total	0.03	1	0.095	0.536
Sodium in unfiltered sample	0.05	1**	0.284	0.521
Zinc, dissolved	0.001	3*	0.0053 (0.0032 - 0.0081)	0.0017
Zinc, total	0.003	1**	0.0462	0.0033

*Positive dissolved Cu, dissolved Pb and dissolved Zn occurred simultaneously in the filtered blank from September 27, 2023

**positive Na and Zn occurred simultaneously in the unfiltered blank from October 10, 2023

Table 4. Field blanks on October 10, 2023 and comparison of total and dissolved analyte concentrations in lake water samples collected the same date.

Analyte	Method detection limit ($mg \cdot L^{-1}$)	Field Blank ($mg \cdot L^{-1}$)	LAK028 ($mg \cdot L^{-1}$)	LAK028D ($mg \cdot L^{-1}$)	LAK028D FD ($mg \cdot L^{-1}$)
Sodium, total[1]	0.05	0.284	0.557	0.872	0.880
Sodium, dissolved[1]	0.05	<0.05	0.500	0.808	0.736
Zn, total	0.003	0.462	0.0039	<0.003	<0.003
Zn, dissolved	0.001	<0.001	0.031	0.001	<0.001

1Sodium is soluble in water and is expected to occur as a cation at the same concentration in ICP scans of filtered (dissolved) and unfiltered samples in the absence of contamination. Finding a very high Na concentration in the blank "total" sample but undetectable Na concentration in the blank "dissolved" sample shows contamination in the blank "total" sample

3.2.2 Precision

Precision is considered high among field duplicates when relative percent difference (RPD) is less than 20% (Ministry of Environment Lands and Parks 2013). Values of RPD >20% indicate a possible problem and > 50% indicate a definite problem potentially including sample contamination or a lack of sample representativeness (high heterogeneity) (Ministry of Environment Lands and Parks 2013). In 2023, the average RPD between replicate pairs of samples was 4% to 20% (Table 5), except DIC that had an average RPD of 25%. Two of the three RPD's for DIC were <20% (19% and 11% respectively) and one was 46%. All three DIC duplicates were collected at LAK028D where very small differences in haul depth between duplicates could yield very different chemical conditions due to slightly different intersections of the steep chemocline as explained in Section 3.2.1.

Table 5. Relative percent difference of analyte concentration between surface replicates in 2023. Data are shown only for sample pairs having analyte concentrations greater than five times the method detection limit (except pH), following protocols reported by the Ministry of Environment Lands and Parks (2013).

Analyte	Average value of relative percent differences between replicate pairs of samples (%)
Aluminum, dissolved	4 (n=19)
Aluminum, total	5 (n=18)
Ammonium-N	16 (n=2)
Calcium, total	6 (n=15)
Chloride	5 (n=3)
Conductivity	12 (n=7)
Conductivity (BASL)	5 (n=19)
Dissolved Inorganic Carbon	25 (n=3)
Dissolved Organic Carbon	12 (n=16)
Fluoride	3 (n=15)
Gran ANC (BASL)	14 (n=19)
Iron, dissolved	11 (n=12)
Iron, total	14 (n=16)
Magnesium, dissolved	2 (n=19)
Magnesium, total	3 (n=19)
Manganese, dissolved	6 (n=19)
Manganese, total	7 (n=19)
Nitrate-N	no values >5X MDL
Nitrogen, total	6 (n=7)
Orthophosphate, dissolved	no values >5X MDL
pH (ALS)	0.010[a] pH units (n=19)
pH (ALS low ionic strength method)	0.008[a] pH units (n=19)
pH (BASL)	0.008[a] pH units (n=19)
pH Field (WTW)	0.009[a] pH units (n=19)
Phosphorus, total	13 (n=8)
Phosphorus, total dissolved	18 (n=2)
Potassium, dissolved	8 (n=4)

Analyte	Average value of relative percent differences between replicate pairs of samples (%)
Sodium, total	4 (n=16)
Solids, total dissolved	9 (n=1)
Strontium, dissolved	4 (n=19)
Strontium, total	5 (n=19)
Sulfide (as S)	18 (n=3)
Sulfide (as H2S)	18 (n=3)
Sulphate	9 (n=15)

3.2.3 Accuracy

Average percent recovery in spiked and certified reference samples tested at the ALS lab ranged from 92% to 107% among all analytes, with an overall average percent recovery of 100% among all analytes (Table 6). These results show high accuracy.

Table 6. Percent recovery of analyte concentrations in lab control and spiked samples for the test of lab accuracy in 2023.

Analyte	Known concentration ($mg \cdot L^{-1}$ unless otherwise noted)	Average recovered concentration ($mg \cdot L^{-1}$ unless otherwise noted)	Sample size	Average percent recovery
Aluminum, dissolved	0.20 – 0.4	0.18 – 0.93	21	99
Aluminum, dissolved	2.00	2.07	21	103
Aluminum, total	0.20 - 0.40	0.18 – 0.40	19	97
Aluminum, total	2.00	2.06	20	103
Ammonium-N	0.2	0.196	22	98
Ammonium-N	0.100	0.099	17	99
Calcium, dissolved	50.0	50.6	21	101
Calcium, dissolved	4.0	3.9	3	96
Calcium, total	4.0	4.0	4	99
Calcium, total	50.0	51.2	20	102
Chloride	100	102.1	40	102
Chloride	100	101.5	20	101
Chlorophyll a (µg/sample)	1	0.985	10	98
Conductivity (µS/cm)	146.9	146	20	99
Dissolved Inorganic Carbon	5.0	5.2	13	103
Dissolved Inorganic Carbon	8.0	8.2	24	103
Dissolved Organic Carbon	5	5.11	14	102

Analyte	Known concentration (mg·L^{-1} unless otherwise noted)	Average recovered concentration (mg·L^{-1} unless otherwise noted)	Sample size	Average percent recovery
Dissolved Organic Carbon	8.57	8.67	21	101
Fluoride	1.00	1.00	20	100
Fluoride	1	1.01	20	101
Iron, dissolved	1.00	1.07	21	107
Iron, dissolved	2.0 - 10.0	1.83 - 9.58	20	97
Iron, total	1.00	1.05	20	105
Iron, total	2 - 10	1.8 - 9.9	19	96
Magnesium, dissolved	1	0.96	5	96
Magnesium, dissolved	50	52	21	104
Magnesium, total	1	0.97	5	97
Magnesium, total	50	51.4	20	103
Manganese, dissolved	0.02 - 0.04	0.02 - 0.04	11	98
Manganese, dissolved	0.25	0.254	20	102
Manganese, total	0.02 - 0.04	0.021	14	97
Manganese, total	0.25	0.254	20	102
Nitrate-N	2.50	2.54	20	101
Nitrate-N	2.5 - 50.0	2.5 - 49.2	15	103
Nitrogen, total	0.40	0.39	13	99
Nitrogen, total	0.500	0.497	22	99
Orthophosphate, dissolved	0.030	0.031	20	102
Orthophosphate, dissolved	0.030	0.032	18	107
pH	7.00	7.02	42	100
Phosphorus, dissolved	10	10.3	21	103
Phosphorus, dissolved	10 - 50	9.4 - 48.9	21	101
Phosphorus, total	0.050	0.046	22	92
Phosphorus, total	0.050	0.047	17	94
Phosphorus, total dissolved	0.03 - 0.05	0.031 - 0.050	21	93
Phosphorus, total dissolved	0.050	0.048	21	95
Potassium, dissolved	4.00	3.99	16	100
Potassium, dissolved	50.0	52.1	21	104
Potassium, total	4.00	3.90	13	97
Potassium, total	50	52.2	20	104
Sodium, dissolved	2.00	2.01	5	101
Sodium, dissolved	50.0	52.0	21	104
Sodium, total	2.00	2.10	6	104
Sodium, total	50.0	530.0	20	106
Strontium, dissolved	0.02	0.02	3	98

Analyte	Known concentration (mg·L^{-1} unless otherwise noted)	Average recovered concentration (mg·L^{-1} unless otherwise noted)	Sample size	Average percent recovery
Strontium, dissolved	0.25	0.261	21	104
Strontium, total	0.02	0.02	5	101
Strontium, total	0.25	0.257	20	103
Sulfate	100.0	102.8	20	103
Sulfate	100.0	103.1	20	103
Sulfide (as S)	0.08	0.082	9	103
Sulfide (as S)	1.00	1.103	9	97
Total Dissolved Solids	1000	1012	24	101

3.3 Handling effects on pH measurement

3.3.1 Effect of electrode immersion time on pH at the ALS lab

The distribution of paired differences of pH between methods did not meet the assumption of normality (Shapiro-Wilk p value <0.001), so the non-parametric Wilcoxin test was used to test for an effect of electrode immersion time on pH. Differences in pH between the methods was not significantly different from zero (p value = 0.15). This finding was the same as in 2021 and 2022 but different from findings in 2020, where longer immersion time was found to produce lower pH values (Limnotek 2022). To be conservative, all tests using ALS pH data from this point forward in the report were based on values using the 10-minute electrode immersion method.

3.3.2 Onset pH electrode drift

Mean drift in pH logged by each of the LAK006 and LAK028 Onsets (the difference between observed and expected values in pH readings taken in solutions of a known pH) was 0.02 – 0.03 pH units immediately after calibration (a measure of calibration accuracy), increasing to 0.03 - 0.06 pH units up to a month of operation in LAK006 and LAK028 (Figure 7) without time course trend or pattern (Figure 8). The magnitude of electrode drift in 2022 and 2023 was among the lowest of all years of continuous pH monitoring in LAK006 and LAK028 (Limnotek 2022, Limnotek 2023).

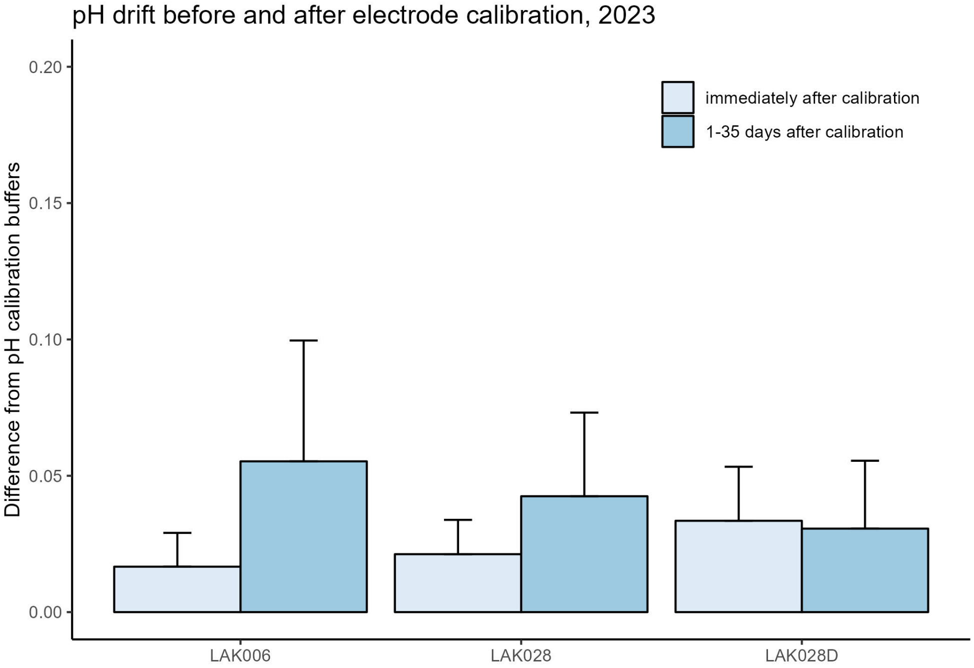

Figure 7. Onset pH electrode drift, shown as the mean difference (± standard deviation) between observed pH (field measured value of a buffer solution) and expected pH (certified pH value of a buffer solution) measured immediately after calibration and after a period up to 35 days in End Lake and LAK028 in 2023.

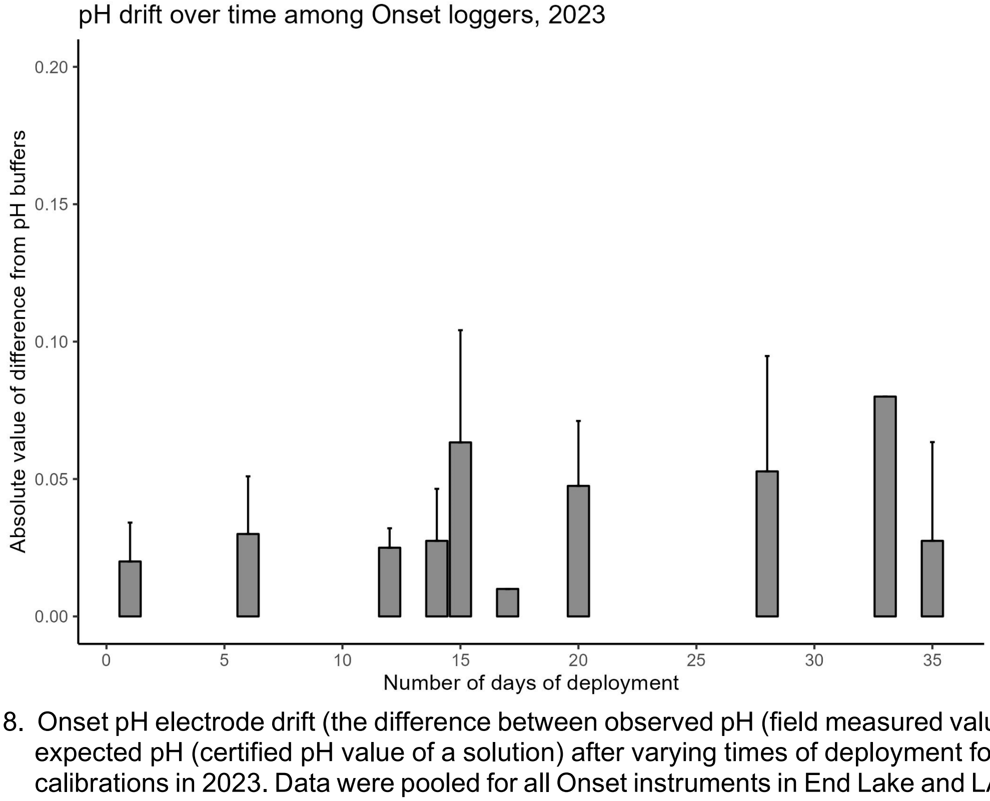

Figure 8. Onset pH electrode drift (the difference between observed pH (field measured value) and expected pH (certified pH value of a solution) after varying times of deployment following calibrations in 2023. Data were pooled for all Onset instruments in End Lake and LAK028.

3.3.3 Single date annual lake water sampling (September 30, 2023)

The batch of paired t-tests run on pH among water samples from the 12 lakes sampled on September 30, 2023 showed no significant difference between pH values among instrument pairs (p>0.017; Bonferroni corrected from 0.05) (Table 7).

Table 7 Mean difference in pH between all combinations of instrument pairs among lakes that were sampled on September 30, 2023 (n=14 includes field duplicates). WTW was the field pH meter used to measure pH in each sample at the end of the sampling day, ALS_{10} was the method at the ALS lab in Burnaby, and BASL was the Mantech PC-titration Plus system used at BASL. An * indicates a significant mean difference (p< 0.017; Bonferroni corrected from 0.05) and "ns" indicates no significant difference in pH between paired instruments.

	Difference in pH between instrument pairs in 2023		
	WTW	**BASL**	**ALS_{10}**
WTW			
BASL	0.02 (ns)		
ALS_{10}	0.11 (ns)	0.10(ns)	

*shows a significant mean difference (p< 0.017; Bonferroni corrected from 0.05).
"ns" indicates no significant difference in pH between paired instruments (p>0.017).

3.3.4 Time course pH in End Lake and LAK028

The Onset pH loggers were installed and retrieved in End Lake and LAK028 according to the schedule shown in Table 8. In 2023, there were no logger failures. A continuous record of data was recorded during May 17, 2023 to November 1, 2023 in End Lake (LAK006) and May 15, 2023 to November 5, 2023 at the two depths in LAK028.

Mean daily pH from each Onset pH logger was plotted with discrete pH values from the other instruments (WTW, ALS lab, and BASL) for each of End Lake and LAK028 surface and LAK028 deep (Figure 9, Figure 10 and Figure 11 respectively).

In mid-July and mid-September, 2023, loggers with new pH electrodes replaced the existing loggers in End lake and at two depths in Lak028 as explained in Section 2.5.4 (Table 8). Upwards shifts in pH of about 0.2 pH units corresponded with instrument replacement in End Lake and the surface of LAK028 but no shift was found in data from the deep logger in LAK028. It is unknown if apparent shifts were related to instrument replacements.

Repeated measures ANOVA showed differences between lab and field measurement of pH at End lake and LAK028-D but not at LAK028-S (Figure 12, Figure 13, and Figure 14). Similar to results observed in 2022, the general pattern of instrument effects (LAK006 and LAK028D) was pH being highest using ALS10 and lowest with the Onset instrument. The BASL pH and the field WTW pH values were in between.

Table 8. Schedule of Onset pH instruments deployment and removal from End Lake (LAK006) and LAK028 in 2023.

pH Instrument Location	pH Instrument and Serial Number	Instrument commissioning date	2023 Installation date	2023 Retrieval date	Record of Data (# of continuous days)	Maximum electrode offset (mV)[1]
End Lake (LAK006), 2 m depth	21737272	2023-05-14	2023-05-17	2023-07-18	62	-12.5
	21737271	2023-07-16	2023-07-18	2023-09-12	56	-18.7
	21737282	2023-05-14	2023-09-12	2023-11-01	50	-13.7
LAK028, 2 m depth	21737270	2023-05-14	2023-05-15	2023-07-17	63	-12.3
	21737281	2023-07-16	2023-07-17	2023-09-11	56	-16.2
	21737270	2023-05-14	2023-09-11	2023-11-05	55	-18.4
LAK028, 13 m depth	21737282	2023-05-14	2023-05-15	2023-07-17	63	-13.4
	21737280	2023-07-16	2023-07-17	2023-08-14	28	-13.1
	21737282	2023-05-14	2023-08-14	2023-09-11	28	-11.5
	21737272	2023-05-14	2023-09-11	2023-11-05	55	-9.1

[1] Maximum electrode offset (MEO) is a value from the instrument that is used to assess electrode function. If the MEO exceeds +30mV or is less than -30mV, the sensor needs replacing. All MEO values show excellent electrode performance.

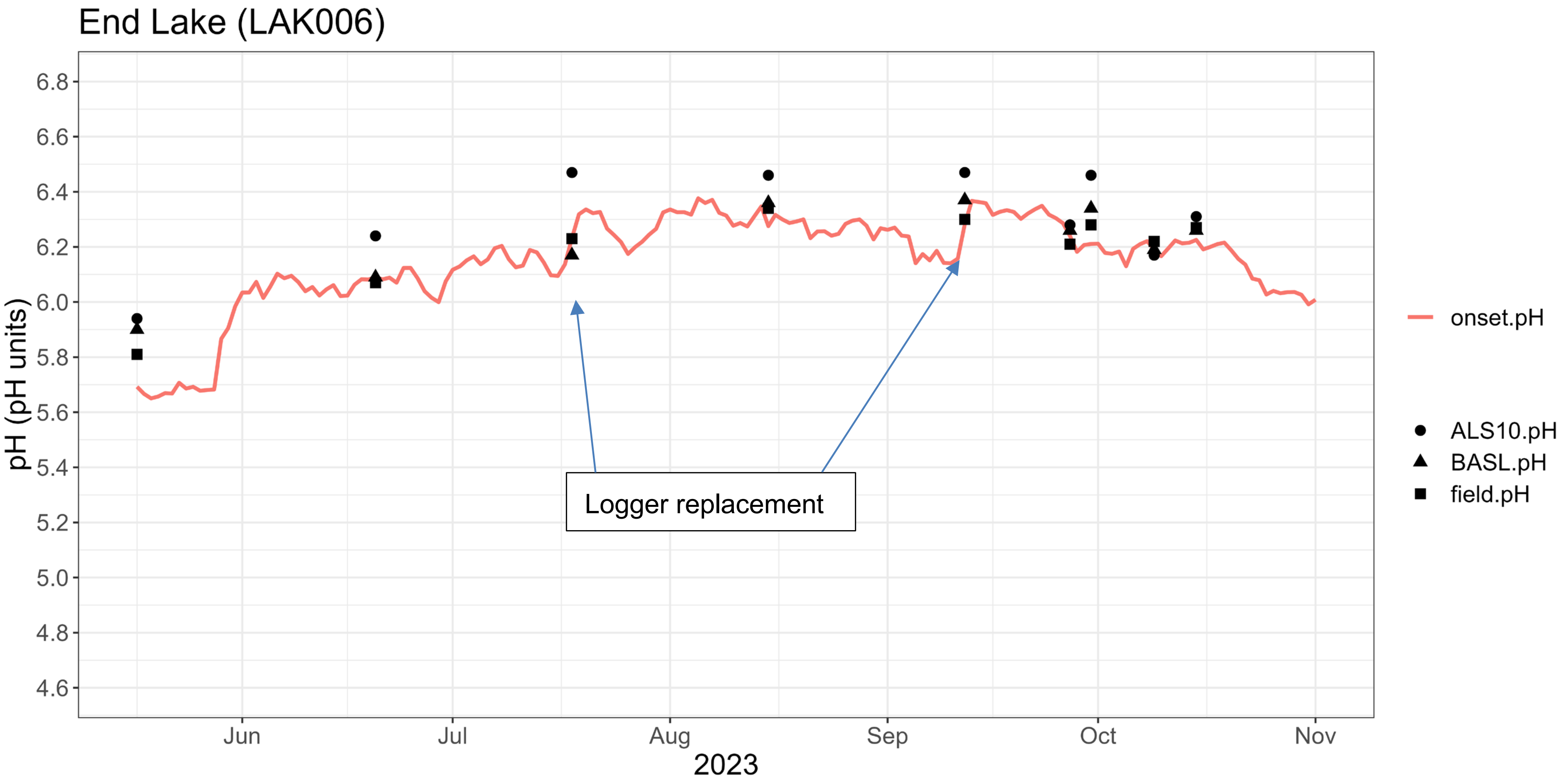

Figure 9. Mean daily pH recorded by the Onset logger in End Lake (continuous red line) shown with discrete pH measurements using other instruments in 2023. Field.pH is WTW meter, ALS10.pH is a bench top meter used at ALS labs in Burnaby using a 10-minute electrode immersion time, and BASL.pH is the Mantech PC-titration Plus system used at BASL. Discrete sampling dates correspond to dates when the Onset logger was calibrated except on Sept. 30th when the lake was sampled from a helicopter.

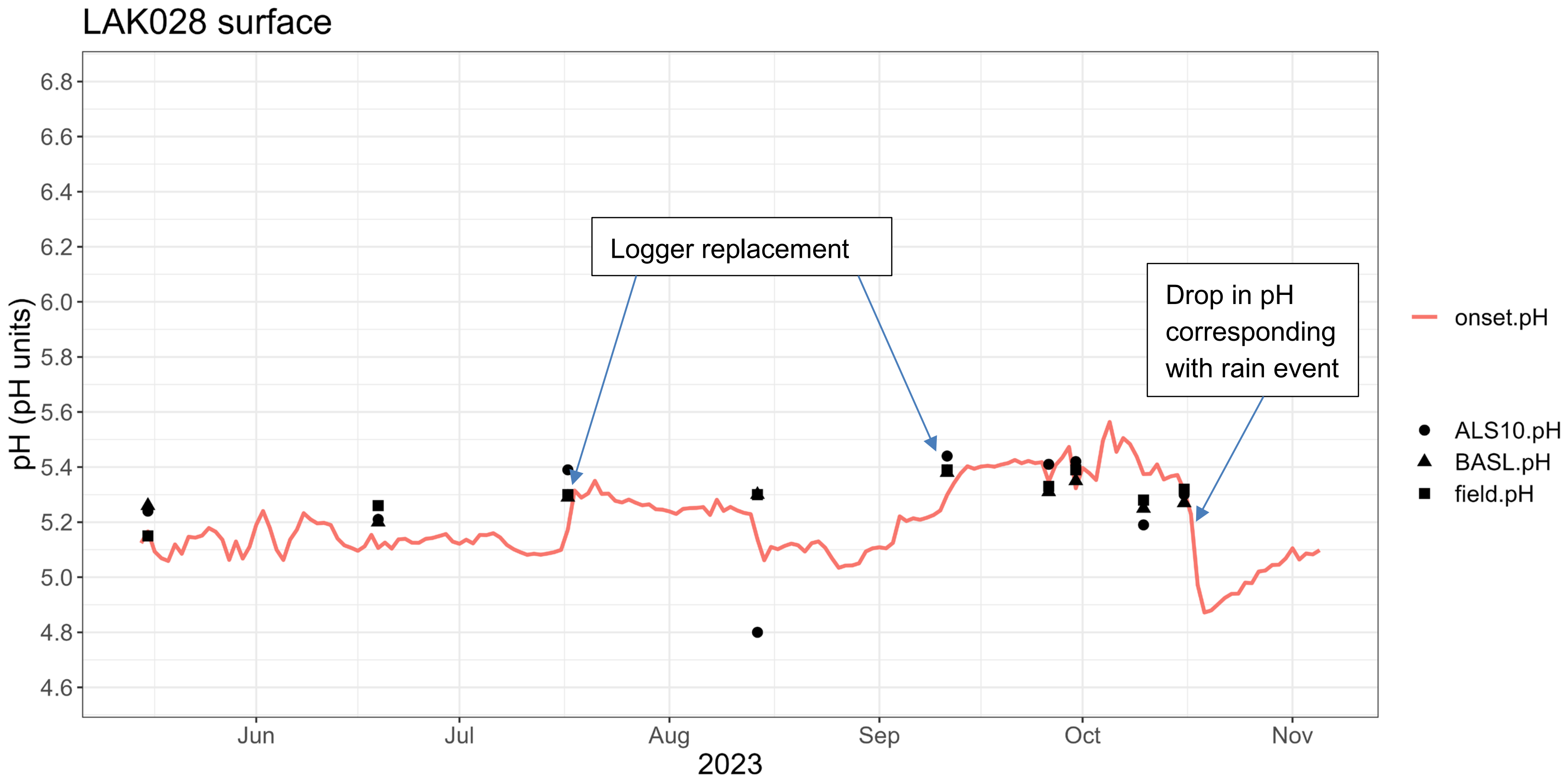

Figure 10. Mean daily pH for Onset pH logger in LAK028 deployed at a depth of 2 m (continuous red line) shown with discrete pH measurements in samples from the same depth using other instruments in 2023. Field.pH is WTW meter, ALS10.pH is a bench top meter used at ALS labs in Burnaby using a 10-minute electrode immersion time, and BASL.pH is the Mantech PC-titration Plus system used at BASL. Discrete sampling dates correspond to dates when the Onset logger was calibrated except on Sept. 30th when the lake was sampled from a helicopter.

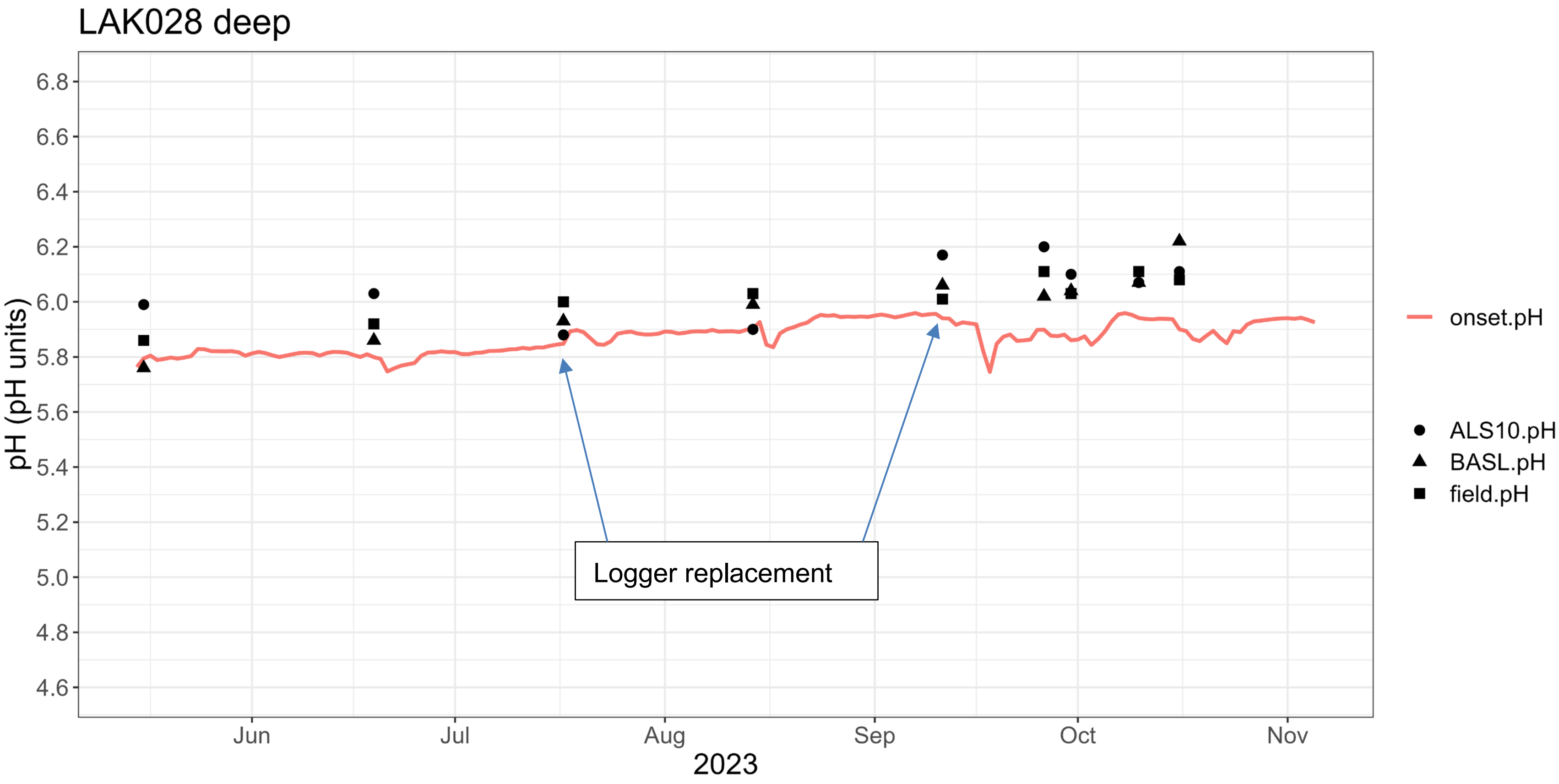

Figure 11. Mean daily pH for Onset pH logger in LAK028 deployed at a depth of 13 m (continuous red line) shown with discrete pH measurements in samples from the same depth using other instruments in 2023. Gaps in the time series show when a logger was not operating due to failure found on a calibration date. A failed logger was replaced on the following calibration date. Field.pH is WTW meter, ALS10.pH is a bench top meter used at ALS labs in Burnaby using a 10-minute electrode immersion time, and BASL.pH is the Mantech PC-titration Plus system used at BASL. Discrete sampling dates correspond to dates when the Onset logger was calibrated except on Sept. 30th when the lake was sampled from a helicopter.

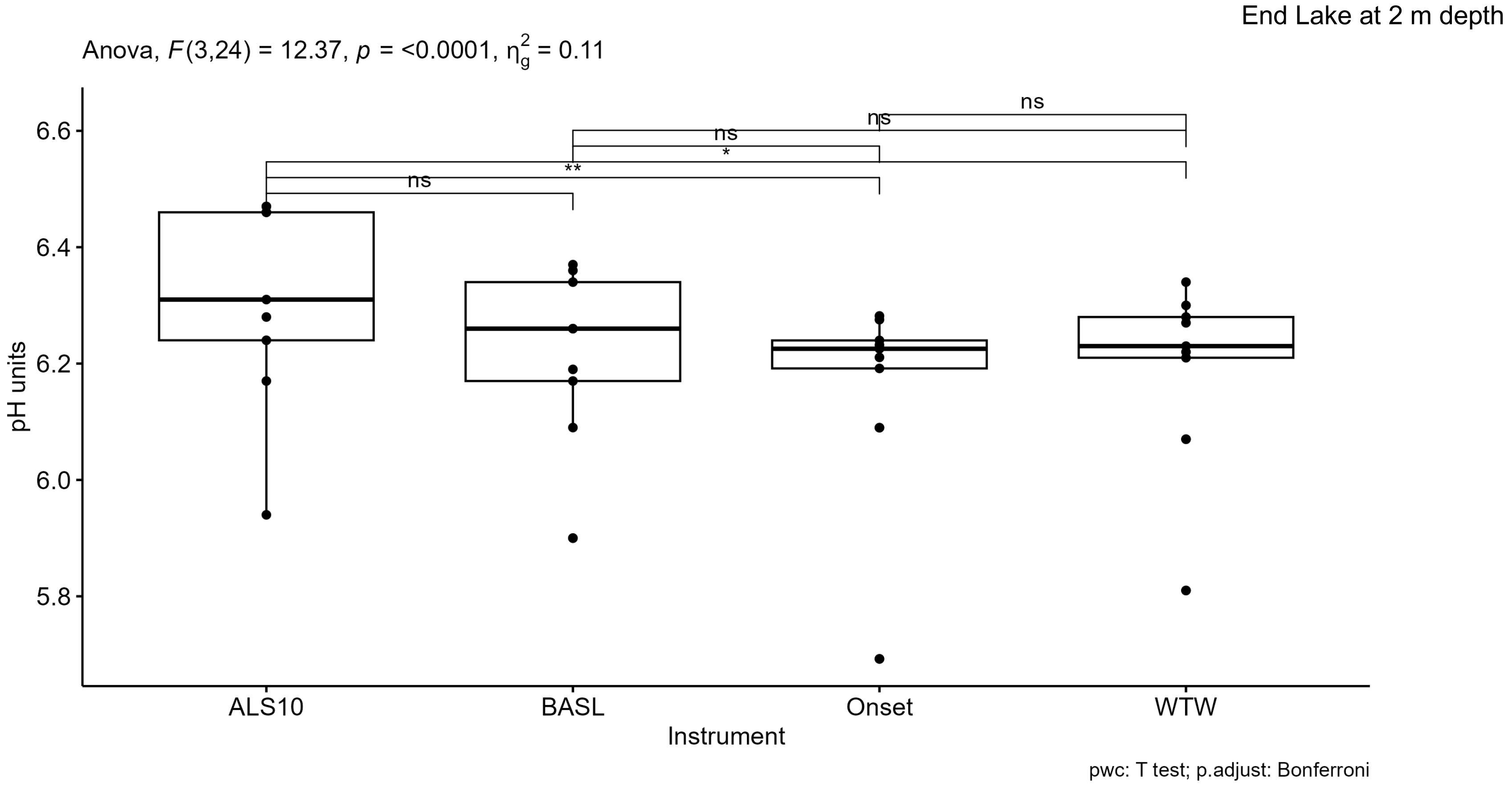

Figure 12.Box plot showing difference in pH in End Lake between all combinations of instrument pairs during sampling in May through October 2023 (n=9). Instrument names are ALS10 (instrument at the ALS lab using 10-minute electrode immersion time), BASL (instrument at the BASL lab), Onset (in situ pH logger), and WTW (field pH meter). Horizontal bars at the top of the box plot span instrument pairs being tested along with symbols indicating significance of a difference in pH using repeated measures ANOVA. The * or ** indicates a significant mean difference and “ns” indicates no significant difference in pH between the paired instruments.

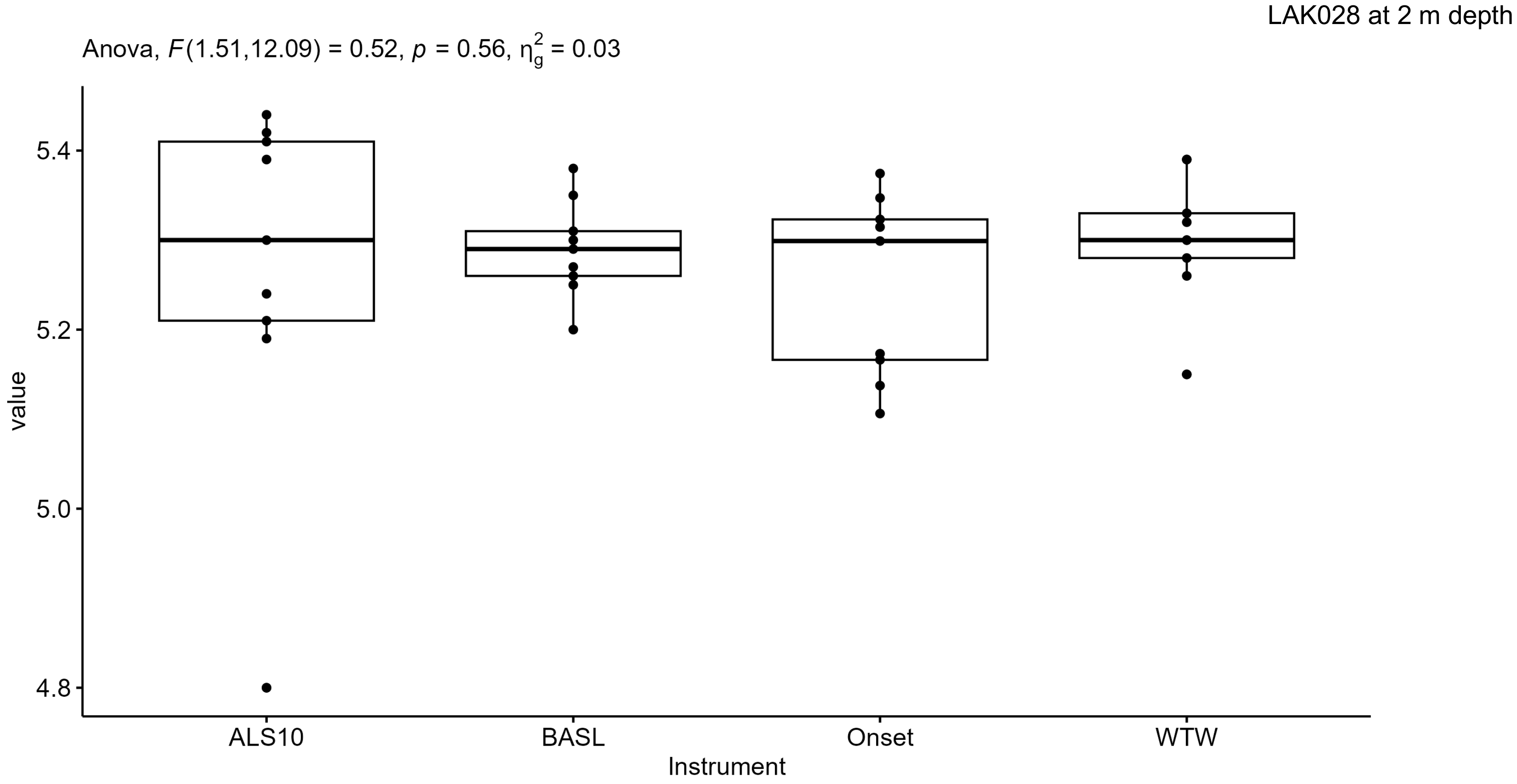

Figure 13. Box plot showing difference in pH in LAK028 (2 m depth) between all combinations of instrument pairs during sampling in May through October 2023 (n=9). Instrument names are ALS10 (instrument at the ALS lab using 10-minute electrode immersion time), BASL (instrument at the BASL lab), Onset (in situ pH logger), and WTW (field pH meter). There were no significant differences in pH between instrument pairs using repeated measures ANOVA.

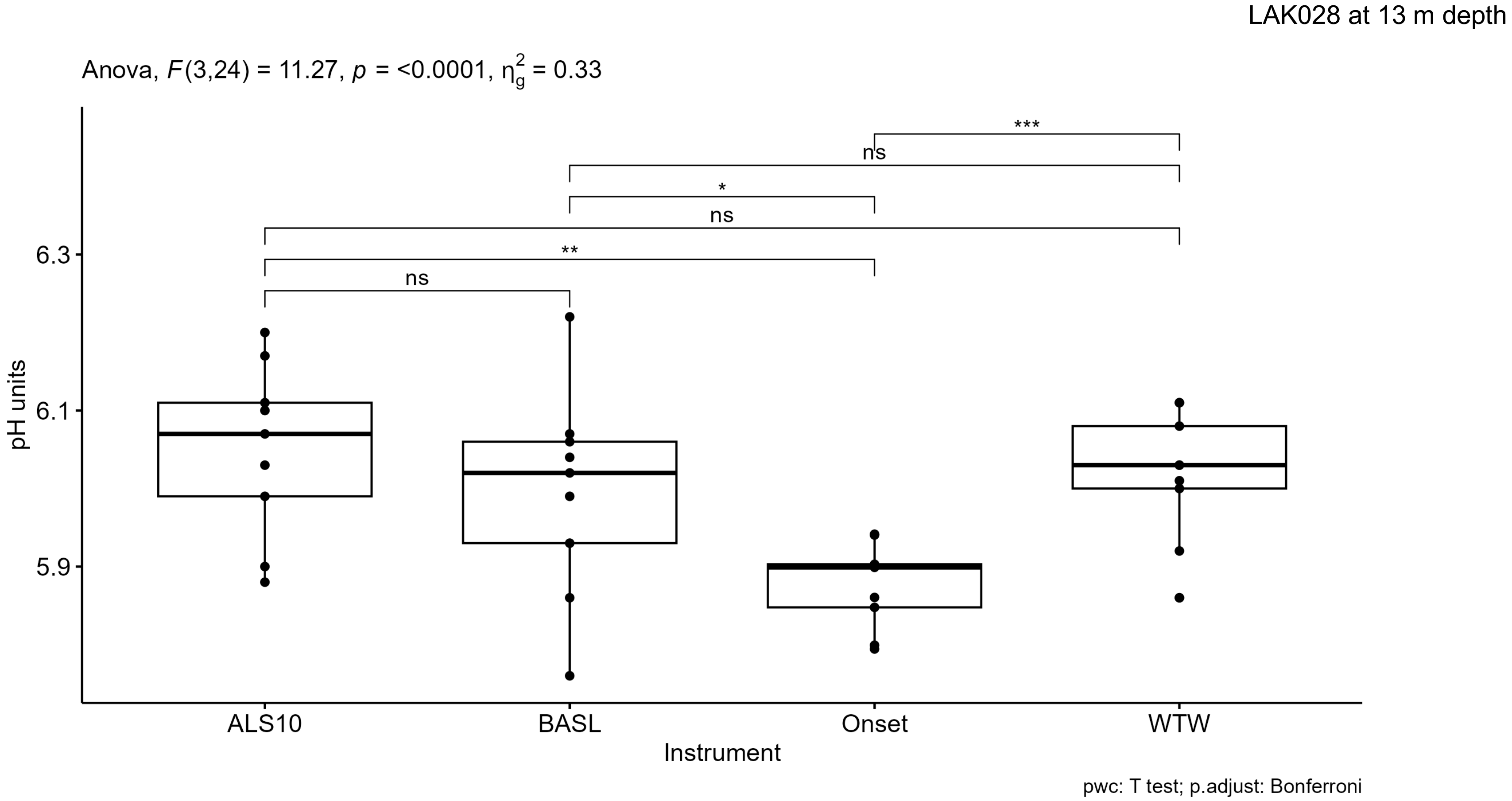

Figure 14. Box plot showing difference in pH in LAK028 (13 m depth) between all combinations of instrument pairs during sampling in May through October 2023 (n=9). Instrument names are ALS10 (instrument at the ALS lab using 10-minute electrode immersion time), BASL (instrument at the BASL lab), Onset (in situ pH logger), and WTW (field pH meter). Horizontal bars at the top of the box plot span instrument pairs being tested along with symbols indicating significance of a difference in pH using repeated measures ANOVA. The * or ** or *** indicates a significant mean difference and "ns" indicates no significant difference in pH between the paired instruments.

3.4 Water surface elevation in End Lake and LAK028.

Water surface elevation varied by 30.4 cm in LAK006 and 46.3 cm in LAK028 in 2023 (Figure 16) in response to rainfall events (compare Figure 15 and Figure 16). All months of 2023 were relatively dry compared to other EEM monitoring years (2017 to 2022). Total precipitation during May to October in 2023 was the second lowest since 2017, with less total rainfall only in 2018 (Table 9). Differences in change of water surface elevation between the two lakes are attributed to spatial variation in rainfall, lake morphometry, and basin hydrology.

Table 9. Total rainfall by month and year reported by Environment Canada at the Terrace Airport (Terrace A) except data marked with an * that is from a nearby Terrace Braun's Island station (Terrace PCC).

Month	**Total rainfall (mm)**						
	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
May	95	58	19	31*	63	67	27
June	90	37	58	24*	73	107	38
July	36	22	75	51*	39	75	58
Aug.	79	9	74	160	83	66	24
Sept.	104	24	99	143	231	71	67
Oct.	310	94	139	135	152	190	109
May – Oct.	714	244	464	438	641	575	323

*from Braun's Island Station.

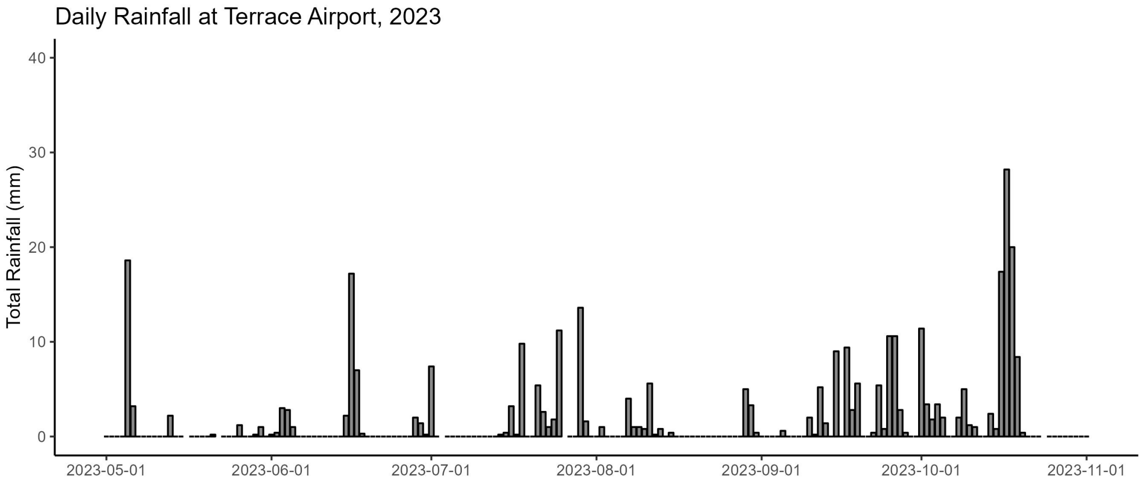

Figure 15 Total daily rainfall reported by Environment Canada at the Terrace Airport (Terrace A) for May through October 2023.

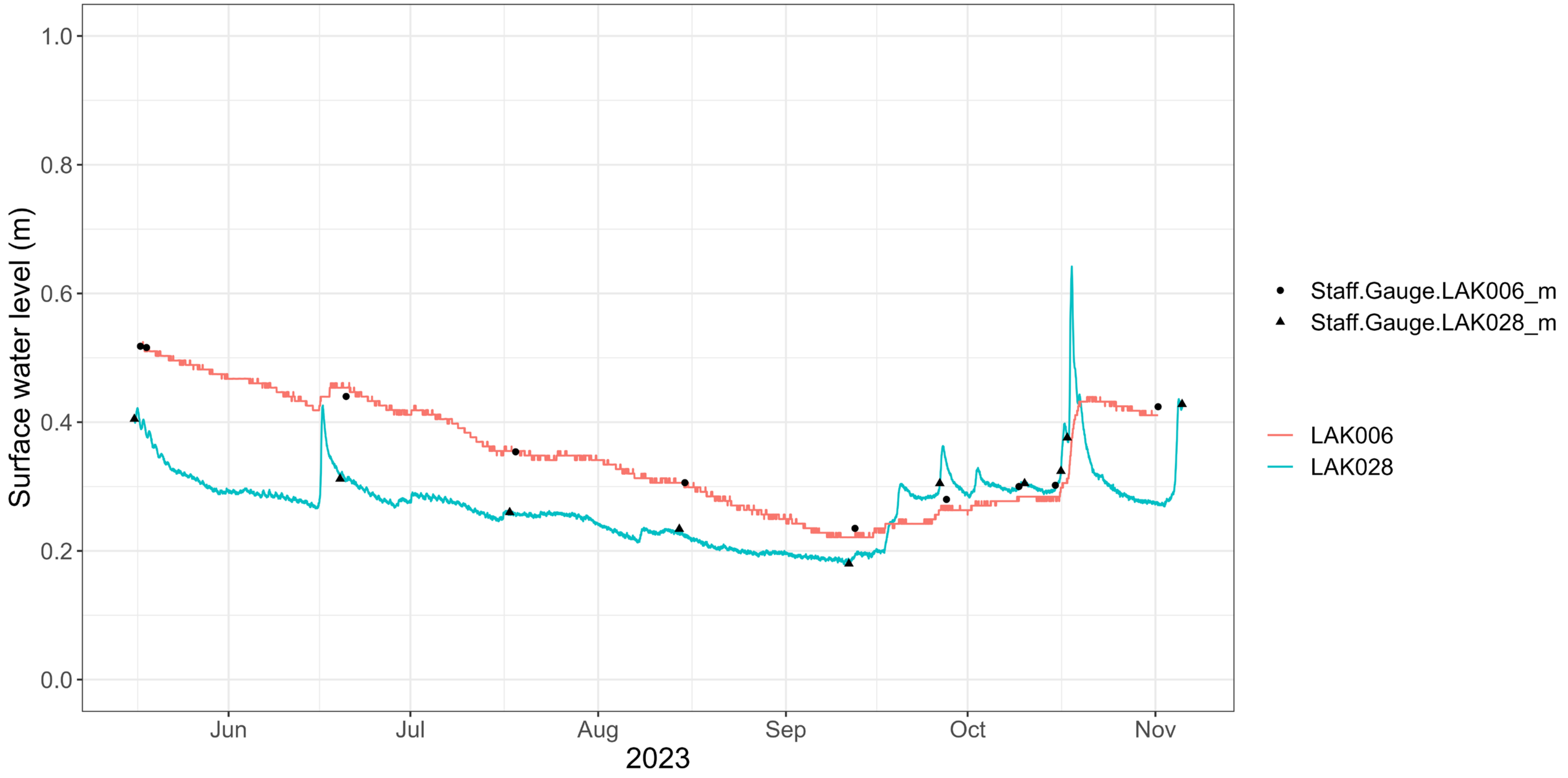

Figure 16. Surface water level (cm) in End Lake and LAK028 in 2023 (measured every 30 minutes). Note that water level is relative to a benchmark at each lake, not to a common benchmark.

3.5 Limnology of LAK006

Temperature stratification was present in LAK006 throughout the monitoring period in 2023 (Figure 17). At the time of the first measurement in May, a surface warm layer (epilimnion) was developing above 2 m which deepened to 5 m in mid-summer and then 6 m in October. By mid-October, the epilimnion cooled and resistance to mixing weakened. The hypolimnion (bottom layer) was 4-5 ºC for the entire monitoring period. The peak surface temperature of 21.1ºC occurred on July 18, 2023.

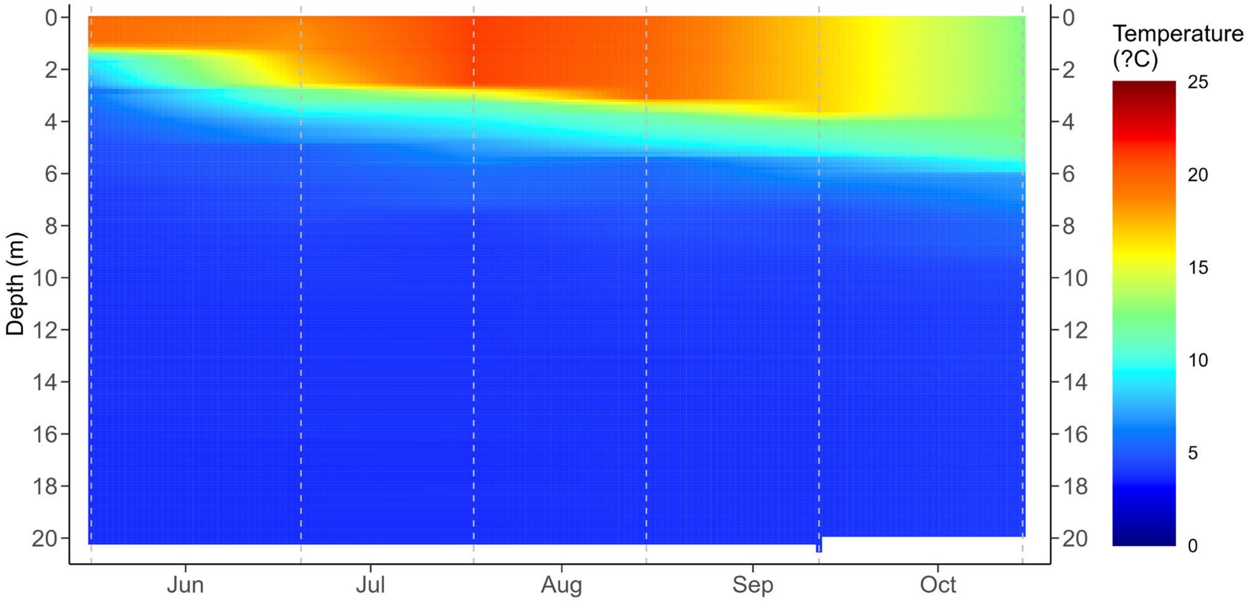

Figure 17 LAK006 water temperature from CTD casts in 2023. The vertical dotted lines indicate dates of measurement. Data between those were linearly interpolated.

Dissolved oxygen (DO) concentrations were highest in surface waters and lowest near the sediment - water interface in 2023 (Figure 18). Patterns were similar to those found in 2022, with DO concentrations near 10 mg·L^{-1} found in June and July at a water depth of 3 – 4 m, likely associated with an algal bloom and equally high concentrations in the top 6 m in October, potentially driven by wind from storm events. DO concentrations close to or less than 5 mg·L^{-1} were found in close proximity to the sediment – water interface in June but expanded to water depths halfway up the water column by mid-July.

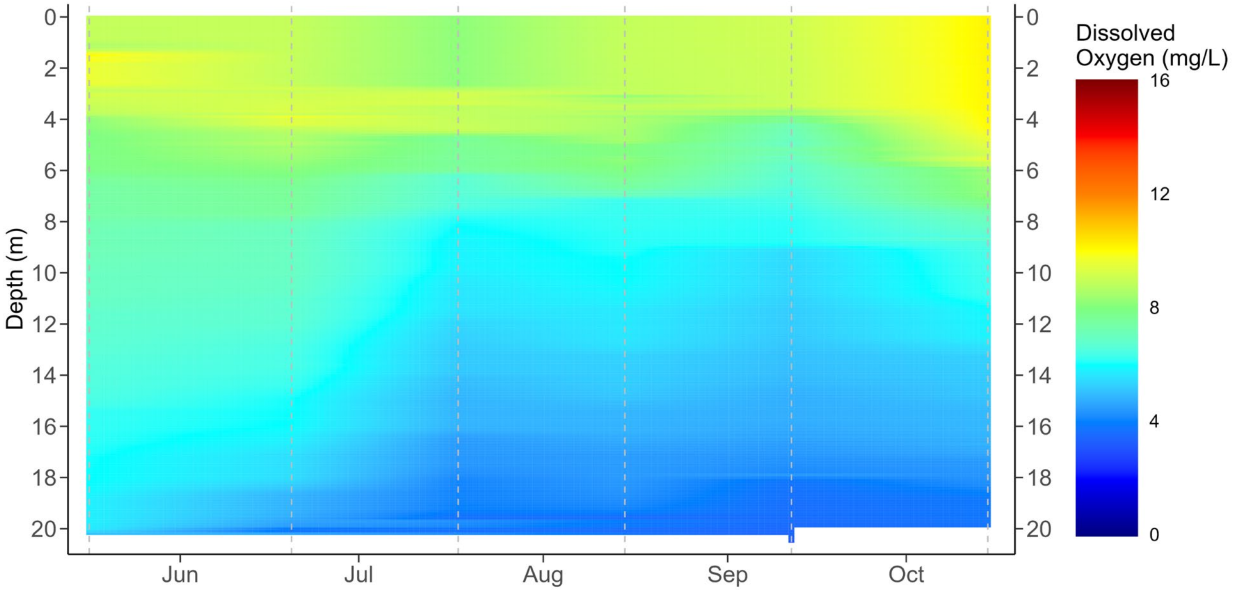

Figure 18 LAK006 dissolved oxygen concentrations from CTD casts in 2023. The vertical dotted lines indicate dates of measurement. Data between those were linearly interpolated.

The CTD casts showed no time or depth variation in specific conductivity or turbidity in 2023 (Figure 19 and Figure 20). Specific conductance was <13 $\mu S \cdot cm^{-1}$ (mean of 10.7 $\mu S \cdot cm^{-1}$) and turbidity was <1.2 NTU (mean of 0.3 NTU) among all casts.

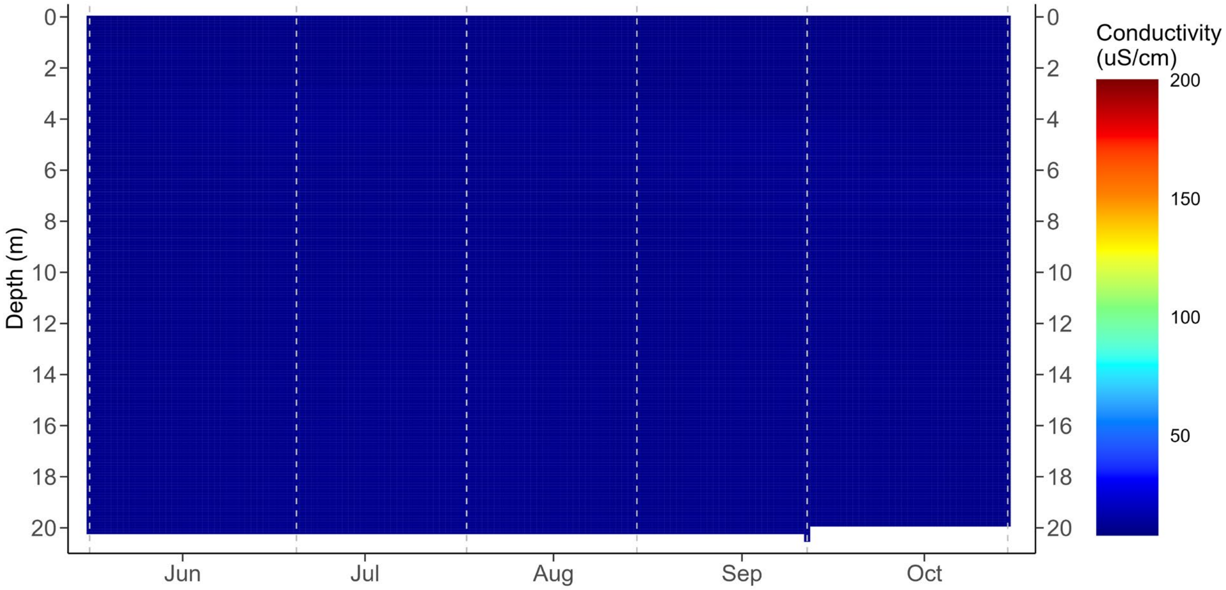

Figure 19 LAK006 specific conductivity from CTD casts in 2023. The vertical dotted lines indicate dates of measurement. Data between those dates were linearly interpolated. Note that the conductivity is relatively uniform at all depths in the lake, resulting in a solid-colored plot.

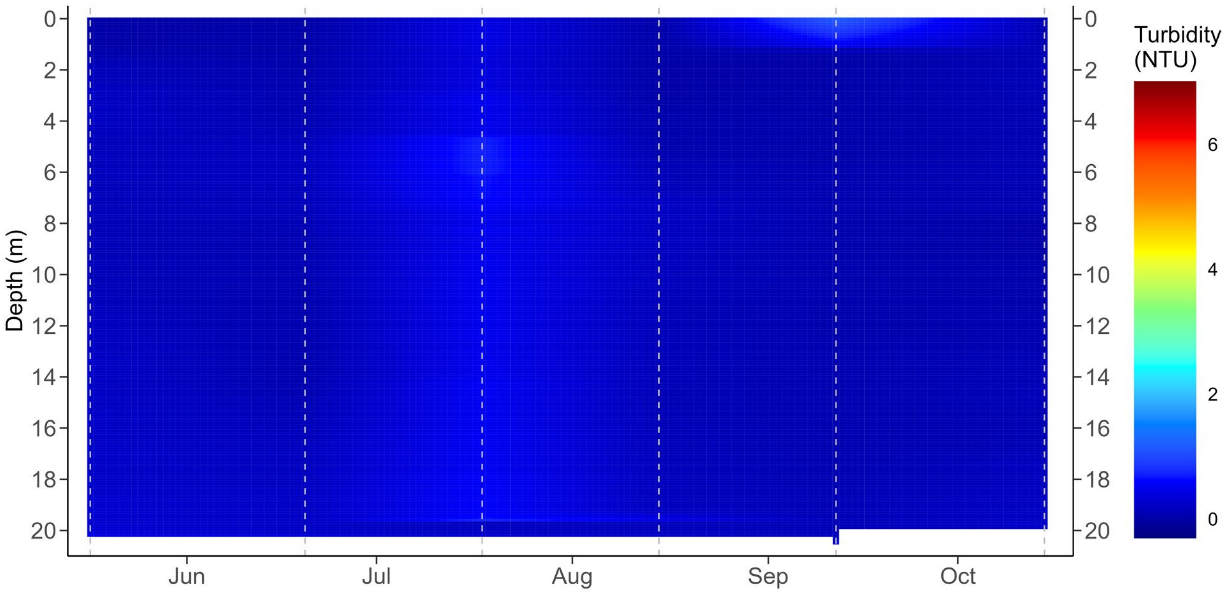

Figure 20 LAK006 turbidity from CTD casts in 2023. The vertical dotted lines indicate dates of measurement. Data between those dates were linearly interpolated. Note that the turbidity is relatively uniform at all depths in the lake, resulting in a solid-colored plot.

3.6 Limnology of LAK028

The year-long data from the LAK028 temperature mooring showed three temporal phases (Figure 21). Isothermal conditions were fully developed on November 6, 2022 (Figure 22), but an inversion then formed in which surface temperature was lower than at depth, possibly due to formation of surface ice. This phase was followed by surface warming in December and early January before an inversion was again set up in February through early May, 2023. A third phase of temperature stratification due to surface heating occurred in late May through late September, 2023 (Figure 21 and Figure 23). Resistance to mixing then declined in October 2023 as surface water cooled. The summertime thermocline was established at a depth of 2 m to 4 m. Isothermal conditions were not re-established by the end of the data record in October. The peak surface temperature in 2023 was 23.6°C in early July, compared to 21.7 °C in mid-August in 2022 (Limnotek 2023). At depths greater than 10 m, water temperature was consistently near 4°C, at which point water has highest density.

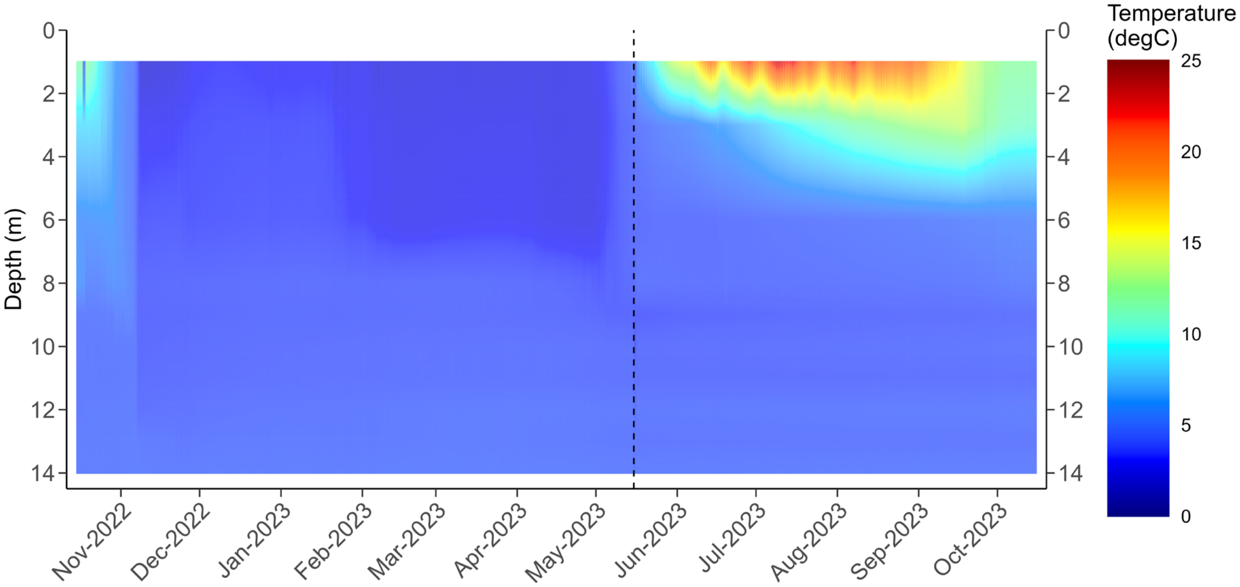

Figure 21 Temperature over time and depth from the mooring in Lak028 during October 15, 2022 through October 15, 2023. Measurements were taken at 10 depths every 30 minutes and data between those depths and times were linearly interpolated.

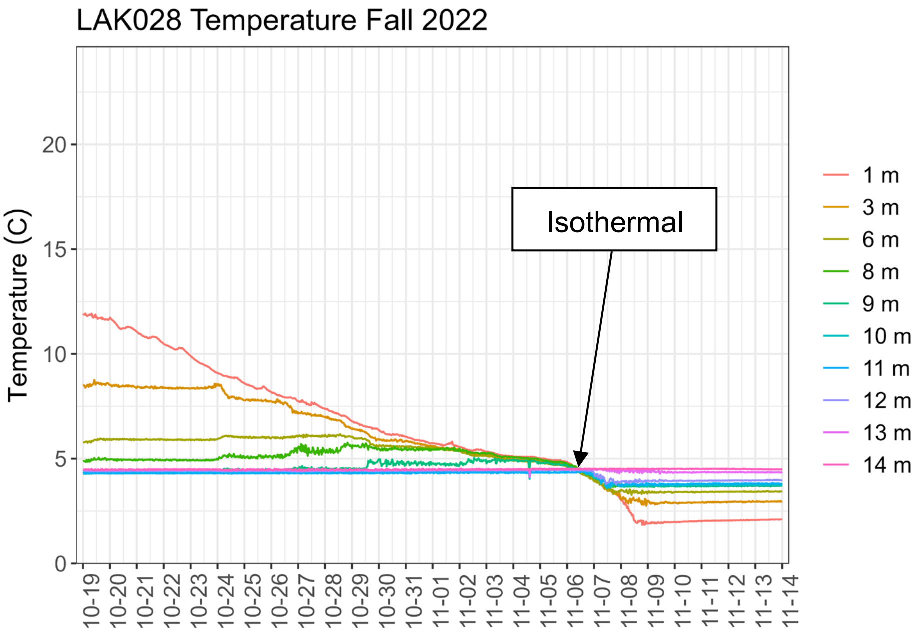

Figure 22 Temperature over time and depth from the mooring in Lak028 during October 19, 2022 through November 14, 2022 to highlight brief isothermal conditions occurring on November 6th in 2022.

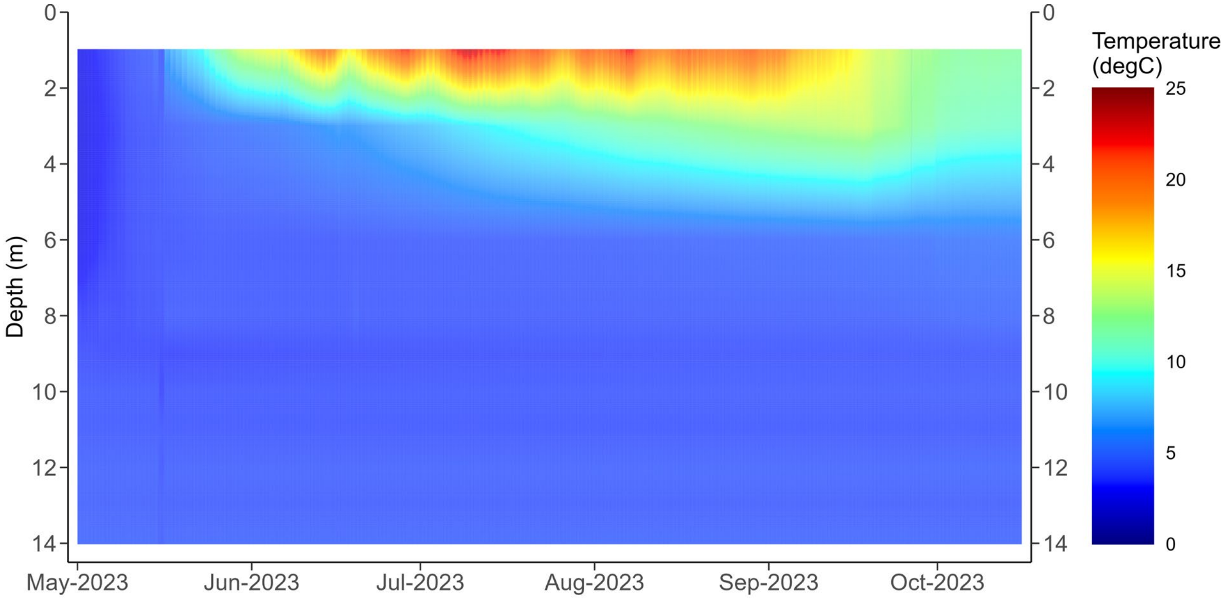

Figure 23 Detail of water temperature over time and depth during May through October 2023 in LAK028.

A strong oxycline was present at 8-10 m in LAK028 from May through October 2023 (Figure 24). DO concentrations were >8 mg·L^{-1} above the oxycline, and the lake was mostly anoxic below the oxycline. DO concentrations >11 mg·L^{-1} were found in mid-May at water depths <8 m, possibly associated with photosynthetic production of oxygen. This effect declined during mid-July to mid-September. Although depths and concentrations of dissolved oxygen concentrations varied slightly, these patterns were similar to those found in 2021 and 2022 (Limnotek 2023).

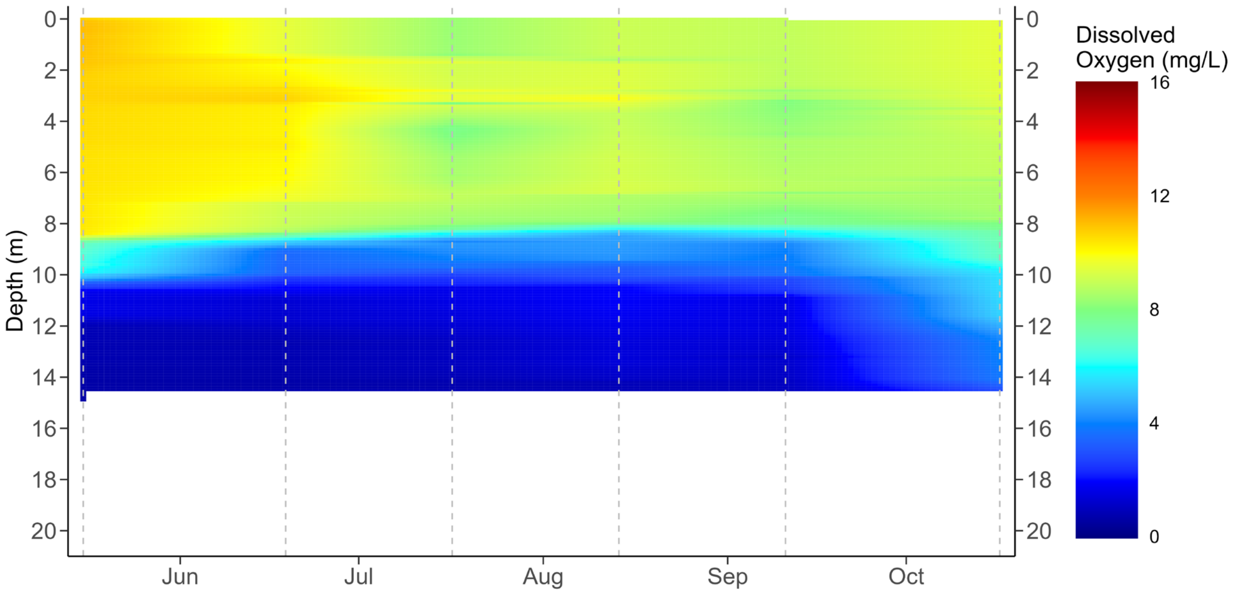

Figure 24 Dissolved oxygen concentrations from CTD casts among dates and depths in LAK028 at the raft station in 2023. The vertical dotted lines indicate dates of measurement. Data between those dates were linearly interpolated.

A stable chemocline observed in Lak028 in previous years (Limnotek 2023) was again found in 2023 (Figure 25). Two anomalies were detected in the continuous conductivity data of 2023. Low conductivity water abruptly extended from 10 m to 12 m, coinciding with the onset of isothermal conditions on November 6, 2022. In March 2023, a reverse shift occurred in which there was a 2 m upward migration of high conductivity water. In spring through fall, 2023, the chemocline was consistently between 13 m and 14 m.

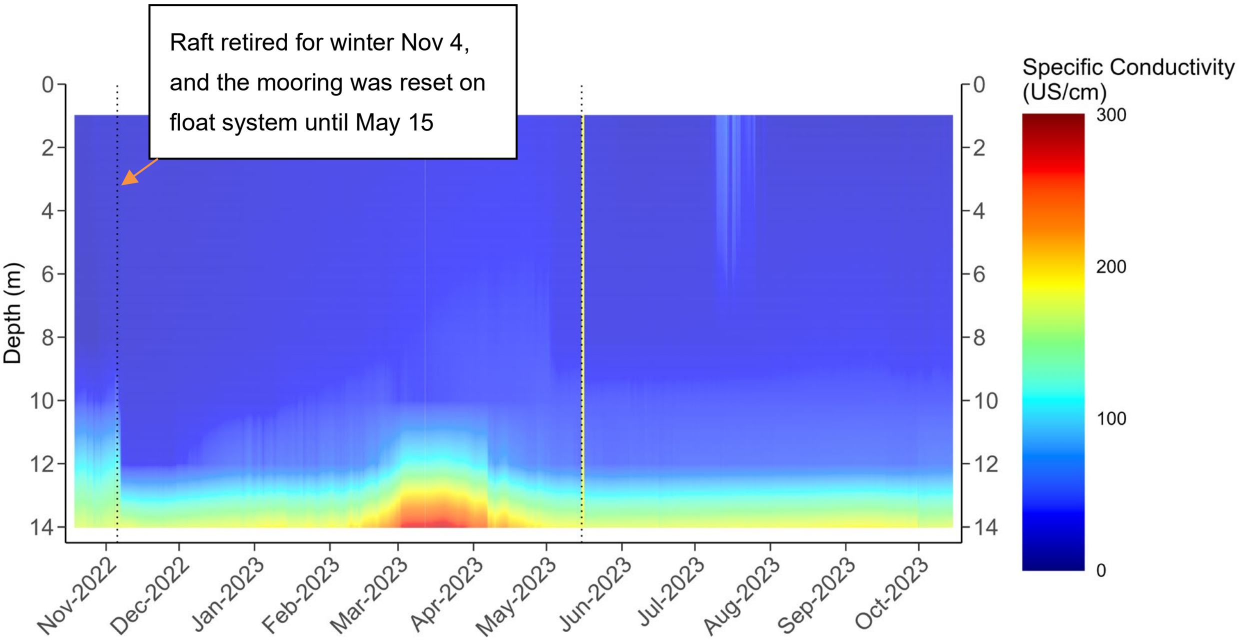

Figure 25 Specific conductivity from the LAK028 mooring among dates and depths in 2023. The vertical dotted line in November 2022 indicates the date the mooring was reset from the raft to the float system. The vertical line in May 2023 shows a one-day removal of the mooring for data download. The conductivity loggers were placed at water depths of 1 m, 8 m, 10 m, 12 m and 14 m on the mooring. Data between those depths were linearly interpolated.

The 2023 chemocline depth was narrower than in previous years (Figure 26), which affected chemical attributes of deep water samples that were routinely collected from a water depth of 13 m in all years. That depth was well within the chemocline before 2023 but not in 2023. The result was that 2023 deep water samples (from 13 m depth) had lower conductivity and were less affected by chemical reducing conditions that were obvious before 2023. It is unknown why the chemocline was more constrained and in closer proximity to lake sediments in 2023 compared to previous years.

Despite this attenuation of the chemocline, chemical differences between water above the chemocline and water in transition into the chemocline were found in 2023. They were just less than in previous years (Table 10). Particularly noteworthy were the differences in SO_4 concentrations that showed greater oxidizing conditions at the 13 m depth in 2023 than earlier. The inter-year differences at that depth in conductivity, Gran ANC, NH_4-N, TN, SRP, TDP, and DIC were other indicators of less reducing conditions at 13 m than in previous years.

The CTD casts from LAK028 showed variation in turbidity by depth in 2023 (Figure 27) as was found in previous years (Limnotek 2023). Relatively high turbidity at depth was possibly associated with bacterial assemblages within anaerobic meromixis of the chemocline (*e.g.* Tonolla et al 2014).

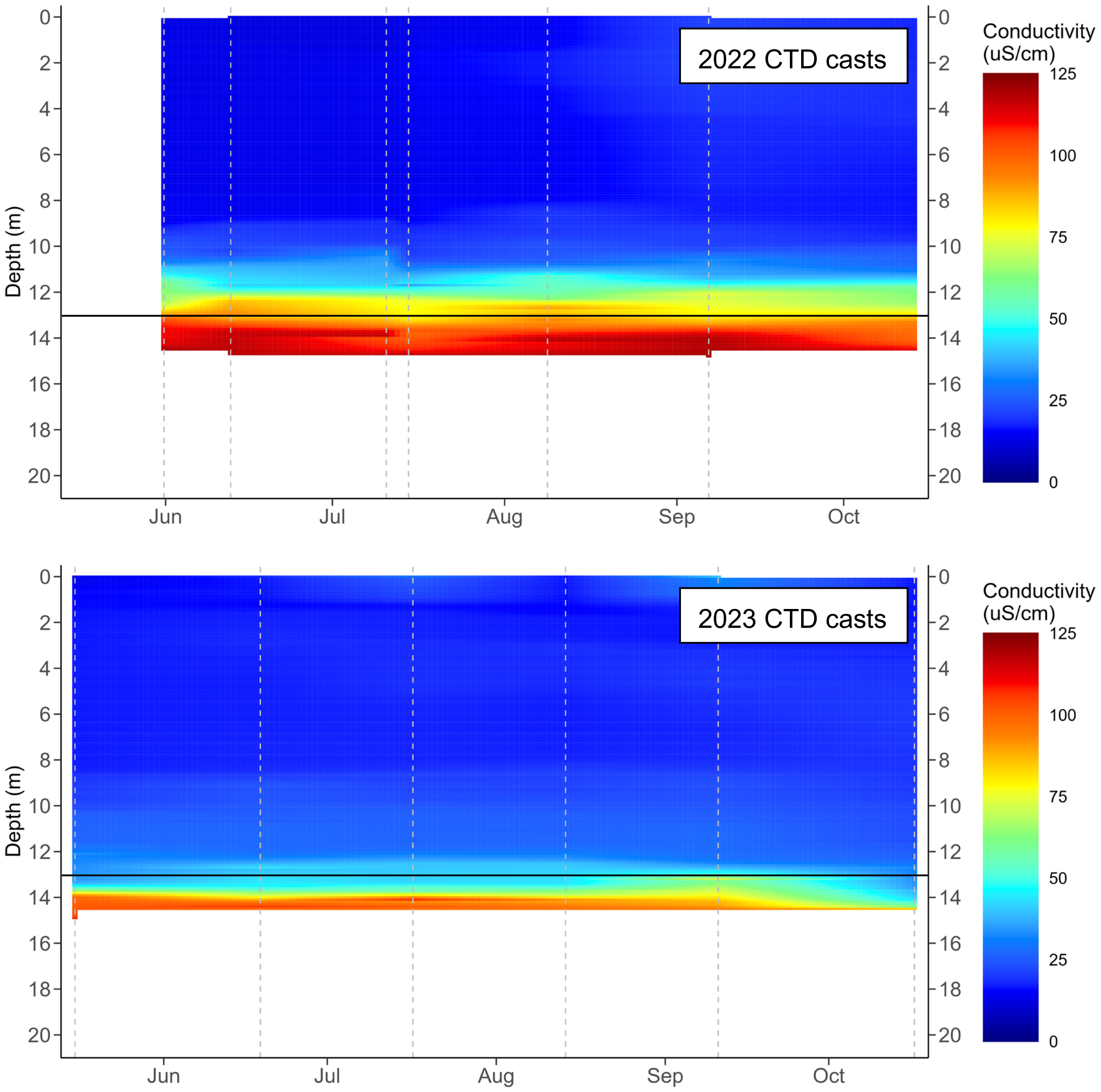

Figure 26 Specific conductivity from the CTD casts across dates and depths in LAK028 at the raft station in 2022 (top) and 2023 (bottom). The vertical dotted lines show dates of measurement. Data between those dates were linearly interpolated. The horizontal black line marks the depth of deep water samples (13 m) to highlight the difference in conductivity at that depth between 2022 and 2023.

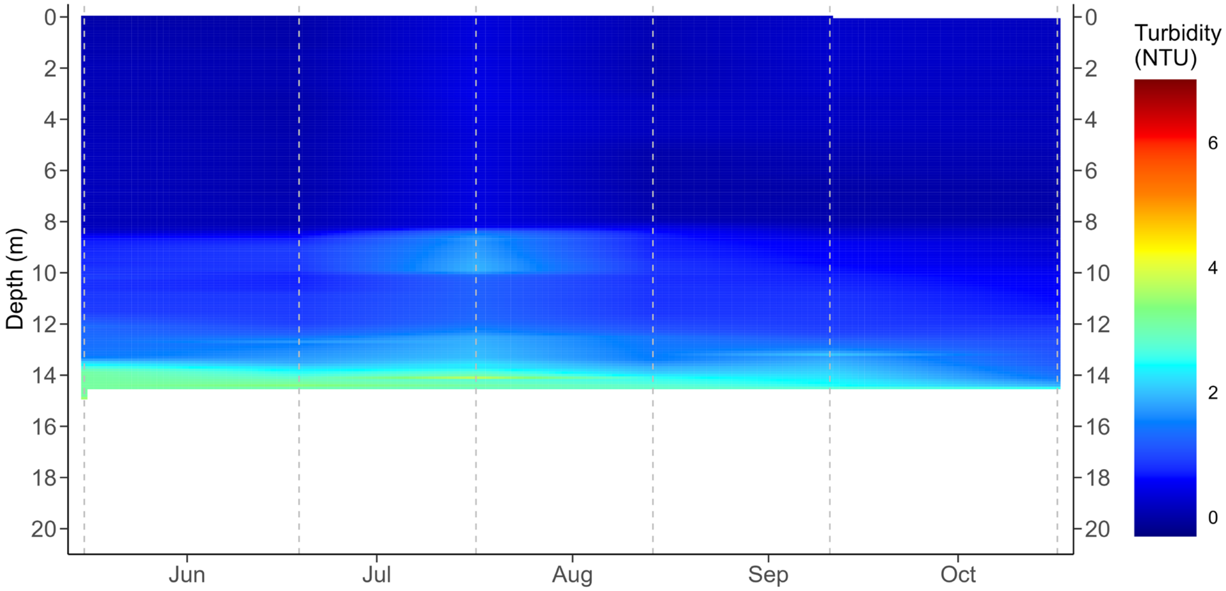

Figure 27 Turbidity from CTD casts across dates and depths in LAK028 at the raft station in 2023. The vertical dotted lines indicate dates of measurement. Data between those dates were linearly interpolated.

Table 10 Average values of chemical attributes at water depths of 2 m and 13 m in LAK028 in May through October, 2023 compared to average values in the same months in 2020, 2021 and 2022.

Analyte	**Units**	**Mean value or concentration ± standard deviation in LAK028**			
		2023		**2020 – 2022**	
		Surface (n=9)	**Deep (2 m off bottom) (n=9)**	**Surface (n=26)**	**Deep (2 m off bottom) (n=26)**
SO_4 (sulfate)	$mg \cdot L^{-1}$	4.0 ± 0.3	1.0 ± 0.7	4.7 ± 1.4	0.2 ± 0.3
Sulfide (as H_2S)	$mg \cdot L^{-1}$	<0.01	0.6 ± 0.2	<0.01	0.6 ± 0.1
Specific conductivity	$\mu S \cdot cm^{-1}$	16 ± 2	37 ± 10	18 ± 4	67 ± 11
Total dissolved solids	$mg \cdot L^{-1}$	34 ± 32	71 ± 13	30 ± 20	74 ± 13
pH- WTW field meter	pH units	5.3 ± 0.1	6.0 ± 0.1	5.0 ± 0.2	6.1 ± 0
pH - BASL	pH units	5.3 ± 0.1	6.0 ± 0.1	5.1 ± 0.2	6.1 ± 0.1
pH - ALS (low ionic strength method)	pH units	5.3 ± 0.2	6.1 ± 0.1	5.1 ± 0.2	6.3 ± 0.2
Gran Alkalinity – BASL	$mg \cdot L^{-1}$ as $CaCO_3$	0.4 ± 0.3	13.9 ± 6.0	0.3 ± 0.9	33.0 ± 7.0
NH_4-N (total ammonia as N)	$\mu g \cdot L^{-1}$	8 ± 5	1885 ± 906	6 ± 2	3859 ± 776
NO_3-N (nitrate as N)	$\mu g \cdot L^{-1}$	39 ± 96	<5	13 ± 11	5 ± 1
TN (total nitrogen)	$\mu g \cdot L^{-1}$	127 ± 15	2244 ± 953	149 ± 36	4205 ± 636
SRP (soluble reactive phosphorus)	$\mu g \cdot L^{-1}$	<1	<1	1.1 ± 0.5	2.5 ± 1.4
TDP (total dissolved phosphorus)	$\mu g \cdot L^{-1}$	2.2 ± 0.3	14.9 ± 3.5	3.9 ± 2.5	24.2 ± 4.4
TP (total phosphorus)	$\mu g \cdot L^{-1}$	6 ± 3	30 ± 5	6 ± 3	38 ± 8
DOC (dissolved organic carbon)	$mg \cdot L^{-1}$	4.4 ± 0.7	12.6 ± 2.1	6.2 ± 1.6	14.3 ± 1.5
DIC (dissolved inorganic carbon)	$mg \cdot L^{-1}$	0.7 ± 0.3	7.0 ± 2.5	1.4 ± 3.1	15.3 ± 3.8

3.7 Trophic State Index

All lakes sampled in 2023 were oligotrophic to mesotrophic (Table 11), with two lakes bordering on eutrophic (LAK012 and LAK023) based on the chlorophyll-a TSI. All lakes, except NC184, had higher TSI values based on chlorophyll-a compared to TSI values based on TP. All but five lakes would be classified as oligotrophic using the TP based index (oligotrophic <30).

Time course of TSI based on TP showed no change in trophic state in four oligotrophic lakes (DCAS14A, LAK027, NC184, NC194), two oligo-mesotrophic lakes (LAK006, LAK028) and three mesotrophic lakes (LAK016, LAK022, and LAK042) over 10 years (Figure 28). In the remaining three lakes, there appears to be an upward trend in trophic state from 2013 to 2023 (LAK012, LAK023, and LAK044).

Table 11 Trophic State of EEM lakes and control lakes (DCAS14A, NC184, NC194) and one non-EEM lake (LAK027) based on a Trophic State Index (TSI) value defined by Wetzel (2001) based on Chlorophyll-a or Total Phosphorus concentration. TP are from surface water samples. Chlorophyll-a data are from the euphotic zone or from the surface water on Sept. 30, 2023.

Station	Secchi Depth(m)*	TSI [Chl-a]**	TSI [TP]***	Classification [Chl-a]
DCAS14A	NA	36	24	Mesotrophic
LAK006	5.1 (n=3)	33 (n=4)	28 (n=9)	Mesotrophic
LAK012	2.7 (n=3)	52 (n=4)	40 (n=4)	Mesotrophic - Eutrophic
LAK016	NA	31	29	Mesotrophic
LAK022	NA	35	34	Mesotrophic
LAK023	2.0 (n=3)	50 (n=4)	42 (n=4)	Mesotrophic
LAK027	NA	35	22	Mesotrophic
LAK028	3.6 (n=3)	37 (n=4)	29 (n=9)	Mesotrophic
LAK042	1.5 (n=3)	45(n=4)	39 (n=4)	Mesotrophic
LAK044	4.5 (n=3)	39 (n=4)	38 (n=4)	Mesotrophic
NC184	NA	23	26	Oligotrophic
NC194	NA	27	18	Oligotrophic

*based on 3 measurements in late September and October, 2023

**based on a single value from a surface water sample on Sept. 30, or a mean value from a surface sample on Sept. 30 and 3 samples from the eutrophic zone in Sept./Oct. (n=4)

***based on single surface water sample on Sept. 30, or a mean of values from Sept. 30 and 3 samples in Sept./Oct. (n=4), or a mean value of all measurements from May-Oct. (n=9, for LAK006 and LAK028 only)

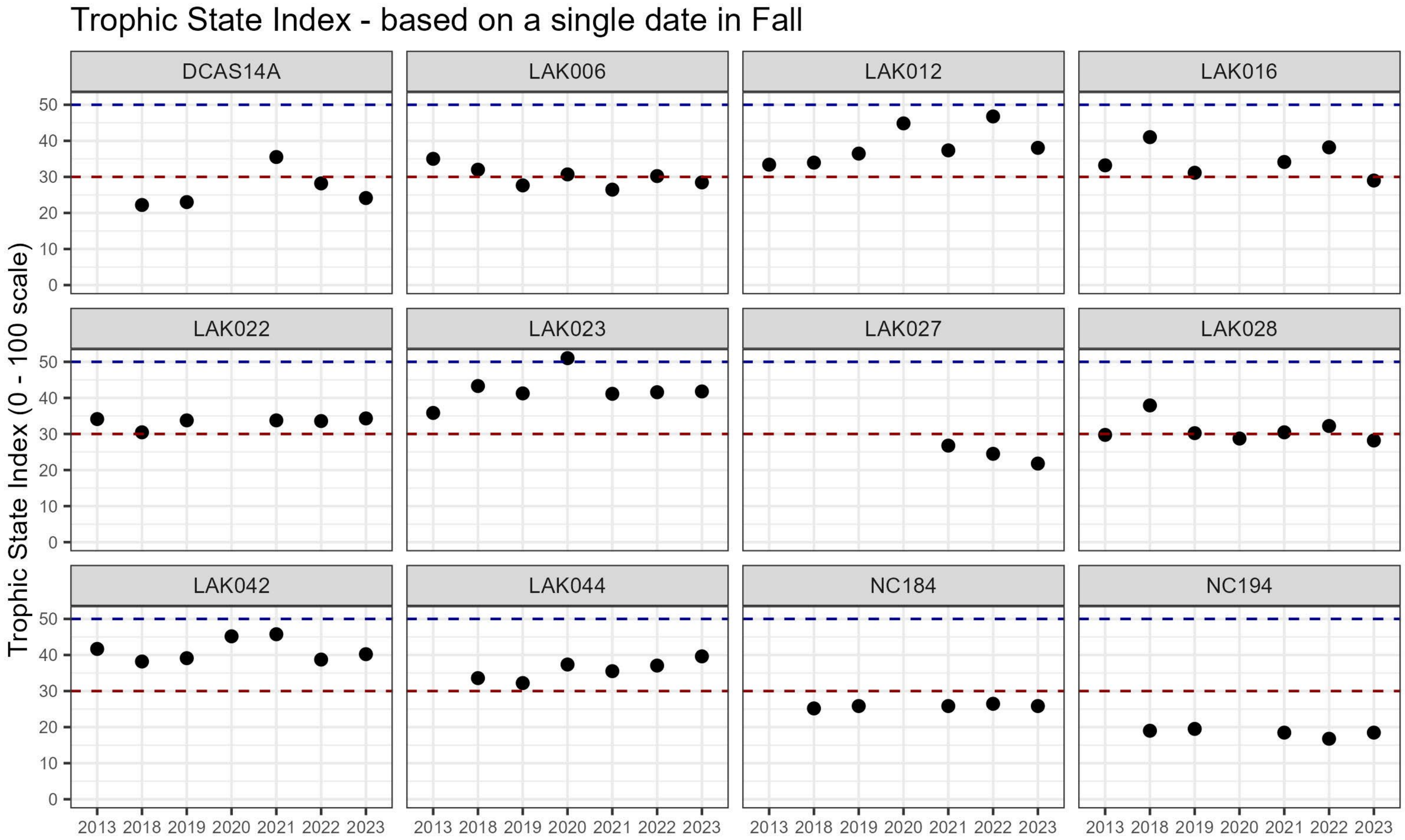

Figure 28 Trophic state index values by year based on a single day measurement of Total Phosphorus during the annual EEM fall lakes sampling. The dark red dashed line indicates the threshold from oligotrophic (<30) to mesotrophic (30 – 50) while values above the blue dashed line indicate an eutrophic lake (>50). There were no measurements of Total Phosphorus from 2014 to 2017.

4 DISCUSSION AND RECOMMENDATIONS

4.1 Data compilation

Data from 2023 were appended to those from previous years (2012 to 2022) to provide an up-to-date compilation of chemical and other descriptive information for further analysis by ESSA Technologies. This process of continuous updates provides a single source of data for review, analysis, and reporting over time. Formatting is structured as a long data frame for reading in R (R Core Team 2022) or other software.

4.2 Quality of chemical data

High precision and excellent percent recovery among analytes provided confidence that the ALS lab was providing sufficient repeatability and accuracy of sample data in 2023.

In past years, positive blanks were minor and coincident with changes in lab supplies (*e.g*. filter type or gloves) (Limnotek 2023). In 2023, there were no changes in supplies that could have caused contamination during sample filtering or handling. A switch to disposable Sartorius Minisart® syringe filter (28 mm, 0.45 µm Hydrophilic Teflon DIGIFilter) cartridges from the previously used Swinnex filter system with GN-6 Metricel® 0.45 µm, 47 mm membrane disc filter made of mixed cellulose esters was made in late 2021. The change in filter effectively eliminated DOC contamination in 2022 and no DOC contamination was found in blanks in 2023.

Recommendation 1. Use Sartorius Minisart® syringe filter (28 mm, 0.45 µm Hydrophilic Teflon DIGIFilter) or similar product for all sample filtrations to avoid DOC contamination caused by filters composed of cellulose esters. A larger diameter Teflon filter may also be used in the Swinnex filter apparatus to avoid DOC contamination.

The source of dissolved Cu, Pb and Zn contamination in the September 27th filtered blank, and Na and total Zn contamination in the October 10th unfiltered blank is not clear. The sample bottles were not uncapped before use and all bottles were precleaned using an automated process by the supplier. If there was contamination at this source, more contamination incidences affecting bottle preparation would be expected. This did not happen. A switch to lab tested vinyl gloves from nitrile gloves was recommended after the 2022 field season since nitrile gloves can carry metals contamination, and specifically zinc (T. Chang, ALS Lab Manager, pers. comm.). However, in 2023, nitrile gloves were again provided by the lab despite a request for “gloves for metals sampling”. Use of these gloves may have introduced contamination, but only if water being dispensed to the sample bottles passed over the gloves, which is not likely because of the way the bottles are held during pouring. The coincidence of Zn and Na contamination in the one blank bottle on October 10 and use of zinc acetate and sodium hydroxide to preserve samples for sulfide analysis cannot be ignored. Transfer of residual preservative from the outside of one of the total sulfide bottles onto the gloves and into the total metals bottle may have occurred. This possibility seems remote because preservative was never spilled onto the outside of sample bottles and gloves were always positioned “downstream” of the bottle intake during dispensing. However remote this path of contamination might be, it is a possible source of error. There are two recommendations to resolve these possible occurrences.

Recommendation 2. It is recommended that all sample handling and filtrations in the field be performed using “lab-certified vinyl gloves for low level metals sampling in freshwater”, not nitrile gloves that may incidentally carry metals contamination. It is also recommended that a filtration stand be used to minimize repeated user contact with the syringe that is purged and filled several times during swapping out of several filter cartridges needed for completing the filtration of a single sample. An example filtration stand is shown in Figure 3.

Recommendation 3. It is recommended that bottles for total sulfides (precharged with zinc acetate and sodium hydroxide (NaOH) be handled separately from other bottles. Gloves should be changed after labelling or filling bottles for total sulfide and samples should be stored in a ziplock bag separate from other lake samples to minimize the risk of cross-contamination of the preservative to other samples.

4.3 Instrument effects on pH measurement

A recommendation following the 2022 field season was to replace all the pH loggers and start the field season with all new instruments. Starting the season with five new loggers and six new electrodes for three stations was effective in eliminating logger failure in 2023. The instruments were calibrated and downloaded a minimum of once per month, and every second month a new logger/electrode combination was assembled, tested in the lab, and used to replace the existing logger the following day. Elimination of electrode replacement in the field reduced the likelihood of logger failure due to the introduction of moisture into the instrument.

Recommendation 4. Start each field season with new pH loggers to minimize risk of both logger and electrode failure during the spring to fall field season. Five new pH loggers with new electrodes and six other replacement electrodes should be purchased new to start sampling each year. Three of the loggers will be installed to start in the spring (2 in LAK028, 1 in End Lake). The other two loggers will be carried into the field to be available for swapping out the installed loggers as needed during the field season. Replace the electrode on a given pH logger once every two months (not longer) to avoid electrode error on long term deployments.

Over years of the EEM, paired comparisons of pH among labs commonly showed pH measured at ALS to be greater than pH from a field instrument, field pH loggers, and the Biogeochemical Analytical Service Laboratory (BASL) at the University of Alberta. Two factors influenced the reported pH values: one was the duration of electrode immersion in a water sample before pH was recorded, and second was the duration that a water sample was exposed to air by removing the bottle cap before pH was recorded (Limnotek 2023). Exposure to air may allow a water sample to release CO_2, thereby increasing pH. This process is enhanced as a sample is warmed to room temperature from low temperature in the field or in a fridge.

Split sample testing of the effect of electrode immersion time on pH showed no significant difference in pH values with the longer electrode immersion times in 2023. Other studies have found that immersion times of up to 15 minutes may be needed in low conductivity waters (Busenberg and Plummer 1987) and two lines of evidence from this study in previous years support that finding: a significant test of paired replicates in 2020, and field tests in 2019 that found up to 9 minutes immersion time was needed for a stable instrument reading (Limnotek 2020 and 2021). However, a review of lab procedures in 2023 found that for samples shipped to ALS, samples for pH measurement using the routine pH method (3 minute) are exposed to air longer than samples for pH measurement using a longer immersion time (10 minute) due to increased handling time of uncapped samples prior to the routine (3 minute) measurement (Limnotek 2023). Longer sample exposure to air allows CO_2 degassing that can increase pH. Despite the finding of no significant difference in pH with immersion time in 2022 and 2023, this other evidence favours use of the 10-minute electrode immersion period when requesting pH measurement at ALS.

Recommendation 5. When requesting pH measurement at ALS, we recommend selection of the method that provides an electrode immersion period of 10 minutes, not the standard method in which the instrument times out after 3 minutes of electrode immersion. The longer immersion period allows for adequate stabilization of voltage in the low conductivity waters of the BC north coast. Water samples assigned to 10-minute immersion times are handled manually, resulting in a shorter time of sample exposure to air before analysis compared to automated handling that incorporates 3-minute electrode immersion times and relatively long periods during which a sample is uncapped before electrode immersion (C Fuginski, account manager, ALS, Pers. Comm.). This shorter time of sample exposure to air will minimize CO_2 degassing that can increase pH.

A survey was conducted in early 2023 to examine typical times that a sample is exposed to air prior to pH measurement between labs and field instruments. In order from longest to shortest, the exposure times at ALS 3-minute > ALS 10-minute ≥ BASL > WTW > Onset logger (Table 12). This ordering shows that the amount of CO_2 degassing was potentially greatest at ALS and lowest with the field instruments resulting in a high bias of pH at ALS compared to the other sources of pH measurement (Table 7, Figure 13, Figure 14, Figure 12). In this respect the “instrument effect” is actually an “air exposure time effect” (*i.e.* the amount of time a sample bottle cap is off the bottle prior to pH electrode immersion).

All statistical analyses of long-term trends in pH throughout the 12 years of the EEM program have been performed using pH measurements from Trent University and BASL. Previous statistical analyses of the two labs showed no significant differences in pH measurements from samples obtained in the 2019 field season (Limnotek 2020). Data from 2023 continues to support the use of BASL measurements of pH for analyses of long-term trends.

Notwithstanding this conclusion, measurement of pH using the field instruments is the most reliable way to achieve accurate pH measurement in samples from north coast lakes. The samples are both fresh and pH is measured following the smallest possible time of exposure to air. Another conclusion is pH is not affected by time between collection and analysis but rather by time between initial exposure to air after removing the sample bottle cap and immersion of the electrode for measurement of pH.

Table 12. Durations of exposure of a water sample to air before pH measurement between field instruments and labs (in alphabetical order by method). Data are from an email survey conducted in January 2023.

Time that a water sample is exposed to air after removing the bottle cap before making a pH measurement (minutes)				
ALS (10 minute electrode immersion method)*	**ALS (routine 3-minute electrode immersion method)***	**BASL****	**Onset pH logger**	**WTW field pH meter**
<30 minutes	<30 minutes then covered with film for up to 72 hours in the que, then up to 12 hours without the film cover while loaded on the autosampler	10 – 120 minutes depending on number of samples in the queue	0 minutes	<3 minutes
*C. Fuginski, account manager, ALS. Personal communication. January 11, 2023. **M. Ma, lab manager, Biogeochemical analytical service laboratory (BASL). Personal communication January 25, 2023.				

Findings in 2023 continue to support use of the WTW field instrument pH data for long term comparisons of pH among years, as an alternative to using data from Trent University and BASL. These field pH data have the longest record in the Rio Tinto SO_2 EEM program among all instruments dating back to the beginning of EEM measurements in 2014. The combined time series of pH measurements from Trent University and BASL go back to 2012, and previous analyses of 2019 data (Limnotek 2020) showed no significant differences between pH measurements from these two laboratories. In contrast, there are only five years of Onset data, and these data were collected in only two lakes. We don’t consider ALS data useful for showing long term trends despite it also having a long history because of potential upward bias in pH values related to high "air exposure time effect" on pH measurement.

Recommendation 6. pH data from BASL should continue to be used for statistical analyses of long-term trends, building on the time series of prior pH measurements from Trent University, and statistical methods used previously. For comparative purposes, pH data from the WTW field instrument could also be used for tracking long term changes. These field data have the smallest sample "air exposure time effect" that can affect pH results and they have the longest record of continuous measurement since the Rio Tinto SO_2 EEM program started.

We do not recommend tracking long term changes in pH values using the ALS data because it can have the strongest upwards bias associated with possible CO_2 degassing during relatively long durations that a sample may be exposed to air in the lab before pH measurement.

Recommendation 7. We recommend running an experiment to test the "air exposure time effect" on sample pH. An experiment is needed because to date our observations are coincidental. The experiment would answer the question as to how the duration of sample exposure to air affects sample pH using water from the north coast lakes. This test can be done with any instrument, but the instrument needs to be the same for all measurements. An example experiment that can be done in the field or lab is as follows.

1. 60 water samples with no air space in the bottles are collected from a lake at the same time. The bottles are the same ones used to send water samples to ALS or BASL.
2. 30 of the samples will have caps removed at a given start time in a field or other lab (called "capoff" bottles). The other 30 samples will not have caps removed at that start time (called "capon" bottles).
3. The caps of all 30 capoff bottles are removed at the same time and time noted.
4. The caps of three capon bottles are removed.
5. Immediately measure pH in three of the capoff bottles and the three capon bottles that had caps removed. Recap bottles and set aside in the fridge.
6. Ten minutes later, measure pH in another three of the capoff bottles. Remove caps from three more of the capon bottles and measure pH in each of those bottles. Recap and set aside in the fridge.
7. Repeat step 6 at various time intervals for all remaining capoff and capon bottles over 8 hours.
8. Draw curves to compare mean (±sd) pH change over time of exposure to air (capoff bottles) and pH change over time to no exposure to air (capon bottles). A difference between curves will show the effect of time of exposure to air on sample pH.

4.4 Meromixis in LAK028

Water chemistry data in LAK028 has been collected to characterize the chemocline and understand the influence of meromixis on chemical endpoints used by ESSA to interpret acid loading and acid neutralizing capacity that is part of the SO_2 Environmental Effects Monitoring Program (*e.g*. ESSA et al. 2022). Accumulation of salts near the lake bottom can be from sediments following decomposition of organic matter that can induce oxygen demand and it can be from release of solutes at the sediment – water interface that do not mix above a chemocline. The lake also has an ample supply of SO_4 originating at the lake surface that eventually is taken up and settles to sediments via assumed bacterial processes. The lake has a pothole shape with small surface area relative to depth and little exposure to wind, which inhibits mixing.

Prior to 2023, the CTD data showed the mixolimnion (the upper stratum of a meromictic lake) was underlain by a strong chemocline lacking oxygen with high conductivity and TDS, relatively high pH and Gran ANC, high soluble phosphorus concentration, and high DOC concentration possibly associated with sulfur-reducing bacteria (bacteria that use sulfur as an electron donor for their metabolism) and phototrophic sulfur bacteria.

Full year information from the conductivity and temperature moorings reported herein (Section 3.6) confirm a highly stable chemocline and no mixing with surface waters that are used to follow change in pH and Gran ANC as part of the Rio Tinto EEM of SO_2 emissions over years of monitoring. These data show a more condensed chemocline in 2023 compared to earlier years. Reasons for this change are not known but the more important finding is continued stability of the chemocline that does not confound interpretation of surface water chemistry for the EEM.

The conductivity and temperature mooring data are the most valuable among all measurements in tracking mixing in LAK028 and need to continue as defined in the following two recommendations.

Recommendation 8. To ensure that LAK028 surface chemistry is not confounded by possible future mixing affecting pH, Gran ANC, base cations, etc., monitoring of the complete water column is required during the course of sampling LAK028. Any future anomaly from LAK028 can then be investigated with respect to potential influence from change in stability of the chemocline. Year-round temperature and conductivity monitoring using in situ moorings must be included in this monitoring. They provide the most precise evidence of time course change in mixing while the wet chemistry provides backup evidence to support interpretation of the mooring data.

Recommendation 9. LAK028 conductivity mooring data can be improved to capture detail of changes in chemocline depth and thereby help with tracking stability in LAK028. Measurement depths as installed in July 2022 were 1 m, 8 m, 10 m, 12 m, and 14 m. It is recommended that one additional logger be placed at 13 m to capture the needed detail.

4.5 Trophic State

Trophic state is an indicator of water quality in lakes and an overall measure of biological production. TSI values ranged from 23 to 50 based on chl-a and 18 to 42 based on TP, which showed all lakes were oligotrophic (<30) or mesotrophic (30 – 50) regardless of what variable is used. Time course TSI[TP] based on a single measurement in the fall showed little or no change in these conditions over the past 10 years.

It is tempting to make comparison of the TSI to the same measure that has been published for other lakes. Here is where caution is warranted. For such a comparison, the inherent variables (*e.g.* chlorophyll-a and TP concentration) must be measured over a year or at least during a complete growing season of April through October on the north coast and samples must be representative of the euphotic zone (depth at which photosynthetically active radiation is greater than 1% of that the surface). Due to logistical constraints and time of decisions to start the trophic state sampling, we used a single fall measurement at the surface and a separate mean value for the euphotic zone measured weekly from mid-September to mid-October in 2023. These data lack sufficient precision to allow comparison to other published values. They can, however, be used as standardized values specific to this project and be compared in a relative way over time and space. We expect that if the trophic state of one or more lakes does change over time, that change will be detected in the fall TSI. It is possible this expectation will not happen if, for example, episodic algal blooms happen at times other than in the fall among lakes and those blooms are contributing to a change in trophic state. As a result, a fall TSI is not ideal but much better than no index for purposes of the Rio Tinto EEM. A recommendation is as follows.

Recommendation 10. Add chlorophyll-a concentration to the list of analytes to be measured in each lake regardless of when sampling occurs. Where lakes are ground accessible, sample from the complete euphotic zone. Resulting chlorophyll-a data along with TP concentration that is already part of the routine list of analytes can be used to calculate a TSI in three ways:

1. Among years from single measurements associated with the annual sampling of all lakes at the end of September or early October each year
2. Multiple samples collected during the fall at LAK006, LAK012, LA023, LAK028, LAK042, LAK044.
3. Monthly samples from the euphotic zone of LAK006 and LAK028 throughout the growing season (April to November)

If funding is available, it would be preferable to do item 3 for all lakes in item 2. The TSI from all six lakes could then be compared to values in the published literature.

A further recommendation is to use an automated method for determining depth of the euphotic zone.

Recommendation 11. It is recommended that a CTD instrument be used that has an irradiance sensor installed to allow direct readout of the depth of 1% of surface irradiance. That depth corresponds to the exact depth the euphotic zone that is needed for defining sampling depths for measurement of chlorophyll-a and TP concentration. The YSI instruments used to date do not meet these criteria. An example instrument that does meet these criteria is the RBR Maestro. The approximate measure of euphotic depth defined as twice the Secchi depth that was used in 2023 can be used as a backup.

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