Sulphur Dioxide Environmental Effects Monitoring for the Kitimat Modernization Project

Volume 1: 2019 Comprehensive Review Report, V.3 Final

October 15, 2020

Prepared for:

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Version Tracking Table

No.	Date	Summary of content /changes
V.1	October 31, 2019	Draft report for review by the B.C. Ministry of Environment and Climate Change Strategy
V.2	June 30, 2020	Draft report for KPAC review
V.3	October 15, 2020	Final report

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Executive Summary and KPI Report Card

Overview

In 2012 and 2013 a technical assessment was conducted for the Kitimat Modernization Project (KMP) to determine the potential impacts of sulphur dioxide (SO_2) emissions along four lines of evidence: effects on human health, effects on vegetation, effects on terrestrial ecosystems (soils), and effects on aquatic ecosystems (lakes and streams, and aquatic biota). Results were detailed in an SO_2 Technical Assessment Report (STAR)[1].

An SO_2 Environmental Effects Monitoring (EEM) Program was then developed to answer questions that arose during the technical assessment, and to monitor effects of SO_2 along these lines of evidence. Results from the SO_2 EEM Program inform decisions regarding the need for changes to the scale or intensity of monitoring, as well as decisions regarding the need for mitigation.

Section 9.2 of the 2013-2018 SO_2 EEM Plan[2] calls for a comprehensive review of the program in 2019. The purpose of the review is to :

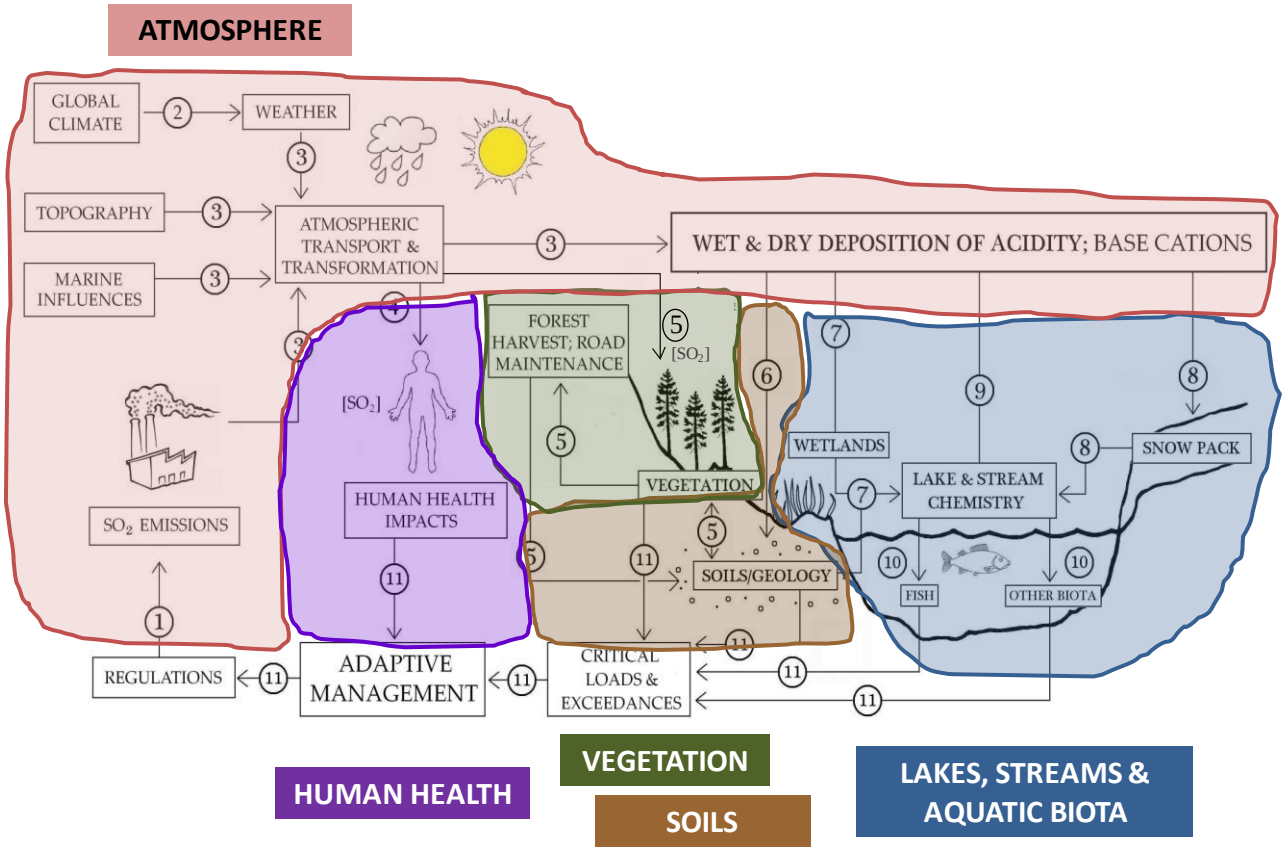
- Summarize what has been learned, and what questions have been answered,
- Describe which if any of the key performance indicator (KPI) thresholds have been reached, and if so, what actions were taken,
- Describe any modifications to KPIs, methods or thresholds that have been made based on annual results to date, and why,
- Look across the data sets of the four lines of evidence to develop an holistic understanding of KMP SO_2 effects on the environment and human health,
- Recommend changes if/as needed to: the suite of KPIs to be continued post-2018, their measurement methods, and/or their thresholds – along with the rationale for these recommended changes, and
- Recommend a date for the next comprehensive review.

The draft terms of reference for the comprehensive review were developed collaboratively by the team of scientists who led the design and implementation of the STAR and EEM Program. The draft terms of reference went through multiple cycles of review and revision with input from Rio Tinto and the Ministry of Environment and Climate Change Strategy (ENV).

This report presents the methods and results of the 2019 comprehensive review. The results and recommendations from the comprehensive review will inform adjustments to the ongoing SO_2 EEM Program, which could include modifications to some KPIs, modifications to how they are monitored, reductions in the overall set of KPIs, or reductions in monitoring effort for some KPIs. Discussions of these and other potential adjustments to the program (many of which are proposed in the comprehensive review) will occur during the development of the next SO_2 EEM Plan in 2020.

[1] ESSA et al. 2013
[2] ESSA et al. 2014a

The SO_2 EEM Program is designed around a source-pathway-receptor conceptual model that represents how SO_2 emissions from the smelter are transported and transformed in the atmosphere, and pathways of exposure for four receptors: human health, vegetation, terrestrial ecosystems (soils) and aquatic ecosystems (lakes, streams and aquatic biota). The conceptual model is shown in the figure below.



Source-pathway-receptor conceptual model for the SO_2 EEM Program.

Each receptor has at least one KPI, and KPIs have quantitative thresholds for action. The KPIs and their thresholds are listed in the table below.

The remaining pages of this section provide a brief summary of the comprehensive review results for atmospheric pathways and each of the four receptors. These are followed by a KPI Report Card that summarizes KPI performance and any adjustments that were made to the program during the first six years or are recommended for the program post-2019. This section ends with a brief summary of the holistic conclusions looking across all lines of evidence.

KPIs and KPI thresholds Receptors in the 2014 SO_2 EEM Plan:

	KPI	Threshold for increased monitoring	Threshold for receptor-based mitigation	Threshold for facility-based mitigation
Human Health	British Columbia Air Quality Objective measured at residential air monitoring stations	NA – there is no threshold for increased monitoring for this KPI	NA – there is no threshold for receptor-based mitigation for this KPI	3-yr average of 97th percentile of the daily one-hr average maximum (D1HM) for 2015-2017; 97.5th percentile for 2016-18; 98th percentile for 2017-2019 There is an allowance of a one-time exceedance of the 75 ppb threshold to a maximum concentration of 85 ppb over 2017-2019
Vegetation	Visible vegetation injury caused by SO_2	More than occasional symptoms of SO_2 injury outside of Rio Tinto Alcan Kitimat properties, causally related to KMP	NA – there are no reasonable receptor-based mitigations	Severe & repeated symptoms of SO_2 injury outside Rio Tinto properties causally related to KMP, including species of economic or social/ traditional importance, or symptoms of SO_2 injury causally related to KMP at long-distance (>15km) monitoring locations
Terrestrial Ecosystems (Soils)	Atmospheric S deposition and critical load exceedance risk	S deposition causally related to KMP emissions exceeding CL in > 1% (~20 km^2) of semi-natural upland forest soils in the study area	S deposition causally related to KMP exceeding CL in >5% (~100 km^2) of semi-natural upland forest soils in the study area within 200 years	S deposition causally related to KMP emissions exceeding CL in >5% (~100 km^2) of semi-natural upland forest soils in the study area within 100 years (based on projected change in base cations)
	Long term soil acidification attributable to S deposition	For one plot: a 40% decrease in 5 years or a 20% decrease in 10 years in exchangeable cation pools for at least one element, and decrease is causally related to KMP emissions	For one or more plots: a 40% decrease in 5 years or a 20% decrease in 10 years in exchangeable cation pools for at least 1 element and in >1% (~20 km^2) of the area of semi-natural upland forest soils	Decrease in the magnitude of exchangeable cation pool of >20% in 10 years, and in > 5% (~100 km^2) of the area of semi-natural upland forest soils, based on modelling, and decrease is causally related to KMP
Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)	Water chemistry - acidification	Observed decrease in pH ≥ 0.30 pH units below mean baseline pH level measured pre-KMP in one or more of the 7 acid-sensitive lakes, and other evidence	More intensive sampling confirms a decrease causally related to KMP of> 0.30 pH units below mean baseline pH level pre-KMP and liming is feasible	More than 2 lakes rated Medium or High (based on relative lake rating) with decrease causally related to KMP of> 0.30 pH units below measured baseline pre-KMP (prior to liming)

Atmospheric Pathways Summary

The CALPUFF dispersion model used in the STAR predicted post-KMP SO_2 concentrations and total sulphur deposition throughout the Kitimat Valley. These atmospheric SO_2 and total sulphur deposition predictions were used to complete receptor-specific impact assessments along the four lines of evidence. In this comprehensive review, we set out to learn how accurate the STAR model predictions were. We also set out to develop more accurate model predictions of current and future post-KMP atmospheric SO_2 and total sulphur deposition using a new CALPUFF model analysis. The new CALPUFF results are used to complete updated receptor-specific impact assessments to vegetation, and terrestrial and aquatic ecosystems.

We use SO_2 atmospheric concentrations to assess the risk of direct impacts on human health and vegetation. Measured SO_2 atmospheric concentrations are used to assess health impact; modelled and measured SO_2 concentrations are used to evaluate the risk of direct injury to vegetation. We use predictions of atmospheric deposition under different emission scenarios to assess the risk of impacts on vegetation, terrestrial, and aquatic ecosystems. Since the effects of SO_2 concentrations and sulphur deposition on receptors are assessed in receptor-specific evaluations, there are no KPIs for atmospheric concentrations or atmospheric deposition. The atmospheric pathway has one atmospheric concentration informative indicator: atmospheric SO_2 concentrations, which is measured through three types of equipment: continuous SO_2 analyzers, passive SO_2 monitors, and filter packs (to assess what fraction of sulphur is in particulate form), and modelled using the CALPUFF model. There are also two atmospheric deposition informative indicators: atmospheric sulphur deposition and base cation deposition, which is measured at two NADP monitoring sites within the study area; sulphur deposition is modelled using the CALPUFF model.

Three SO_2 emission scenarios were modelled: actual emissions from the smelter during 2016-2018 which averaged 29.3 tonnes per day (tpd), a 42 tpd scenario representing the highest level of SO_2 emissions allowed under the permit, and a 35 tpd scenario representing SO_2 emissions of a magnitude that is midway between actual emissions and the maximum allowable.

What did we learn during the first six years of the SO_2 EEM Program?

The updated regional-scale 2016–2018 CALPUFF modelling reduced uncertainty in post-KMP model predictions. We used as-built source parameters and actual 2016–2018 SO_2 emission rates from the smelter, combined with corresponding 2016–2018 meteorological data, to evaluate the model performance. We learned that this new regional-scale 2016-2018 model is more accurate overall than the STAR model. In particular, the new model aligns with observations better than the STAR model at all residential monitors. In addition, the STAR model under-predicted slightly at the Haul Road monitor, while the new model over-predicts at the Haul Road monitor at a level similar to over-prediction at the other continuous monitors (the regional-scale model predicted 3-year average SO_2 at Haul Road of 1.8 times the 3-year average monitored SO_2 concentration). In addition to its value for evaluating CALPUFF model accuracy, the continuous SO_2 monitoring data also show monthly average trends indicating the Haul Road (fenceline) concentrations have generally increased with increasing SO_2 emissions from the smelter, while SO_2 concentrations in residential areas are influenced more by meteorological conditions than by changes in SO_2 emission rates.

We used the local-scale CALPUFF model to evaluate the SO_2 monitoring network. The CALPUFF results indicate that the Riverlodge monitor station is located near the highest concentrations within the town of Kitimat, and that the most suitable locations for measuring the highest concentrations within Kitamaat Village are along the western shoreline of Kitamaat Village. This analysis is preliminary based on new CALPUFF results only. The formal conclusions for the continuous SO_2 monitoring network evaluation and optimization will be made in the Phase 2 monitoring network optimization report.

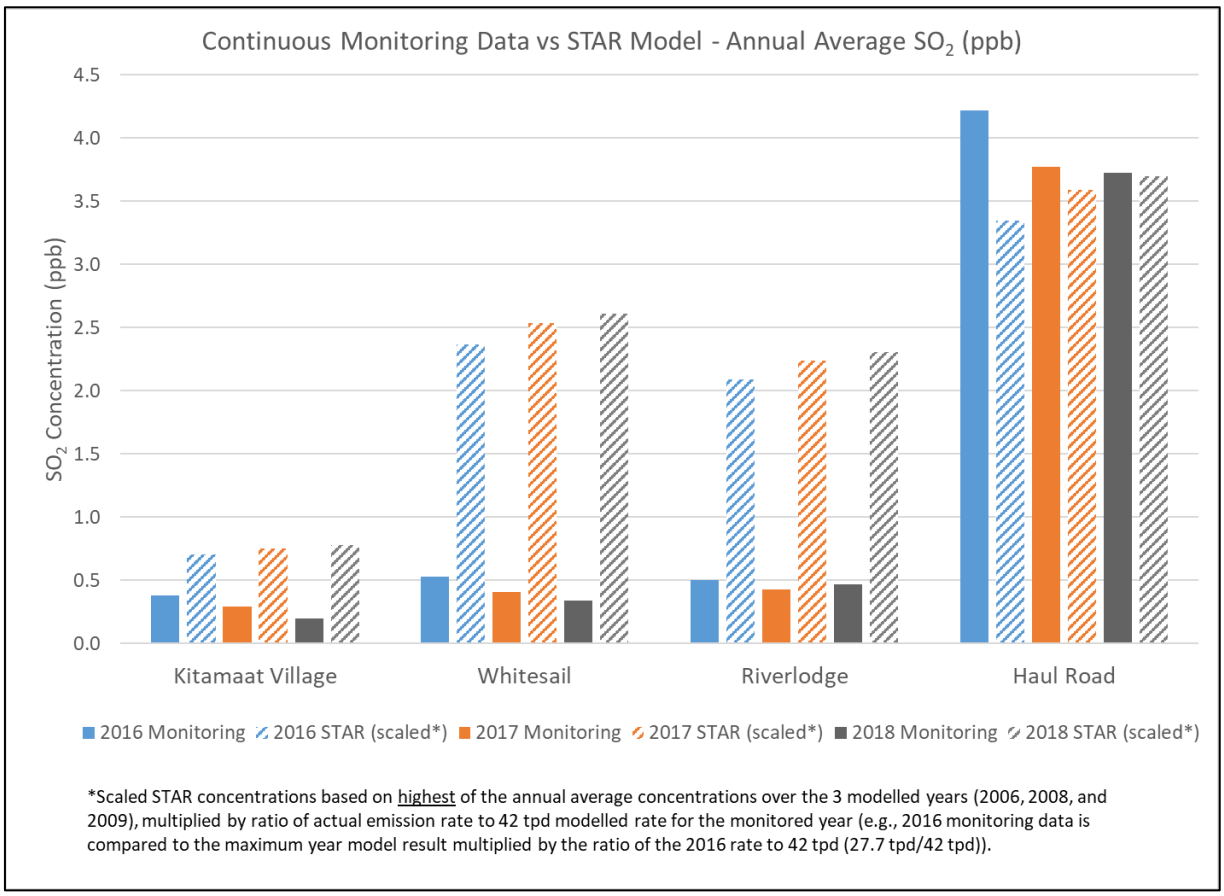
The passive sampling urban network study confirmed the entire Kitimat urban area has low SO_2 concentrations. Passive sampling at sites co-located with existing monitoring stations demonstrated that there was a strong linear relationship between estimates of the average monthly concentration of SO_2 from the passive samplers and monthly averages based on the continuous SO_2 analyzers. The network of passive samplers along the Kitimat Valley revealed that average monthly concentrations of SO_2 were highest close to and south of the smelter (about 12 $\mu g/m^3$), and then declined exponentially with distance from the smelter (reaching < 2 $\mu g/m^3$ at Lakelse Lake). A short study of particulate sulphate sampling using filter packs also confirmed that only a very small fraction of total sulphur in the atmosphere is particulate sulphate.

The new 2016–2018 CALPUFF model predicts a similar spatial distribution of deposition as was predicted in the STAR, however some differences are notable; the 7.5 kg SO_4^{2-}/ha/yr isopleth extends farther to the southwest, and does not extend as far to the north.

Only a small fraction of SO_2 emitted from the smelter is deposited through wet or dry deposition within the study area. This fraction is 8.1% for the 42 tpd scenario based on the 3-year average new 2016–2018 CALPUFF model results. The remaining SO_2 stays in the atmosphere and eventually exits the model domain. Deposition rates beyond the CALPUFF domain are well below levels we use to define the effects domain for terrestrial ecosystems (7.5 kg/ha/yr), and the primary area used to select lakes for study in the STAR (10 kg/ha/yr).

STAR question A1: Does the CALPUFF model accurately predict post-KMP SO_2 air concentrations?

As detailed in the annual EEM reports, comparisons performed each year between continuous SO_2 monitoring data and CALPUFF model results showed that the actual measured SO_2 concentrations were substantially lower than model predictions of post-KMP SO_2 concentrations from the STAR at most locations, and near model predictions at Haul Road. This comparison confirmed expectations based on the STAR CALPUFF model comparison of pre-KMP model results to pre-KMP monitoring data: that CALPUFF model results in the STAR over-predicted post-KMP SO_2 concentrations at most locations. Annual average STAR SO_2 concentration over-predictions at residential continuous SO_2 monitoring sites ranged from 1.9 times (compared to 2016 at Kitamaat Village) to 7.7 times (compared to 2018 at Whitesail); while the concentrations were slightly under-predicted at Haul Road as shown in the figure below (which includes the background concentration used in the STAR of 0.4 ppb).



The updated 2016–2018 CALPUFF model reduces uncertainty in post-KMP model predictions by using as-built source parameters and updated meteorological data. The new 2016–2018 model aligns with observations better than the STAR model at all residential monitors, and the new model over-predicts at the Haul Road monitor by 1.8 times compared to a slight under-prediction at Haul Road by the STAR model.

Analysis of data from the passive samplers revealed that the amount of CALPUFF over-prediction by the new CALPUFF model was relatively uniform in the Kitimat Valley to the north, with under-prediction to the south of the smelter (comparison based on only a few passive samplers south of the smelter).

STAR question D1: Does the CALPUFF model accurately predict post-KMP total sulphur deposition?

Overall, the new CALPUFF model predictions of total sulphur deposition compare well to the monitored results. When considering that the model results do not include background deposition (which may be up to 3.6 kg SO_4^{2-}/ha/yr), the new model over-estimates actual deposition rates at Haul Road by 24% to 29% and predicts actual deposition at Lakelse Lake from 16% under-estimation to 47% over-estimation (three-year average comparison of observed to modelled without background and to modelled with maximum background).

STAR question D2: What are the base cation deposition values in the study region?

We evaluated annual base cation (BC = Ca^{2+} (calcium) + Mg^{2+} (magnesium) + K^+ (potassium) + Na^+ (sodium)) precipitation chemistry at three NADP stations (Haul Road, Lakelse Lake and Port Edward) during 2014–2018 (2013–2018 for Haul Road). Following correction for sea salts, Mg^{2+} and Na^+ were zero at both stations (i.e., there was no observed non-sea salt deposition of Mg^{2+} and Na^+). Long-term $Ca^{2+}$and K^+ in precipitation were almost equal at Lakelse Lake and Port Edward. In contrast, the precipitation concentrations at Haul Road were 1.5 (K^+) to >2 (Ca^{2+}) times larger than the other two sites. It was assumed that precipitation chemistry at Haul Road was influenced by anthropogenic sources; as such, regional base cation precipitation was set to the average for Lakelse Lake and Port Edward. Average base cation concentration in precipitation was estimated as 0.8 µeq/L.

Did we make any adjustments to the SO_2 EEM Program during 2013-2018?

We added a new informative indicator to the SO_2 EEM Program: contribution of dry deposition to total deposition. This indicator is not used to assess impacts due to sulphur deposition, but provides valuable information to understand the factors that could lead to variation in deposition rates.

What changes do we recommend to the SO_2 EEM Program going forward?

Overall, we recommend continuing the atmospheric monitoring within the SO_2 EEM Program. The Phase 1 monitoring network evaluation indicated that the Riverlodge monitor site is in the most suitable location for measuring the highest concentrations within the town of Kitimat, and that the Kitamaat Village monitoring station is in the best location for Kitamaat Village. The Kitimat Haul Road station should also be continued because it serves as a fenceline monitor with a long historic record. The Phase 2 network evaluation is planned to start in the second quarter of 2020. Therefore, no changes should be made to these monitoring stations until and unless the Phase 2 network evaluation recommends changes. Lastly, we recommend establishing a temporary or fixed continuous SO_2 monitoring station within the Service Centre commercial area to provide information on model performance in this area. These recommendations are preliminary and may change as a result of the final Phase 2 network optimization effort.

We also recommend continuing the passive sampling network in the Kitimat Valley because it adds value for understanding the spatial distribution of SO_2. In particular, the passive sampling network added substantial value for evaluating CALPUFF model performance. Accurate CALPUFF prediction of SO_2 (and sulphur deposition) reduces uncertainty when using the CALPUFF output for evaluating impacts to receptors. However, the number of sites and frequency of monitoring should be reviewed. For example, in order to gain a better understanding of the plume position and extent in the east-west direction, we recommend adding passive sampling sites to the east and west of current sites located the north of the smelter, where possible based on access and British Columbia (B.C.) air monitoring site selection guidelines for passive sampling for passive sampling. The current north to south network could be reduced to accommodate the proposed east to west expansion. Two or three cross sections over two to three years will be sufficient for model evaluation needs. Additionally, we recommend evaluating whether additional passive sampling sites can be established in locations south of the smelter. Lastly, the passive sampling site locations should be assessed for whether some sites should be moved to align with the proposed vegetation biodiversity assessment plots (or vice versa).

The passive sampling urban network study has been successful in confirming the entire Kitimat urban area has low SO_2 concentrations. There are no plans to continue the study beyond 2019, and no benefit in continuing the study has been identified through the comprehensive review. Similarly, the short study of particulate sulphate sampling using filter packs was successful in confirming that only a very small fraction of total sulphur in the atmosphere is particulate sulphate. There are no plans to continue particulate sulphate study, and no benefit in continuing the study has been identified through the comprehensive review.

For the deposition monitoring program, we recommend continuing the Lakelse Lake monitor and considering discontinuing the Haul Road wet deposition monitor. The monitoring of wet deposition at Haul Road provides no ecological value (i.e., for the assessment of impacts) owing to its fence line location and because it provides limited value for model (CALPUFF) evaluation.

Human Health Summary

The STAR was prepared in 2013. At that time the Province of British Columbia did not have an Air Quality Objective for sulphur dioxide that was based on recent human health evidence. As a result, the STAR included predictions of the annual number of restricted airway events based on the ambient air concentrations in residential areas. The ambient air concentrations were predicted by the air dispersion modelling that was conducted as part of the STAR, similar in structure to the modelling done for this comprehensive review.

The contents of the STAR informed the SO_2 EEM Program. The 2013-2018 SO_2 EEM Plan included an informative performance indicator for human health based on updated predictions of the annual number of restricted airway events based on each year's actual emissions and meteorological observations.

In the time between the preparation of the STAR and this comprehensive review, the Province of British Columbia adopted an Interim Air Quality Objective (IAQO) and modified the SO_2 EEM Program to apply the IAQO as a KPI. The KPI is based on measurements at residential monitoring stations. Starting in the year 2020, the B.C. IAQO for SO_2 becomes equivalent to the Canadian Ambient Air Quality Standards (CAAQS) adopted by the Canadian Council of Ministers of the Environment (CCME). During the development of the terms of reference for this comprehensive review, it was determined that the informative indicator was no longer necessary for the SO_2 EEM Program or the comprehensive review.

Did we exceed a KPI threshold as calculated starting in 2017 under the 2014 SO_2 EEM Plan?

The human health KPI is based on maintaining concentrations of SO_2 below a threshold value for a significant proportion of the year at three residential monitoring stations: Riverlodge, Whitesail and Kitamaat Village. Annual calculation of the KPI for Human Health began in 2017. It has one threshold, for facility-based mitigation, and this threshold has not been exceeded.

What did we learn during the first six years of the SO_2 EEM Program?

The levels of SO_2 in the residential areas of Kitimat and Kitamaat Village change on an hourly basis. Despite being variable, the levels of SO_2 are below 1 ppb in more than half of the hours of each year, at all three sites. Even when considering only the worst hour of each day, the average concentration in that worst hour is less than 1 ppb in more than half of the days at each site in each year.

Due to the nature of meteorological conditions and other variables, there are relatively infrequent excursions of the SO_2 concentration above 10 ppb. For the period from 2016 to 2018, the maximum hourly averaged concentration for all stations (44.7 ppb) occurred at Riverlodge Station (Lower Kitimat) in 2017.

Did we make any adjustments to the SO_2 EEM Program during 2013-2018?

In 2016, the Province of British Columbia adopted an IAQO. This objective was established as 75 ppb for hourly averaged concentration of SO_2 and applies in the SO_2 EEM Program for the years 2017-2019. From the year 2020 forward, the IAQO value will be replaced by the CAAQS values of 70 ppb, and 65 ppb (starting in 2025).

What changes do we recommend to the SO_2 EEM Program going forward?

There are no recommendations for changes to the existing KPI since it is in the process of changing in alignment with the adoption and further adjustment of the CAAQS.

Vegetation Summary

The SO_2 EEM Vegetation Program was designed to monitor the potential effects of the modernized smelter on plants in the Kitimat Valley. The vegetation program centered around two measures: a visual inspection of plants at an array of sites throughout the valley, and the sulphur (S) content of western hemlock needles collected at those same sites.

The KPI for vegetation is based on visible injury of sensitive vegetation due to SO_2. Although the modelling results from the STAR indicated that visible injury was unlikely to occur, modelled concentrations were high enough to warrant such a KPI, particularly given that the sensitivity of most vegetation in the valley has not been documented through controlled exposure studies. Sulphur content in hemlock needles was used as an informative indicator.

Did we exceed a KPI threshold as identified in the 2014 SO_2 EEM Plan?

No KPI thresholds were exceeded. No visible injury due to SO_2 was observed at any location post-KMP. Visible injury due to SO_2 has not been reported in the results of the vegetation monitoring program since before 1999.

What did we learn during the first six years of the SO_2 EEM Program?

Given the results of air monitoring and dispersion modelling, the KPI will not be an effective tool as visible injury due to SO_2 seems highly unlikely to occur. From the results of measurements and observations to date, the risk to higher vegetation remains unlikely or very unlikely and of minor consequence.

STAR question V1: Validation of the dispersion model – are we looking in the right place?

For the most part, the locations of vegetation sampling and inspection sites align well with the predicted path of the plume. Additional sites are well outside the areas of projected deposition and provide reference information. The areas off the Rio Tinto B.C. Works site where the highest concentrations are projected to occur are not safely accessible from the ground or the air. The predicted 1-hour maximum concentrations at some of those locations exceed the 1-hour threshold used in the STAR but other thresholds are not exceeded. Aerial survey of the area doesn't reveal any indication of change in forest condition. The vegetation informative indicator of sulphur concentration in western hemlock needles did not help verify model predictions as there was a poor correlation between sulphur in needles and measured or modelled air concentration of SO_2 or deposition of SO_4^{2-}.

STAR question V2: How healthy is vegetation in sites with predicted exceedance of critical loads of soil and/or lakes and streams south of Lakelse Lake?

No significant differences in plant heath throughout the Kitimat Valley have been observed post-KMP. There were no significant insect outbreaks or plant disease epidemics during the period under review. The greatest stress to vegetation during the period was associated with drought in 2018. No differences were observed in vegetation in the areas of soil critical load exceedance under actual emissions. On-the-ground or aerial inspection of vegetation in the area of predicted soil critical load exceedance under the maximum permitted level (42 tpd) did not reveal differences in the health of vegetation compared to sites located at distance, including reference sites.

STAR question V3: Are plants of public importance showing symptoms in areas with the highest exceedances of soil critical loads?

No symptoms associated with emissions from the smelter were observed.

STAR question V4: Do plants at Kitimat that have unknown sensitivity to SO_2 and associated pollutants (acidic deposition) fall within the range of variation in the literature?

It appears that plants in the Kitimat Valley are within the range of sensitivities reported in the scientific literature. Given the low ambient concentrations of SO_2, injury would not be expected to occur, and it did not.

Did we make any adjustments to the SO_2 EEM Program during 2013-2018?

No adjustments were made to the SO_2 EEM Program.

What changes do we recommend to the SO_2 EEM Program going forward?

We recommend that a terrestrial ecosystem line of evidence be established to integrate the vegetation and soils lines of evidence. The current KPI for vegetation should be discontinued and measures of plant health and plant biodiversity should be developed to replace the current KPI and informative indicators. A plant biodiversity pilot project needs to be conducted to develop appropriate thresholds and related measures of variability to assure success.

We recommend establishing informative indicators of changes in plant biodiversity and changes in plant health due to emissions from the B.C. Works. These should be based on plant biodiversity field plots (to be established) and a triennial inspection to assess and document plant and ecosystem health, and will support the soil critical load KPI. Documented changes in plant and ecosystem health would trigger increased measurement and inspection frequency.

We also recommend changing the focus of the vegetation sampling and inspection program to detecting mid- to long-term effects related to Rio Tinto's B.C. Works on terrestrial ecosystems. This could be done by implementing a set of biodiversity plots to detect changes in plant communities, revisiting lichen plots at appropriate intervals to document changes in lichen communities, conducting a triennial inspection to document changes in plant and ecosystem health, and discontinuing sampling and chemical analysis of western hemlock foliage in favor of maintaining a valley passive sampler network and measuring more informative endpoints of vegetation health.

Terrestrial Ecosystems (Soils) Summary

The soils component of the SO_2 EEM Program set out to reduce uncertainty and fill information gaps that were identified in the STAR regarding the regional coverage of soils data, the use of bedrock type to regionalise soil weathering rates, and lack of empirical observations for soil base cations.

There are two KPI for soils: atmospheric sulphur deposition and critical load exceedance, and long-term soil acidification (rate of change of base cations) attributable to sulphur deposition. The first KPI is prediction-based and uses measured soil physical and chemical data from regional surveys to model and map the spatial distribution, magnitude and the level of exceedance of critical loads of acidity for soils. The second KPI is observation-based and uses measured soil chemistry data at two long-term monitoring plots to track changes in soil base cations over time.

Did we exceed a KPI threshold as identified in the 2014 SO_2 EEM Plan?

The thresholds for the two terrestrial KPIs were not reached. The area of critical load exceedance was < 1% and there was no statistical change (decrease) in soil base cations at the two long-term soil plots between 2015 and 2018. Long-term soil plots show no statistically significant decrease in any soil property between 2015 and 2018 in the 0-30 cm depth.

What did we learn during the first six years of the SO_2 EEM Program?

In general, the areal extent of critical load exceedance was similar to that reported in the STAR: areas with exceedance under the 42 tpd scenario were close to the smelter. If exceedance is limited to areas outside the fence line, then areal exceedance drops by 55%. Exceedance is not driven by sensitive soils; it is driven by high modelled sulphur deposition close to the smelter.

Regarding the long-term soil plots, in general, the Minimum Detectable Difference (i.e., the percent change in base saturation that can be detected with high statistical reliability, given the number of samples and the variability in soil properties) is lower for soil base cation concentrations compared with base cation pools. In addition, base cation pools have the added requirement to measure bulk density. Soil base saturation is the only soil property (related to base cations) that provides a reliable detectable difference of 40% in top 0-30 cm of mineral soil.

STAR question S1: Are estimates of average weathering rates by bedrock type valid for vulnerable areas (i.e. where lakes have low base cations)?

STAR question S2: What is the current buffering capacity (base cation pool) of the soils in the exceeded areas, and when would this base cation reservoir be used up?

STAR question S3: What is the rate of soil acidification measured as loss of base cations owing to acidic deposition?

These three questions, identified under the STAR, are no longer relevant as soil weathering rates are now mapped using regression kriging rather than 'averaged by bedrock type' (S1), the current buffering capacity of soils in exceeded areas is only addressed if the KPI for critical loads is exceeded (S2) and long-term soil plots were established to assess changes in soil base cation pools (S3).

Did we make any adjustments to the SO_2 EEM Program during 2013-2018?

No adjustments were made to the SO_2 EEM Program.

What changes do we recommend to the SO_2 EEM Program going forward?

We recommend maintaining both of the KPIs (atmospheric sulphur deposition and critical load exceedance, and long-term soil acidification attributable to sulphur deposition) going forward as they are both well-established and widely used indicators of the impacts from sulphur deposition. We also recommend establishing plant biodiversity plots (a recommendation in the vegetation section) located within the accessible exceeded areas south of the smelter to increase monitoring of the potential effects of sulphur deposition. Further, as noted in the vegetation section, a terrestrial ecosystem line of evidence should be established to integrate the vegetation and soil lines of evidence.

We recommend no changes to the critical loads KPI and suggest that critical loads only be revised if new data or revised critical limits become available; however, exceedance should continue to be routinely estimated for any updated sulphur [and nitrogen] deposition scenarios. To address several uncertainties in the regional assessment of impacts to terrestrial receptors, we recommend that a survey of wetland geochemistry and sulphur storage be carried out, since wetlands make up almost 25% of the exceeded area yet there is no chemical information on

wetlands in the Kitimat valley. We recommend an assessment of aluminium solubility in mineral soils be carried out; aluminium solubility is a key parameter in the determination of critical loads, associated with the critical limit and $ANC_{leaching}$.

For the long-term soil plot KPI, we recommend using a change (decrease) in base saturation (%) to calculate the KPI rather than a change in exchangeable base cation pools, since base saturation was the most sensitive parameter in detecting a change of 40% in exchangeable cations between two sampling periods (accommodating the variability in soil chemistry during both sampling events). We recommend using soil concentrations in the top 0-30 cm of mineral soil rather than pools to assess changes in soil chemistry. We recommend further analysing the minimum detectable difference, to evaluate the potential of an early warning change in soil base saturation using a lower level of significance and/or lower power. We also recommend carrying out the next sampling of long-term plots during 2025 (to return to a 5-year sampling period), and measuring trees (diameter at breast height) at time of soil sampling.

Aquatic Ecosystems (Lakes, Streams and Aquatic Biota) Summary

The STAR predicted that under the maximum post-KMP emissions of 42 tpd, pH would decrease by greater than 0.1 pH units in 7 of the 41 lakes that were sampled and modelled. Five of these lakes with potential significant declines in pH were also predicted to exceed their critical loads under such deposition conditions. The rest of the 34 sampled lakes (including Lakelse Lake) and all the 20 sampled stream sites were predicted to decline by less than 0.1 pH units in response to KMP. The STAR concluded that there would be a moderate impact on aquatic ecosystems (lakes, streams and associated aquatic biota) within the study area post-KMP if emissions reach the maximum permitted amount of 42 tpd. The moderate impact was deemed acceptable but requiring monitoring through the SO_2 EEM Program.

The KPI for aquatic ecosystems is based on the risk of biological effects due to lake acidification, as measured through a decrease in pH. Seven informative indicators provide evidence to support the lake acidification KPI. Some of these are prediction-based, such as the risk of exceeding critical loads which uses measured water chemistry data and measured sulphur deposition data as inputs for updated modelling of critical loads. Others are observation-based, such as the comparison of measured pH in selected lakes with the predicted steady state pH predicted in the SO_2 technical assessment.

Did we exceed a KPI threshold as identified in the 2014 SO_2 EEM Plan?

There have been no exceedances of the KPI thresholds.

What did we learn during the first six years of the SO_2 EEM Program?

We have learned that pH is more highly variable than anticipated. Our expectations were based on literature and data from other regions. We have also learned that it is difficult to measure pH well in lakes with low ionic strength. The low ionic strength means that a long time is needed to get stable readings – longer than factory settings for some instruments or laboratory protocols at some facilities. Not allowing sufficient time for readings to stabilize results in less reliable pH data. Furthermore, even when allowing sufficient time for stabilization (as with the laboratory

measurements that comprise the primary pH data set used in the analyses of the KPI), the measurement error for the different instruments is still high relative to the effect size of interest.

The results of the water quality sampling at the Rio Tinto intake on the Kitimat River showed no exceedances of the B.C. water quality objectives. The maximum measured sulphate concentration was less than 1% of the B.C. Drinking Water Guideline.

STAR question W1: How do assumptions in deposition and surface water models affect the predicted extent and magnitude of critical load exceedance post-KMP?

In general, the model results are robust to wide variation in assumptions.

STAR question W2: How many of the 7 to 10 potentially vulnerable lakes actually acidify, and to what extent?

Of the 14 lakes in the SO_2 EEM Program (7 acid-sensitive lakes, 4 less sensitive lakes, 3 control lakes), 12 lakes show no evidence of sulphur-induced acidification causally related to the Kitimat smelter. The sensitive lakes have shown considerably less response to increased emissions than was predicted in the STAR. LAK028, a 1 ha fishless lake close to the Kitimat smelter, shows some evidence of sulphur-induced acidification causally related to the smelter, evidence which also existed prior to the development of the new smelter. The trends in the chemistry of LAK028 show no support for a decline beyond its ANC threshold and low support for decline below the pH threshold. LAK012 (Little End Lake), a 2.3 ha lake to the southwest of Lakelse Lake, has shown increased concentrations of sulphate and some evidence of a decline in ANC, but no evidence of sulphur-induced acidification causally related to the smelter that exceeds the ANC or pH thresholds established in the EEM Plan to protect aquatic biota.

STAR question W3: What is the current status of the fish community in the potentially vulnerable lakes that can be safely accessed for fish sampling?

Four of the seven sensitive lakes, (West Lake (LAK023), End Lake (LAK006), Little End Lake (LAK012), Finlay Lake (LAK044)), were sampled for fish in 2013, and a fifth sensitive lake was sampled in 2017 (LAK028). No fish were caught in Finlay Lake (which has no inlets or outlets) or in LAK028 (which has no inlet and a blocked outlet). Threespine stickleback and coho salmon were present in West Lake, End Lake and Little End Lake. In West Lake the coho were confirmed to remain in freshwater for their entire life cycle, rather than going to sea. End Lake and Little End Lake also had coastal cutthroat trout and dolly varden char.

Three of the less sensitive lakes were sampled in 2015: Clearwater Lake (LAK007), LAK016 and LAK034. They generally had similar fish assemblages and numbers of fish species to the sensitive lakes with fish. Coastal cutthroat trout was common in all three lakes. Other species found included coho salmon and dolly varden char (in LAK007 and LAK016), threespine stickleback (in LAK007 and LAK034), and (in LAK007 only) rainbow trout and Chinook salmon. Altogether, six species were found in LAK007, three in LAK016, and two in LAK034.

STAR question W4: If some of the potentially vulnerable lakes that can be safely accessed for fish sampling show an acidifying trend, then do these lakes also show changes in their fish communities?

None of the lakes have shown an acidifying trend beyond the SO_2 EEM thresholds requiring them to be resampled.

We also learned the answers to a number of additional questions that arose during 2013 to 2018.

How do the observed changes in SO_4, Gran ANC and pH compare to the steady-state predictions from the STAR?

The observed changes in SO_4, Gran ANC and pH have generally been much less than the steady-state predictions from the STAR (adjusted to reflect actual emissions rather than maximum emissions). The only exceptions have been LAK024 (which increased in sulphate more than predicted); LAK028 (which increased in sulphate much more than predicted); LAK007 (a lake with a very high level of Gran ANC that is not sensitive to acidic deposition which decreased in Gran ANC despite a prediction of no change); and LAK034 (which decreased in pH, not associated with smelter emissions) despite a prediction of no change.

Can we estimate F-factors from the empirical sampling results?

We can only estimate an empirically-based F-factor for LAK028, where there was a sufficient change in lake sulphate to permit an estimate of the F-factor. The revised empirically-based estimates of the F-factor are in the range from 0.65 to 0.85, compared to an initial estimate of 0.44 in the STAR, indicating that over the period of the EEM Program approximately 65% to 85% of the deposited acidity associated with sulphur deposition was neutralized by exchanges for base cations in the watershed of LAK028. Thus, LAK028 was able to neutralize a larger fraction of the deposited acidity than had been assumed in the STAR.

Do we see any evidence of regional acidification if we analyze the lakes as a group rather than individuals?

No. There is a spatial pattern to changes in lake sulphate, with lakes closer to the smelter being more likely to show an increase in sulphate, but none of the lakes have acidified beyond the established thresholds for pH and Gran ANC.

Is there a benefit to adding appropriate control lakes to the SO_2 EEM?

Yes. The control lakes provide insights and statistical inferences on natural variability in water chemistry unrelated to the smelter (e.g., year-to-year variation in regional weather patterns and longer term changes in climate), and can be used in statistical analyses to detect changes in the sensitive lakes that differ from the control lakes. The power analysis completed in 2016 demonstrated that inclusion of control lakes increases statistical power. Inclusion of the control lakes also permits statistical analyses using a Before-After-Control-Impact (BACI) design, in addition to Before-After comparisons.

Is there a benefit to more intensive water sampling?

Yes. Intensive water sampling provides a better estimate of within-year variability in water chemistry, allows for a more precise estimate of lake chemistry for the fall period, and provides an additional data set for examining long term trends in pH. It is sufficient to have data from just one intensively monitored lake rather than three.

Is there a benefit to collecting other data on the SO_2 EEM lakes?

Yes. The bathymetric analyses have provided a much more accurate estimate of lake volume and therefore improved our initial estimates of water residence time so we can better understand the temporal lag (or lack of) in lake chemistry responses to changes in deposition levels. The lake

level data have provided information by which to examine the extent to which intra-annual changes in lake chemistry may be associated with hydrologic events. The lake level data provide information specific to the watershed rather than general regional patterns that are represented by weather stations or flow data from major rivers.

Will increased emissions result in immediate (i.e., same year) changes to lake chemistry or will there be a lag?

Reductions in sulphur emissions from the smelter, and therefore decreases in SO_4^{2-} deposition, from 2013 to 2014 resulted in apparent responses of the lakes' chemistry. Most of the sensitive lakes showed increases in both lake pH and lake ANC from 2012 to 2013 and 2013 to 2014. Lake chemistry has not shown a consistent response to the increase in sulphur emissions after 2015, most likely reflecting spatial variation in the path of the plume as well as differences in lake sensitivity to acidification. Improved estimates of water residence time suggest that all seven sensitive lakes should respond within a year or two to changes in watershed inputs.

Did we make any adjustments to the SO_2 EEM Program during 2013-2018?

We made numerous adjustments to the EEM Program, including increasing the frequency of sampling 6 of the 7 sensitive lakes, from once per year in the fall to four times in the fall; adding intensive monitoring of pH to four lakes; adding three control lakes to the annual monitoring program; and sampling various streams downstream from LAK028.

What changes do we recommend to the SO_2 EEM Program going forward?

We recommend that ANC become the primary KPI for the EEM Program, with pH as an informative indicator, since ANC better fulfills the criteria for a KPI. We further recommend that the KPI include two components: a *level of protection* to prevent acidification of lakes that are currently not at risk of aquatic impacts (i.e., an absolute threshold); and a *change limit* (i.e., a relative threshold) which prevents further acidification (for lakes already below the level of protection due to natural organic acids or past acidic deposition).

We recommend that the seven sensitive EEM lakes should continue to be the core of the EEM Program, maintaining the current frequency for sampling full water chemistry (i.e., four samples within the fall index period for the six sensitive lakes that are accessible and one annual sample for LAK022, which is not accessible).

For the EEM less sensitive lakes, we recommend continuing the annual sampling of the full chemistry of LAK016 (which has an intermediate level of sensitivity) and we recommend discontinuing the annual sampling of LAK007 (Clearwater Lake), LAK024 (Lakelse Lake) and LAK034, as the EEM Program has shown these lakes to be insensitive under both *current* and *maximum future* levels of sulphur emissions.

Annual sampling of the full chemistry of the three control lakes should be continued, to provide reliable measures of year-to-year changes in lake chemistry, an assessment of regional factors such as changing weather patterns, and critical data for statistical analyses of changes in sensitive lakes relative to control lakes. We recommend including one year with multiple sampling visits of the three control lakes during October (added to the 2019 October lake sampling), so as to estimate the within-year variability in lake chemistry, and thereby improve statistical inferences.

We recommend that the EEM lakes be re-evaluated in the 2021 Annual Report with respect to their inclusion in the EEM Program going forward. Some of the EEM lakes (which were all identified in the STAR as being potentially sensitive to increased acidic deposition) are now not predicted to acidify under updated modelling based on additional years of data.

We do not recommend adding any additional lakes to the EEM Program. We examined the critical loads and exceedances in the context of the updated CALPUFF deposition modeling for all the original STAR lakes, KAA lakes located within the study area, and additional lakes sampled early in the EEM Program. These analyses did not provide evidence that any of the lakes excluded from EEM Program should be re-considered for inclusion in the program in light of newer information.

We recommend continuing intensive sampling of LAK006 (End Lake) with the new Onset continuous pH monitor, and continuing measurements of lake levels to assess pH changes associated with storm events. Continuous monitoring of LAK012 (Little End Lake) and LAK023 (West Lake) is no longer needed, as these lakes have shown very similar patterns to End Lake and provide no incremental value beyond the intensive monitoring of End Lake.

We recommend a thorough review of the report on Kitimat Valley streams prepared by Paul Weidman once it is released, as one input to discussions on potential next steps in stream monitoring. We recommend discontinuing the monitoring of Anderson Creek, which has not provided useful information to the EEM Program.

If additional fish sampling is required (i.e., additional sampling is triggered by specific conditions in the EEM design), we recommend exploring the use of eDNA sampling to estimate any changes in the presence of fish species and avoiding the potential population impacts of gill-net sampling.

The critical load of a particular lake is an inherent property of the lake based on the geochemical characteristics of its watershed and is not interpreted to be a property that changes over time. With seven years of water chemistry data, we now have greatly improved estimates of the critical loads of the EEM lakes. We have also greatly improved upon the modelling of critical loads that was done in the STAR by conducting extensive sensitivity analyses. The prediction of exceedances does not need to be updated again in the future unless actual or predicted SO_2 emissions are in excess of 42 tpd or if the emissions modelling framework is significantly modified. These two metrics will not be responsive to potential changes in deposition due to smelter operations over the next phase of monitoring and therefore do not satisfy a critical criterion for a good indicator.

We recommend that the SO_2 EEM Annual Report be significantly streamlined where possible. The Annual Report should focus on reporting the new data from the monitoring program and updating critical analyses. The Annual Report should not attempt to make interpretations or inferences with respect to year-to-year changes in water chemistry, but should update statistical evaluations of long term changes between pre-KMP and post-KMP periods. However, the scope of the future annual reports will be determined as part of the collaborative discussion and development of the next phase of the EEM Program with ENV.

Holistic Synthesis

The KPIs in the SO_2 EEM Program were chosen to provide early warning of potential impacts on the receptors, and thus far we see no cause for concern. None of the KPI thresholds have been reached, not even the thresholds for increased monitoring. No prediction-based KPI threshold exceedances are projected even under the 42 tpd scenario. Air concentrations of SO_2 at residential monitoring stations are well below the B.C. Air Quality Objective. The concentrations are also below the CAAQS which will become the B.C. Air Quality Objectives starting in 2020. Air concentrations of SO_2 in the valley are well below concentrations that would cause visible injury to vegetation. Soil plots show no evidence of acidification. One small lake near the smelter shows some evidence of sulphur-induced acidification causally related to the smelter (as it did prior to the construction and operation of the new smelter: it shows only low support for a decline below the pH threshold and no support for decline beyond its ANC threshold. Prediction-based KPIs for soils and lakes are not expected to reach mitigation thresholds even under SO_2 emissions at 42 tpd.

Looking across these lines of evidence we do not see signs of harm in the valley, under present or predicted future conditions. Through all of the analyses, discussions, and results of the comprehensive review we are confident in these conclusions and feel that it is warranted to go forward with a more consolidated, efficient program. We recommend that the next review occur in 2026.

SO_2 EEM KPI Report Card for 2013-2018

		Atmospheric Pathways	Human Health	Vegetation	Terrestrial Ecosystems (Soils)	Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)
Performance	KPI(s) below threshold for increased monitoring?	Not applicable	Not applicable	**Yes**	**Yes**	**Yes**
	KPI(s) below threshold for receptor-based mitigation?	Not applicable	Not applicable	**Yes**	**Yes**	**Yes**
	KPI(s) below threshold for facility-based mitigation?	Not applicable	**Yes**	**Yes**	**Yes**	**Yes**
Recommended Changes	Do we recommend changes to the KPI(s)?	Not applicable	**No**	**Yes**	**No**	**Yes**
	Do we recommend changes in how to calculate the KPI(s)?	Not applicable	**No**	**Yes**	**Yes/No***	**Yes**
	Do we recommend other changes to the SO_2 EEM Program?	**Yes**	**No**	**Yes**	**Yes**	**Yes**

* 'Yes' for the soil acidification KPI, 'No' for the critical loads KPI

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Glossary

acid deposition	Transfer of acids and acidifying compounds from the atmosphere to terrestrial and aquatic environments via rain, snow, sleet, hail, cloud droplets, particles, and gas exchange
acidification	The decrease of acid neutralizing capacity in water, or base saturation in soil, by natural or anthropogenic processes
acid neutralizing capacity	The equivalent capacity of a solution to neutralize strong acids; ANC and alkalinity are often used interchangeably; ANC includes alkalinity plus additional buffering from dissociated organic acids and other compounds
anion	An ion with more electrons than protons, giving it a negative charge, e.g., SO_4^{2-}
base cations	An alkali or alkaline earth metal (Ca^{2+}, Mg^{2+}, K^+, Na^+)
base cation exchange	The replacement of hydrogen ions in the soil water by base cations from soil particles
critical load	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
dissolved organic carbon	Organic carbon that is dissolved or unfilterable in a water sample (0.45 µm pore size in the National Surface Water Survey)
dry deposition	Transfer of substances from the atmosphere to terrestrial and aquatic environments via gravitational settling of large particles and turbulent transfer of trace gases and small particles
environmental effects	Impacts on receptors from SO_2 emissions from the modernized smelter
facility-based mitigation	Sulphur dioxide (SO_2) emission reduction at B.C. Works
F-factor	A simple way to represent cation exchange processes, specifically the proportion of incoming acidity accompanying sulphate that is exchanged in the soil for base cations
Gran ANC	The capacity of a solution to neutralize strong acids, determined by titration to the inflection point of the pH-alkalinity titration curve
informative indicator	Indicators that will provide supporting information for key performance indicators, and may have quantitative thresholds triggering additional monitoring or modelling, but on their own will not trigger mitigation
key performance indicator	An indicator that have quantitative thresholds triggering additional monitoring or modelling, receptor-based mitigation, and/or facility-based mitigation

liming	The addition of any base materials to neutralize surface water or sediment or to increase acid neutralizing capacity
pH	A measure of how acidic or basic a solution is, on a scale of 0-14; the lower the pH value, the more acidic the solution; pH 7 is neutral; a difference of 1 pH unit indicates a tenfold change in hydrogen ion activity
pre-KMP	The period of the VSS smelter operations
post-KMP	The period from 2016 forward
receptors	Components of the environment assessed for potential impacts from SO_2 emissions from the modernized smelter: human health; vegetation; soils; and lakes, streams and aquatic biota
receptor-based mitigation	Receptor-specific actions to reduce exposure or effects, such as air quality advisories in local communities or liming of selected lakes
residential stations:	Air quality monitoring stations in the residential areas of Kitimat and Kitamaat Village, which are currently the Riverlodge, Whitesail and Kitamaat village stations
wet deposition	Transfer of substances from the atmosphere to terrestrial and aquatic environments via precipitation (e.g., rain, snow, sleet, hail, and cloud droplets)
percentile	A statistical measure for the value below which a given percentage of observations fall within a data set

Abbreviations, Acronyms and Symbols

Δ	delta, meaning quantitative change (e.g. ΔANC or ΔSO_2)
<	is less than what follows
≤	is less than or equal to what follows
>	is greater than what follows
≥	is greater than or equal to what follows
[ ]	the concentration, e.g., $[SO_2]$ means the concentration of SO_2
AERMOD	AMS/EPA Regulatory Model Improvement Committee (AERMIC) working group Model; a dispersion model for predicting air pollutant concentrations from industrial sources
AERSCREEN	The screening version of AERMOD that predicts 1-hour air pollutant concentrations from a single source
Al	Aluminium
ANC	Acid neutralizing capacity
ANC_{limit}	Acid neutralizing capacity limit
ANC_{OAA}	Organic anion adjusted acid neutralizing capacity

AQO	Air quality objective
BACI	Before-after-control-impact
Bc	Base cations
BC	Base cations that include calcium, potassium, magnesium and sodium
B.C.	British Columbia
Bcu	Base cation uptake
BSe	Effective base saturation; the percentage of effective CEC made up of base cations
BCS	Base cation surplus
C	Ambient air concentration of a substance
Ca^{2+}	Calcium ion
CAAQS	Canadian Ambient Air Quality Standards
CALMET	Meteorological model that generates hourly three-dimensional meteorological fields
CALPOST	Post-processor model for CALPUFF that computes pollutant concentration and deposition
CALPUFF	California Puff model that simulates non-steady state transport, dispersion, and chemical transformation of air pollutants emitted from a source in "puffs"
CBANC	charge balance ANC
CCME	Canadian Council of the Ministers of the Environment
CDC	Conservation Data Centre
CEC	Cation exchange capacity
CECe	Effective cation exchange capacity
Cl^-	Chloride ion
CL	Critical load
CV	Coefficient of variation
D1HM	Maximum 1-hour average SO_2 concentration measured in a 24-hour calendar day
DBH	Diameter at breast height
DFO	Fisheries and Oceans Canada (formerly Canadian Department of Fisheries and Oceans)
DOC	Dissolved organic carbon
EEM	SO_2 environmental effects monitoring
ENV	British Columbia Ministry of Environment and Climate Change Strategy
F	Fluoride
F_{dry}	Dry deposition flux
F_s	Sulphur concentration ratio
H^+	Hydrogen ion
HF	Hydrogen fluoride
IAQO	Interim Air Quality Objective
K^+	Potassium ion
KAEEA	Kitimat Airshed Emissions Effects Assessment

K_{gibb}	Gibbsite equilibrium constant
KMP	Kitimat Modernization Project
KPAC	Kitimat Public Advisory Committee
KPI	Key performance indicator
LFH	Deep Organic Soil Layer
LOAEC	Lowest Observed Adverse Effect Concentration
LOI	Loss-on-ignition
MCT	Measure of central tendency
MDD	Minimum detectable difference
Mg^{2+}	Magnesium ion
MOD	Magnitude of difference
MW	Molecular weight
N	Nitrogen
Na^{+}	Sodium ion
NA	Not applicable
NAD	North American Datum
NADP	National Atmospheric Deposition Program
NaOH	Sodium hydroxide
N_{exp}	Number of exposures
NO_2	Nitrogen dioxide
O_3	Ozone
NO_3^-	Nitrate ion
ppb	Parts per billion
pSO_4^{2-}	Particulate sulphate
QA/QC	Quality assurance / quality control
QPs	Qualified professionals (for the SO_2 EEM Program)
Q-Q plot	Quantile-quantile plot
R^2	Coefficient of determination
RfC	Reference concentration
S	Sulphur (as in sulphur deposition)
SO_2	Sulphur dioxide
SO_4^{2-}	Sulphate ion
SO_2 EEM	Rio Tinto B.C. Works' SO_2 Environmental Effects Monitoring Program
SPR	Source-pathway-receptor (conceptual model)
SSWC	Steady State Water Chemistry (model)
STAR	SO_2 Technical Assessment Report (for KMP)
TOR	Terms of reference for the SO_2 EEM 2019 Comprehensive Review
tpd	Tonnes per day
UTM	Universal Transverse Mercator
V_d	Deposition velocity of a substance

VSS	Vertical stud Söderberg Smelter
WGS 84	World Geodetic System (1984)
WRF	Weather Research and Forecasting

List of Measurement Units

$eq/m^3/a$	equivalents per cubic metre per annum (year)
g/m^3	grams per cubic metre
ha	hectares
km	kilometre
kg/h	kilograms per hectare
keq/ha/yr	kiloequivalents per hectare per year
kg/ha/yr	kilograms per hectare per year (units of deposition flux)
kg S/ha/yr	kilograms sulphur per hectare per year
kg SO_4^{2-}/ha/yr	kilograms sulphate per hectare per year
L min^{-1}	litres per minute
m	metres
mm	millimetres
m/s	metres per second
m^3/s	cubic metres per second
mg/L	milligrams per litre
Mg/d	mega grammes per day, equivalent to metric tonnes per day
mg/m^3	milligrams per cubic metre
$meq/m^2/yr$	milliequivalents per square metre per year
ng/g	nanograms per gram
ng/m^3	nanograms per cubic metre
ppb	parts per billion
ppm	parts per million
tpd	tonnes per day
t/month	tonnes per month
t/yr	tonnes per year
$t/km^2/yr$	tonnes per square kilometer per year
µeq/L	microequivalents per litre
$µg/m^3$	micrograms per cubic metre (conversion: 1ppb = 2.614 $µg/m^3$ SO_2)
µm	micrometres (µ can also be shown as u)

1 Introduction

1.1 Background

Rio Tinto operates an aluminium smelter that is currently the only major source of SO_2 emissions in the Kitimat Valley. During 2015 and early 2016, the Kitimat Modernization Project (KMP) replaced the 60-year old vertical stud Söderberg smelter (VSS) with a state-of-the-art AP-40 pre-bake smelting technology.

In 2012 and 2013, we conducted a technical assessment for the KMP to determine the potential impacts of sulphur dioxide (SO_2) emissions from the modernized smelter along four lines of evidence: effects on human health, effects on vegetation, effects in terrestrial ecosystems (soils), and effects on aquatic ecosystems (lakes and streams, and aquatic biota). We used the CALPUFF modelling system to estimate atmospheric concentrations of SO_2 and to estimate sulphur deposition from the modernized smelter. These estimates were then used in the analyses for the four lines of evidence. We documented the assessment methods and results in the SO_2 Technical Assessment Report (STAR; ESSA et al. 2013).

An SO_2 Environmental Effects Monitoring (EEM) Program was then developed to answer questions that arose during the technical assessment, and to monitor effects of SO_2 along these lines of evidence. Results from the SO_2 EEM Program inform decisions regarding the need for changes to the scale or intensity of monitoring, as well as decisions regarding the need for mitigation. The Program Plan for 2013-2018 (ESSA et al. 2014a, provided in Appendix 1.1) describes the monitoring and modelling activities that were planned out for the first six years of the SO_2 EEM Program.

The SO_2 technical assessment and SO_2 EEM Program were structured according to the source-pathway-receptor (SPR) conceptual model shown in Figure 1-1. The numbered arrows in the diagram represent the pathways of potential effect that were considered in the technical assessment, and the shading represents the lines of evidence in the SO_2 EEM Program.

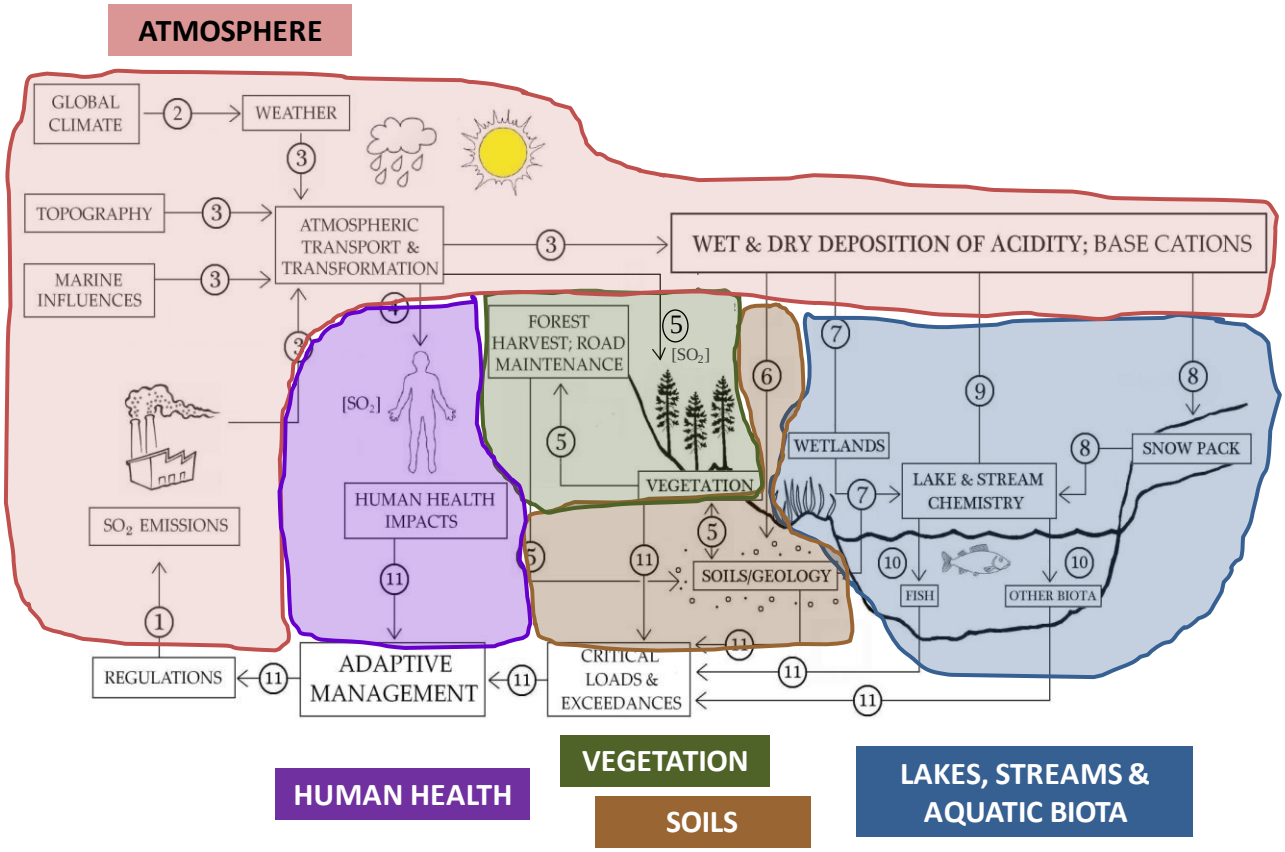


Figure 1-1. SO_2 Source-Pathway-Receptor conceptual model for the SO_2 EEM Program.

The SO_2 EEM Program follows a three-phase decision framework, presented in Figure 2 of the SO_2 EEM Program Plan for 2013-2018, and reproduced here in Figure 1-2. The first phase occurred in 2012-2013 and included the SO_2 Technical Assessment to predict whether there would be significant adverse human health and environmental effects from SO_2 emissions from the modernized smelter, and development of the SO_2 EEM Program. The second phase involved the implementation of the first six years of the SO_2 EEM Program, from 2013 to 2018. This phase spanned the final years of the 60-year old VSS smelter operations, the KMP period of ramping down production and transitioning the technology, and the period of ramping production back up with the modernized smelter. The third phase began in 2019 by reviewing results for the first six years, examining what we have learned from the first phase, and identifying new questions that have emerged. These results will inform the design of the SO_2 EEM Program for the next six years, which could include modifications to some Key Performance Indicators (KPIs), modifications to how they are monitored, and potentially reductions in the set of KPIs, or reductions in monitoring intensity for some KPIs.

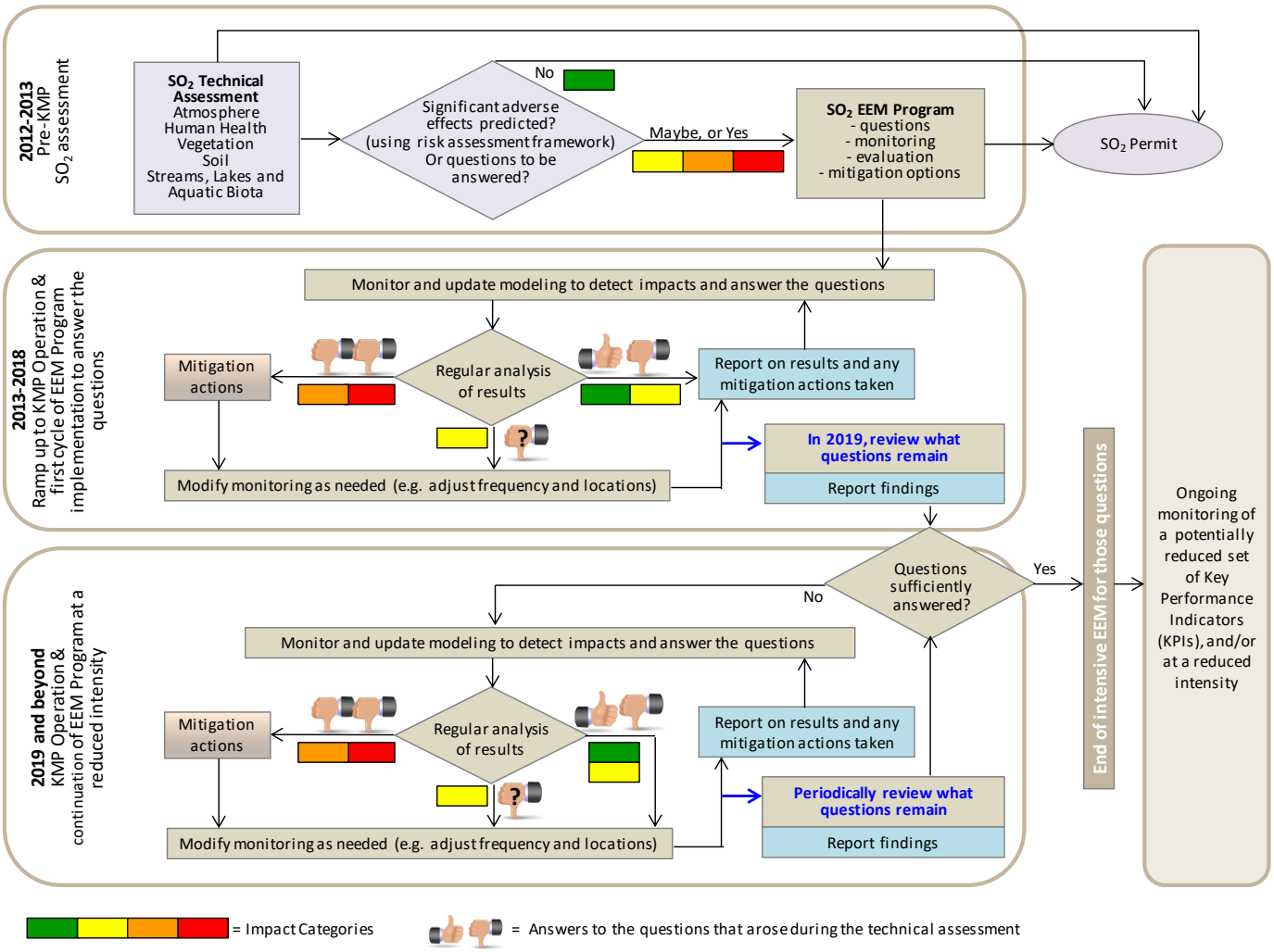


Figure 1-2. SO_2 EEM Framework for KMP.

1.2 Purpose and Scope of the Comprehensive Review

The SO_2 EEM Program calls for a comprehensive review in 2019 to examine results from the first six years, and preparation of a report that:

- Summarizes what has been learned, and what questions have been answered,
- Describes which, if any, of the KPI thresholds have been reached, and if so, what actions were taken,
- Describes any modifications to KPIs, methods, or thresholds that have been made based on annual results to date, and why,
- Looks across the data sets of the four lines of evidence to develop a holistic understanding of KMP SO_2 effects on the environment and human health,
- Recommends changes if/as needed to: the suite of KPIs to be continued post-2018, their measurement methods, and/or their thresholds – along with the rationale for these recommended changes, and
- Recommends a date for the next comprehensive review.

The purpose of this report is to present the methods, results and recommendations of the comprehensive review. The terms of reference (TOR) for the comprehensive review are provided in Appendix 1.2.)

For the comprehensive review, we modelled three SO_2 emission scenarios: actual emissions from the smelter during 2016 to 2018, which averaged to just under 30 tpd, a 42 tpd scenario representing the highest level of SO_2 emissions allowed under the permit, and a 35 tpd scenario representing SO_2 emissions of a magnitude midway between actuals and the maximum allowable. Further explanation about these scenarios is provided in Section 3.

The study area for the comprehensive review is shown in Figure 1-3. The figure shows two study area boundaries. The area within the light grey dashed line is the study area we used for the STAR. The area within the black dashed line is the study area we used for the comprehensive review. We have expanded the study area from that used in the STAR because S deposition under the highest emission scenario extended beyond the southwest boundary used in the STAR. This is explained further in Section 3.

Recommendations in this report are specific to the contents of the 2013-2018 SO_2 EEM Plan and will inform revisions to the next plan for SO_2 EEM Program post-2019. This report does not explore new indicators for the program going forward. Discussions of these and other potential adjustments to the program will occur during the development of the next SO_2 EEM Plan in 2020.

Figure 1-3. Map of the study area for the comprehensive review

1.3 Facility Production and Emissions from 2013 to 2018

Annual hot metal production from the Kitimat aluminium smelter is shown in Figure 1-4, and annual SO_2 emissions from the smelter are shown in Figure 1-5. Metal production from the smelter was low in 2013, 2014, and 2015 in preparation for the transition to the modernized smelter. The transition to AP-40 technology occurred in 2015 and the first quarter of 2016. Smelter stabilization took another 24 months. During the stabilization period, emissions of SO_2 increased from the 8.3 tpd rate in 2015 to 30.6 tpd in 2016.

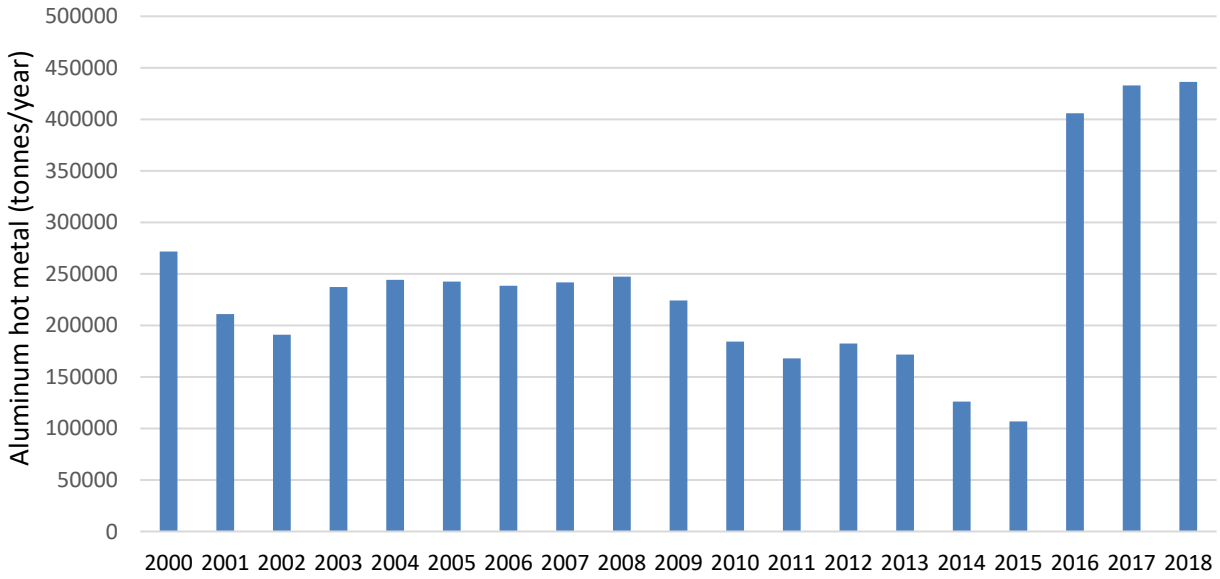
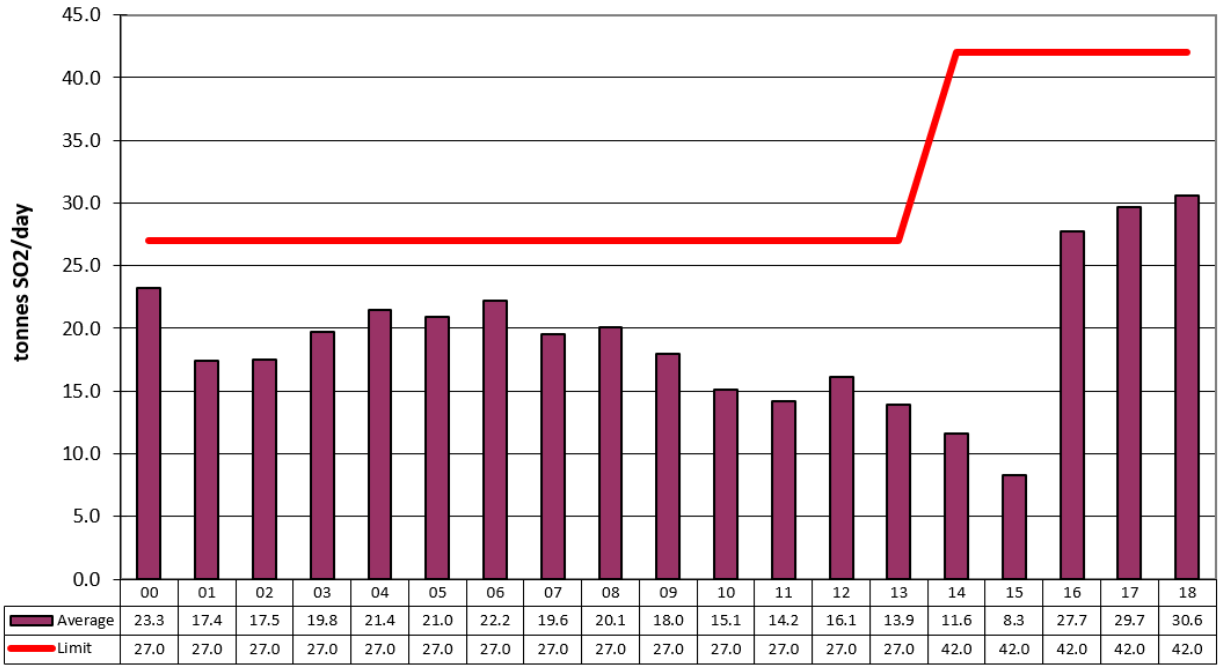


Figure 1-4. Annual hot metal production from the Kitimat smelter from 2000 to 2018. (Source: Rio Tinto)



	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18
Average	23.3	17.4	17.5	19.8	21.4	21.0	22.2	19.6	20.1	18.0	15.1	14.2	16.1	13.9	11.6	8.3	27.7	29.7	30.6
Limit	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	42.0	42.0	42.0	42.0	42.0

Figure 1-5. Annual SO_2 emissions from the Kitimat smelter for 2000-2018. (Source: Rio Tinto)

Post-KMP SO_2 emissions have varied over the 2016 to 2018 period of the SO_2 EEM Program. Emissions increased over that period as the smelter ramps up to the mid-term forecasted emission range of 33 to 35 tpd. Between 2016 and 2018, annual average emissions increased by 2.9 tpd. In 2016, emissions increased in the first quarter as the smelter was being commissioned. The last pot started at the end of March 2016.

Emissions fluctuate from month-to-month dependent on the sulphur content of green coke, imported calcined coke, and recycled carbon that are used to form the carbon anodes for the Al smelting process. Emissions will decrease twice per year due to the routine maintenance shutdowns of the coke calciner. During the typical 10 to 15 day shutdown periods, emissions from the coke calcining operation will cease. The tpd minimum, maximum, and range are provided in Table 1-1.

Table 1-1. Post-KMP SO_2 Emissions. (Source: Rio Tinto)

Year	Average tpd	Standard Deviation tpd	Minimum tpd	Maximum tpd	Range tpd
2016	27.7	2.4	22.2	31.4	9.2
2017	29.7	2.1	25.5	32.9	7.3
2018	30.6	3.1	25.3	36.2	10.9

1.4 Organization of this Report

This report is organized by the lines of evidence shown in Figure 1-6, which is a simplified version of the SPR model. Comprehensive review results for atmospheric pathways are provided in Section 3. Results for human health are provided in Section 4, results for vegetation are provided in Section 5, results for terrestrial ecosystems (soils) are provided in Section 6 and results for aquatic ecosystems (lakes, streams and aquatic biota) are provided in Section 7. Section 8 provides a holistic synthesis of what we have learned thus far in the SO_2 EEM Program across the lines of evidence.

Technical details underlying the analyses and results in this report are provided in a separate document (SO_2 EEM Comprehensive Review Report Volume 3: Technical Appendices). A summary report (Volume 1) is also available for a higher-level overview of the results of the comprehensive review.

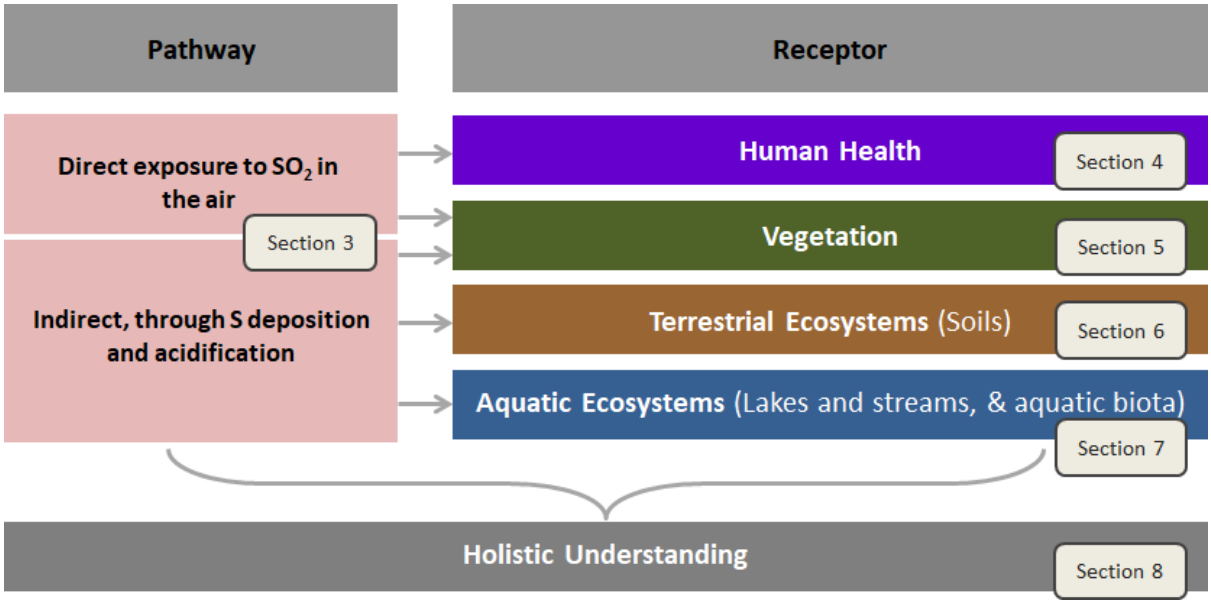


Figure 1-6. Framework for the organization of this report.

2 Evaluation of KPIs against Thresholds, Informative Indicators, & Synthesis of Results

This section provides a summary of comprehensive review results with a focus on KPI performance against thresholds, recommendations for KPIs and informative indicators going forward, learning under the STAR questions, and new questions to consider. Details for atmospheric pathways and the four receptors are provided in Sections 3 through 0, and a holistic synthesis across lines of evidence is provided in Section 8.

Table 2-1 summarizes whether KPIs where reached and whether any responses were needed, which KPIs or informative indicators were modified during the implementation of the 2013-2018 SO_2 EEM Plan, and our recommendations for modifying KPIs or informative indicators for the next phase of the SO_2 EEM Program. While still at a summary level, the table expands on the information conveyed in the KPI Report Card provided in the Executive Summary.

None of the thresholds for any of the KPIs were reached, therefore no responses (either increased monitoring or mitigation) were needed. Atmospheric SO_2 concentrations and atmospheric S deposition were informative indicators analysed under the Atmospheric Pathways component of the program. Measured concentrations of SO_2 were substantially lower than model predictions of post-KMP SO_2 concentrations from the STAR at most locations, and near model predictions at Haul Road. When considering that the model results do not include background deposition, the new CALPUFF model over-estimates actual deposition rates at Haul Road by 24% to 29%, and predicts actual deposition at Lakelse Lake from 16% under-estimation to 47% over-estimation (3-year average comparison of observed to modelled without background and to modelled with maximum background).

The only KPI modification we made during the first six years of the SO_2 EEM Program was for the human health component. When the STAR was prepared in 2013, the Province of British Columbia (B.C.) did not have an Air Quality Objective for sulphur dioxide that was based on recent human health evidence. Since then, the Province of British Columbia adopted an Interim Air Quality Objective (IAQO) and we modified the SO_2 EEM Program to apply the IAQO as a KPI. Starting in 2020, the IAQO value will be replaced with the CAAQS value of 70 ppb, and will be lowered to 65 ppb in 2025. During the development of the terms of reference for the comprehensive review, it was determined that the informative indicator for human health was no longer necessary for the SO_2 EEM Program or the comprehensive review.

We added a new informative indicator to the atmospheric pathways: contribution of dry deposition to total deposition. This indicator is not used to assess impacts due to sulphur deposition, but provides valuable information to understand the factors that could lead to variation in deposition rates. We also added three control lakes to the aquatic ecosystems (lakes, streams and aquatic biota) receptor.

We have several recommendations for modifying KPIs and informative indicators, and modifying the methods for monitoring and calculating them. For the atmospheric pathways component of the program, we recommend minimal changes to the continuous monitoring, and a review of the number and location of passive samplers that were deployed during the first six years of the program. For the deposition monitoring program, we recommend continuing the Lakelse Lake monitoring and considering discontinuing the Haul Road wet deposition monitor.

We recommend establishing a terrestrial ecosystem line of evidence to integrate the vegetation and soils lines of evidence, developing a KPI based on soil chemistry, and developing measures of plant health and biodiversity. We recommend monitoring these new indicators at appropriate locations including areas where critical loads (CLs) for soils or lakes are predicted to be exceeded under the 42 tpd emission scenario. For long-term soil plots, we recommend using % base saturation to calculate the KPI, focusing detection of change on the 0-30 cm soil layer, and returning to a 5-year sampling period.

For aquatic ecosystems (lakes, streams and aquatic biota), we recommend changing the KPI to ANC (acid neutralizing capacity), and using pH as an informative indicator. We also recommend discontinuing annual sampling of LAK007 (Clearwater Lake), LAK024 (Lakelse Lake) and LAK034, and we also believe that continuous monitoring of LAK012 (Little End Lake) and LAK023 (West Lake) is no longer needed. A complete list of recommendations for the next phase of the SO_2 EEM Program is provided in Section 9.

The SO_2 EEM Program also set out to reduce a number of critical uncertainties that were identified in the STAR and reiterated in Appendix A of the 2014 EEM Plan (provided in Appendix 1.1 of this comprehensive review). Four of these uncertainties are no longer relevant and the rest are answered in summary form in Table 2-2 with further details provided in the subsequent sections of this report. The table also lists several new uncertainties that have arisen, which should be considered during the design of the EEM Program going forward.

Table 2-1. Summary of results pertaining to KPIs or informative indicators.

	Atmospheric Pathways	Human Health	Vegetation	Terrestrial Ecosystems (Soils)	Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)
KPI	Not applicable (NA)	British Columbia (B.C.) Air Quality Objective measured at residential air monitoring stations	Visible injury to vegetation caused by SO_2	Critical load (CL) exceedance risk Long-term soil acidification	Water chemistry - acidification
Informative indicators	• SO_2 concentrations • S deposition • Base cation deposition	None	• S content in hemlock needles	• Magnitude of exchangeable cation pools • Time to depletion of exchangeable cation pools • Base cation weathering rates	• Atmospheric CL exceedance risk • Predicted steady stage pH vs current pH • Estimates of natural variability in pH and other indicators • Evidence that pH decrease is causally related to KMP • Aquatic biota • Episodic pH change • Amphibians
Were any KPI thresholds reached? If so, what was the response?	NA	There is only one threshold, for facility-based mitigation, and this threshold has not been reached.	None of the thresholds for the vegetation KPI have been reached.	None of the thresholds for the two KPIs for terrestrial ecosystems have been reached.	None of the KPI thresholds for aquatic ecosystems have been reached.
Were any KPIs or informative indicators modified? Are any modifications recommended to KPIs, informative	No modifications were made to the three informative indicators. We added a new informative indicator: contribution of dry deposition to total deposition, to help us	An IAQO was adopted as the KPI in December 2016, and annual calculation of the KPI began in 2017. The informative indicator of 'predicted annual number of	No modifications were made to the KPI or the informative indicator. We recommend that a terrestrial ecosystems line of evidence be established to integrate	No modifications were made to the KPI or the informative indicators. For long-term soil plots, we recommend using %base saturation to calculate the KPI which can detect a change <	No modifications were made to the KPI or the informative indicators. We recommend that ANC be the primary KPI, and that pH be an informative indicator.

	Atmospheric Pathways	Human Health	Vegetation	Terrestrial Ecosystems (Soils)	Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)
indicators that support KPIs, or the methods for monitoring and calculating them?	understand the factors that could lead to variation in deposition rates. No modifications were made to the informative indicator methods. We recommend continuing the continuous SO_2 monitoring with minimal changes, and reviewing the passive sampling Valley Network frequency and locations with a focus on increased number of passive samplers in east-west transects and (if possible) to the south of the smelter. We also recommend considering discontinuing the Haul Road wet deposition monitoring.	SO_2-associated respiratory responses' was removed from the program. Starting in 2020 the IAQO value for the KPI will be replaced by the CAAQS value of 70 ppb and will change to 65 ppb starting in 2025.	the vegetation and soils lines of evidence. We recommend informative indicators of changes in plant biodiversity and plant health due to emissions to support a terrestrial Ecosystems KPI that will be based on soil chemistry.	40% from baseline and focusing detection of change on the 0-30 cm layer (weighted). We recommend carrying out the next sampling of long-term plots during 2025 (to return to a 5-year sampling period). We recommend that a terrestrial ecosystems line of evidence be established to integrate the vegetation and soils lines of evidence.	We added 3 control lakes to the program. We recommend discontinuing the annual sampling of LAK007 (Clearwater Lake), LAK024 (Lakelse Lake) and LAK034. Continuous monitoring of LAK012 (Little End Lake) and LAK023 (West Lake) is also no longer needed.

Table 2-2. Summary of what questions from the SO_2 EEM Program have been answered thus far under, and whether any questions remain to be answered or new questions to be addressed under the next SO_2 EEM Plan.

	STAR questions the 2014 SO_2 EEM Program intended to answer	New questions for the SO_2 EEM Program
Atmospheric Pathways	*A1. Does CALPUFF accurately represent post-KMP SO_2 air concentrations?* Measured SO_2 concentrations were substantially lower than model predictions of post-KMP SO_2 concentrations from the STAR at most locations. *D1. Does CALPUFF accurately predict post-KMP total S deposition?* Overall, the new CALPUFF model predictions of total sulphur deposition compare well to the monitored results. *D2. What are base cation deposition values in the study region?* Following correction for sea salts, magnesium (Mg^{2+}) and sodium (Na^{+}) were zero. Long-term calcium (Ca^{2+}) and potassium (K^{+}) in precipitation were almost equal at Lakelse Lake and Port Edward. Precipitation concentrations at Haul Road were 1.5 (K^{+}) to >2 (Ca^{2+}) times larger than at the other two sites, and we assume that precipitation chemistry at Haul Road was influenced by anthropogenic sources. Average base cation concentration in precipitation was estimated as 0.8 µeq/L.	*What is the spatial extent of SO_2 concentrations and S deposition in the Kitimat Valley?*
Human Health	*HH1. How conservative is the CALPUFF model in predictions of SO_2 levels?* This is answered under question A1; however, the ability of CALPUFF to adequately represent residential SO_2 concentrations *is no longer applicable* for the human health component of the SO_2 EEM Program, as the KPI for human health is calculated using measured SO_2 concentrations at residential monitoring stations *HH2. What is the peak-to-mean relationship for shorter duration exposures?* The modelling approach employed in the human health analysis in the STAR is no longer being applied in the EEM Program or in this comprehensive review.	None
Vegetation	*V1. Are we looking for vegetation injury in the right places?* The array of sampling and inspection sites provided coverage of areas both inside and outside the path of the plume and area of deposition. Some areas could not be sampled safely. *V2. How healthy is vegetation in sites with predicted exceedance of critical loads of soil and/or lakes and streams south of Lakelse Lake?* No significant differences in plant heath throughout the Kitimat Valley have been observed post-KMP.	*What methods should be used to detect mid- to long-term indirect effects?*

	STAR questions the 2014 SO_2 EEM Program intended to answer	New questions for the SO_2 EEM Program
	V3. Are plants of public importance showing symptoms in areas with the highest exceedances of soil critical loads? No symptoms associated with emissions from the modernized smelter were observed. *V4. Do plants at Kitimat have unknown sensitivity to SO_2 and associated pollutants fall within the range of variation in the literature?* Plants in the Kitimat Valley appear to be within the range of sensitivities reported in the scientific literature. Given the low ambient concentrations of SO_2, injury would not be expected to occur, and it did not.	
Terrestrial Ecosystems (Soils)	*S1. Are estimates of average weathering rates by bedrock type valid for vulnerable areas?* This question is no longer relevant as soil weathering rates are now mapped using regression kriging rather than 'averaged by bedrock type. *S2. What is the current buffering capacity (base cation pool) of soils in the exceeded areas, and when would this reservoir be used up?* This question is no longer relevant as the current buffering capacity of soils in exceeded areas is only addressed if the KPI for critical loads is exceeded. *S3. What is the rate of soil acidification measured as loss of base cations owing to acidic deposition?* This question is no longer relevant as long-term soil plots were established to assess changes in soil base cation pools.	*What is the Al solubility in upland soils?* *How sensitive are wetlands to acidification?* *Is there evidence of acidification and associated impacts in exceeded areas?*
Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)	*W1. How do assumptions in deposition and surface water models affect the predicted extent and magnitude of critical load exceedance post-KMP?* In general, the model results are robust to wide variation in assumptions. *W2. How many of the 7 to 10 potentially vulnerable lakes identified in the SO_2 technical assessment actually acidify, and to what extent?* Of the 14 lakes in the SO_2 EEM program (7 acid-sensitive lakes, 4 less sensitive lakes, 3 control lakes), 12 lakes show no evidence of sulphur-induced acidification causally related to the Kitimat smelter. LAK028 and LAK012 show some evidence of reductions in ANC or pH, but not exceeding the thresholds for these parameters that were established in the EEM Plan to protect aquatic biota.	*Has there been a statistically significant change in dissolved organic carbon (DOC) and organic anions over time?* *What is the within-year variability of the chemistry of the control lakes?* *How do the 3 metrics of ANC (i.e. Gran ANC, ANC_{OAA} and base cation surplus (BCS)) compare over time?*

	STAR questions the 2014 SO_2 EEM Program intended to answer	New questions for the SO_2 EEM Program
	W3. What species, age classes, and size of fish are present in the potentially vulnerable lakes that can be safely accessed for fish sampling? Across the six accessible lakes with fish, we found a total of six fish species: coho salmon, cutthroat trout, threespine stickleback, dolly varden char, rainbow trout and Chinook salmon. Two lakes (LAK028 and LAK 044) had no fish. *W4. If some of the potentially vulnerable lakes that can be safely accessed for fish sampling show an acidifying trend, then do these lakes also show changes in their fish communities?* None of the lakes have shown an acidifying trend beyond the SO_2 EEM thresholds requiring them to be resampled.	

3 Review Results for Atmospheric Pathways

3.1 Atmospheric Concentrations

3.1.1 What did we set out to learn?

The STAR identified an uncertainty within the atmospheric pathway, framed as a question to be addressed through the EEM program:

- STAR question A1: *Does the CALPUFF model accurately predict post-KMP SO_2 air concentrations?*

The CALPUFF dispersion model used in the STAR predicted post-KMP SO_2 concentrations and total sulphur deposition throughout the Kitimat Valley. These atmospheric SO_2 and total sulphur deposition predictions were used to complete receptor-specific effects assessments along the four lines of evidence. In this comprehensive review, we set out to learn how accurate the STAR model predictions were and to understand the base cation deposition levels in the study region. We also set out to develop more accurate model predictions of current and future post-KMP atmospheric SO_2 and total sulphur deposition using a new CALPUFF model analysis. The new CALPUFF results are used to complete updated receptor-specific effects assessments to vegetation, and terrestrial and aquatic ecosystems.

In addition, the new CALPUFF model, in combination with the 2012-2018 atmospheric monitoring data, provides information to understand the spatial and temporal variability of post-KMP SO_2 concentrations and total sulphur deposition.

3.1.1.1 *EEM informative indicators*

The atmospheric pathway has one atmospheric concentration informative indicator: *atmospheric SO_2 concentrations*. The atmospheric deposition informative indicators are discussed in Section 3.2.1.1. We use the SO_2 atmospheric concentrations to assess the risk of direct impacts on human health and vegetation in Section 4 and Section 5, respectively. Measured SO_2 atmospheric concentrations are used to assess the risk of health impacts; modelled and measured SO_2 concentrations are used to evaluate the risk of direct injury to vegetation. Since the effects from SO_2 concentrations on receptors are assessed in receptor-specific evaluations, there are no KPIs for atmospheric concentrations.

The measured SO_2 concentrations are an important informative indicator because the continuous SO_2 analyzers provide real-time, accurate, and reliable direct measurements, which can be directly tied to the smelter's current SO_2 emissions. In contrast, human health and vegetation effects are difficult to measure in real time and infeasible to measure on a continuous basis. The continuous SO_2 analyzers also provide hourly and sub-hourly data that can be used to understand how concentrations change over time and how 1-hour or 5-minute peak concentrations relate to long-term average concentrations (see Section 4.3.2 for a discussion of 5-minute peak versus 1-hour concentrations and Atmospheric Appendix Section 3.1.2 for 1-hour average versus 30-day average concentrations). The continuous SO_2 analyzer data combined with the passive sampling data also provide valuable information to understand the spatial distribution of the plume, including:

- the extent of the plume (how far away from the smelter elevated SO_2 concentrations occur),
- the position of the plume (in which direction elevated concentrations occur, i.e., north-northeast and south-southwest versus east or west); and
- the concentration gradient or relative concentration distribution (how high concentrations are at the highest levels close to the smelter versus at mid-point and lower concentrations)

The SO_2 concentration measurements also provide key information about the accuracy of the STAR model used for the STAR SO_2 effects assessments and to make decisions when developing the EEM. Learning whether the STAR over-predicted or under-predicted concentrations at various locations provides important information about whether the STAR SO_2 effects assessments over-predicted or under-predicted risk of impacts on receptors. Understanding the model accuracy at various locations (i.e., whether the model accurately predicted the extent and position of the plume) also provides valuable information about the design of the EEM program related to the locations selected for monitoring. Measured SO_2 concentrations are also used in the comprehensive review to evaluate the performance of the new CALPUFF model simulations, which in turn indicate the level of accuracy of the updated effects assessments that use the new CALPUFF model output.

3.1.2 What methods did we use?

This comprehensive review uses both monitoring data and the new CALPUFF model output of atmospheric SO_2 concentrations and sulphur deposition. The new CALPUFF model uses 2016–2018 meteorological data and includes three emissions scenarios: actual 2016–2018 (average 29.3 tpd), 35 tpd, and 42 tpd emissions.

- Actual emissions model results are compared to monitored data in order to evaluate model performance.
- 42 tpd model results are used to assess effects on vegetation, terrestrial and aquatic ecosystems under the permitted levels (maximum future SO_2 emission scenario).
- 35 tpd model results are included at the request of ENV[3] to assess a level midway between actual levels and maximum permitted levels.

The primary purpose of the new model analysis is to provide updated predictions of SO_2 concentrations and total sulphur deposition rates throughout the Kitimat Valley. These updated SO_2 and sulphur deposition predictions are then used for updating assessments of risk of impacts to vegetation, and terrestrial and aquatic ecosystems. We used the continuous SO_2 monitoring information directly to assess impacts to vegetation and human health and indirectly to evaluate the performance of the updated CALPUFF model. The passive SO_2 monitoring information was used to: (a) assess spatial and temporal changes, and (b) evaluate modelled concentration fields. Particulate sulphate (pSO_4^{2-}) was measured using a two-stage filter pack to assess its extent throughout the Kitimat Valley.

[3] During development of the comprehensive review report TOR for aquatic ecosystems, ENV requested a 35 tpd scenario. Members of the KPAC also expressed interest in a 35 tpd scenario.

3.1.2.1 *Data we collected: monitoring methods*

Atmospheric SO_2 concentrations were measured at four continuous SO_2 analyzers at Haul Road, Riverlodge, Whitesail, and Kitamaat Village. In addition, a fifth SO_2 monitoring location was added to the continuous SO_2 monitoring network at Lakelse Lake in 2018 to estimate dry deposition (Figure 3-1). While the measurements are continuous, the data are available on the British Columbia (B.C.) Air Data Archive webpage as 1-hour average concentrations.[4] ENV validates all data in this archive on an annual basis, with the previous year's data validated by June 30 of each year. The four complete 2018 datasets from the Kitimat area stations listed above were validated by ENV prior to using the data for the comprehensive review analyses. The Lakelse Lake data set is used for sulphur deposition and is not currently part of ENV's quality assurance program (i.e., ENV conducts audits on all monitors within their quality assurance program in addition to validating the data annually). In addition, the 2018 Lakelse Lake data set is not complete. Therefore, the SO_2 data from Lakelse Lake are not used in the comprehensive review analysis. Atmospheric Appendix Section 3.1.1 includes further details on the continuous monitoring network and equipment.

In addition to the primary SO_2 monitoring using the continuous analyzers, Rio Tinto established two other atmospheric monitoring networks: SO_2 passive sampling and pSO_4^{2-} monitoring using filter packs. The SO_2 passive sampler network began with a pilot program at three stations in 2015 (Technical Memo P03, 2016), and expanding to 16 sites throughout the Kitimat Valley in 2016 through 2018 (Technical Memo P04, 2017; Technical Memo P05, 2018). The SO_2 passive sampling program includes two networks:

- The Valley Network included 16 monitoring sites primarily located along the Wedeene and Bish roads (Figure 3-1) to capture the plume path.
- The second network was established in urban and residential areas of Kitimat to support the 'multi-seasonal air quality' and the 'air quality network optimization' studies. During 2016, the urban network included 17 sites but expanded to 22 sites during 2018 (Figure 3-1).

The passive sampler networks employed IVL passive SO_2 samplers (URL: diffusivesampling.ivl.se) with an exposure period of one month (see Technical Memo P03, 2016). In general, both networks operated between June and October, providing four one-month exposures. However, the urban network was extended to year-round sampling in 2018. Duplicate samplers were deployed ~25% of the time at varying locations (to assess variation in measurements). To evaluate the performance of the passive samplers, the networks also included co-location with four ambient stations (Haul Road, Riverlodge, Whitesail and Lakelse Lake[5]). Following deployment, all samplers were returned to IVL for laboratory analysis.

Further, SO_2 and pSO_4^{2-} were measured using a two-stage filter pack during several discrete campaigns throughout the Kitimat Valley in 2017–2018 (Rio Tinto Voluntary). These observations are used to assess what fraction of atmospheric sulphur is in the form of pSO_4^{2-} in

[4] https://envistaweb.env.gov.bc.ca/
[5] ENV is not currently validating Lakelse Lake SO_2 data. ENV will validate data if/when there is a data sharing agreement and if the analyzer is part of ENV's quality assurance program (including conducting audits).

the region. The two-stage filter pack network was established to monitor SO_2 and pSO_4^{2-} at several discrete locations (n = 9) during four campaigns throughout the Kitimat Valley (Figure 3-1). The two-stage filter holders were developed by the Norwegian Institute for Air Research (URL: www.innovation.nilu.no). The first stage holds a 47 mm Teflon (PTFE) filter to capture particulates, and the second stage holds a 47 mm cellulose filter impregnated with potassium hydroxide to capture SO_2. (see Technical Memo F01, 2018). The holder is connected to a diaphragm pump with a recommend flow rate of 15 L min^{-1} for daily sampling. Exposures ranged in duration from 24 to 48 hours (depending on the pump volume). All filter pack analysis was carried out at Trent University.

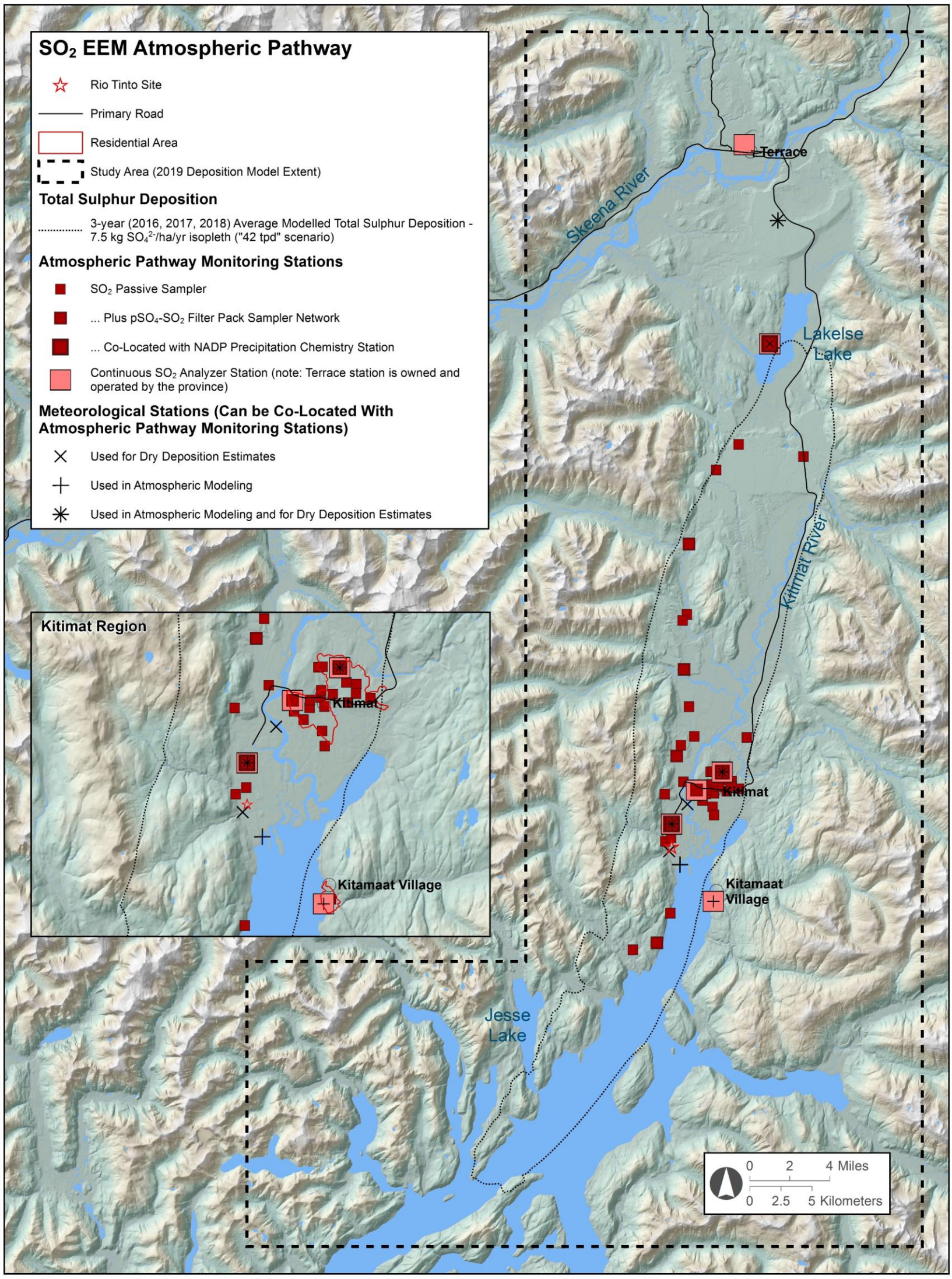


Figure 3-1. Locations of atmospheric SO_2 concentration and sulphur deposition monitoring for the SO_2 EEM Program. The location of meteorological stations is also shown.

3.1.2.2 *Atmospheric concentrations monitoring data analysis methods*

This section describes the methods used to analyze the atmospheric concentration monitoring data. Section 3.2.2 describes the monitoring data analysis of atmospheric deposition, including comparison of measured S deposition to modelled S deposition (results in Section 3.2.3.4).

SO_2 continuous monitor data analysis methods

As part of the EEM annual reporting, each year we compared the continuous analyzer measurements to modelled SO_2 air concentrations from the STAR for the 1-hour, 3-hour, 24-hour, and annual averaging periods, consistent with the objectives relevant during the STAR. As part of the comprehensive review, SO_2 continuous monitor data are used for model performance evaluation (see Section 3.1.3.5).

Multi-seasonal air quality study methods

We began development of a multi-seasonal air quality study on the seasonal and spatial variability of SO_2 concentrations in the residential areas of Kitimat. The study has been cancelled, but we plan to use the year-round data from the passive samplers deployed in the Urban Network (up to October 31, 2019) for the Kitimat air quality monitoring network optimization.

Air quality network optimization methods

Rio Tinto committed to evaluating the air monitoring network as part of the EEM program because KMP has changed the emissions profile from the smelter, which affects the spatial distribution of SO_2 ambient concentrations. Following U.S. EPA guidance,[6] Trinity analyzed the results from air dispersion modelling of the 42 tpd maximum permitted SO_2 emissions scenario (same source input as used for the STAR) using the 2006, 2008, and 2009 meteorological data similar to the data used for the STAR and post-KMP SO_2 monitoring data (Phase 1 network optimization[7]). The results of the Phase 1 analysis showed that the Riverlodge monitor is in a suitable location to represent the highest concentrations expected within the Kitimat residential area; that Whitesail monitor location does not provide added benefit for measuring the maximum SO_2 air concentrations within Kitimat; and that the Kitamaat Village monitor is in the most suitable location within Kitamaat Village.

Phase 2 of the air quality network optimization is planned to start in the second quarter of 2020, using the new 2016 to 2018 modelling results and incorporating the latest data from SO_2 concentration monitoring. In 2015, a draft TOR for the air quality monitoring network optimization was provided to ENV and other stakeholders for review and comment. Comments were received and discussed in January through June 2016, including at the June 2016 Air Quality workshop. The 2016 Air Quality Workshop provided detailed information to the Kitimat Public Advisory Committee (KPAC) on the continuous monitoring network, monitoring data, optimization process, and passive sampling program. As a key outcome of the workshop and public feedback received, the Urban Passive Sampler Network was established. Both Phase 1 and

[6] U.S. EPA technical assistance document for "source-oriented monitoring" for SO_2 available at: https://www.epa.gov/sites/production/files/2016-06/documents/so2monitoringtad.pdf
[7] Trinity Consultants. Air Quality Network Evaluation. April 2019.

Phase 2 network optimization efforts use the passive sampling data to better understand spatial patterns within urban and residential Kitimat.

Rio Tinto submitted a revised version of the TOR addressing the comments received and focused on Phase 2 of the optimization in April 2019. The TOR proposes using zoning maps[8] to define the study area rather than census data because the Kitimat residential network should represent any locations where people may reside now or in the near future. The zoning maps provide the best information to define current and future residential areas. In 2020, Rio Tinto will submit a revised version of the TOR submitted in April 2019 to reflect the most up to date status of the available monitoring and modelling data.

In addition to residential areas, the Kitimat SO_2 air quality monitoring network also represents commercial areas in Kitimat (e.g., City Centre Mall). However, the existing monitors may or may not sufficiently represent the Service Centre commercial area. Passive sampling data indicate that 30-day average concentrations in summer months are higher in the Service Centre area than measured at the nearby Riverlodge monitoring station. The new CALPUFF model predicts annual 1-hour concentrations are higher in the Service Centre than at Riverlodge. However, because of the uncertainty inherent in the CALPUFF model and the inconsistent relationship between 30-day average and 1-hour peaks, the available information is not sufficient to provide clear conclusions whether the peak 1-hour actual concentrations are higher in the Service Centre area than measured at the nearby Riverlodge monitoring station. As such, we may consider new continuous SO_2 monitoring in the Service Centre.

Monitoring data analysis that focuses on the Phase 2 network optimization will begin in 2020. Preliminary analysis of the local-scale CALPUFF results focused on the network evaluation has been completed as part of the comprehensive review. The preliminary model results are analyzed following the methods detailed in the draft TOR and similar to those outlined in the Phase 1 report (both in Atmospheric Appendix Section 3.1.9). The procedure follows the U.S. EPA guidance for the SO_2 national ambient air quality standard source oriented monitoring.[9] Equal weight is given to highest concentrations over the three model years (in the form of the standard) and frequency (locations that would most frequently measure the highest concentration in a given day versus other modelled locations). Following the guidance, the approach also excludes locations that cannot be accessed due to terrain or other impediments prior to the data analysis. A summary of the preliminary network optimization CALPUFF results are presented in Section 3.1.3.7 of this report. Details of the preliminary Phase 2 monitoring network evaluation (methods and results) are included in Atmospheric Appendix 3.1.3, and a copy of the Phase 1 network rationalization and draft Phase 2 network optimization TOR reports are included in Atmospheric Appendix 3.1.9.

[8] Kitimat Townsite Zoning Map and District of Kitimat Zoning Map, https://www.kitimat.ca/en/business-and-development/resources/Documents/Townsite-Zoning-Map.pdf, https://www.kitimat.ca/en/business-and-development/resources/Documents/District-of-Kitimat-Zoning-Map.pdf. Downloaded April 2019.
[9] Ibid.

SO_2 passive sampler data analysis methods

The SO_2 passive sampler results were used to evaluate the spatial and temporal changes in Kitimat Valley, and to evaluate CALPUFF modelled concentration data (under the actual emissions scenario).

The performance of the passive samplers was evaluated through duplicate exposures to estimate the variability (as percent difference) between samplers. Further, individual monthly passive sampler exposures were compared to average continuous SO_2 data (for the same period) at co-located sites: Haul Road and Smeltersite (2015 only) for the valley network, and Riverlodge and Whitesail for the urban network (2016 to 2018 only). The best-fit linear regression between passive samplers and continuous analyzers was used to calibrate the passive sampler data.

Individual exposures were summarised to produce annual Spring–Autumn (June–October) and long-term (2016–2018) averages (weighted by exposure period)[10] for each site. All data were adjusted (calibrated) to account for deviations between the passive and continuous SO_2 data. The spatial variation in SO_2 passive samplers in the Kitimat Valley was evaluated through spatial mapping of the three-year average concentrations and evaluation of the change in concentrations with distance from the smelter. The temporal variability between annual Spring–Autumn (June–October) averages was evaluated through coefficient of variation (also known as relative standard deviation), which was estimated as the standard deviation between the three years divided by the annual Spring–Autumn average (multiplied by 100 for units of percent). The three-year average SO_2 passive sampler concentrations for the Valley Network sites were compared against modelled (actual emissions scenario) SO_2 data summarised for the identical period to evaluate the performance of CALPUFF. We also evaluated if passive samplers could be scaled from Spring–Autumn (June–October) to annual values using the ratio (for the same period) observed at continuous stations; however, the approach was not used as we focused only on monitoring stations with full year continuous SO_2 data to estimate annual total deposition values (see Section 3.2).

We evaluated continuous SO_2 monitoring data at the 4 stations to assess if a peak-to-mean ratio (1-hour peak to 30-day average) can be established for use with the SO_2 passive sampler results. The analysis concluded that the 1-hour peak to 30-day average ratio is inconsistent and highly variable and should not be used to draw conclusions about 1-hour peak concentrations based on 30-day average passive sampling data. Details of the methodology and results are included in Atmospheric Appendix Section 3.1.2.

Filter pack monitoring data analysis of particulate sulphate methods

Filter pack results of pSO_4^{2-} and SO_2 collected under four campaigns during 2017–2018 were analysed first to evaluate the performance of filter pack SO_2 measurements by comparison to continuous station SO_2 (for all co-exposures). Second, the contribution (importance) of pSO_4^{2-} to

[10] The annual Spring–Autumn and long-term average concentrations were weighted by the exposure period (hours) for each individual sampler, i.e.,

$$\bar{x} = \frac{w_1 x_1 + w_2 x_2 + \cdots + w_n x_n}{w_1 + w_2 + \cdots + w_n}$$

where x is the individual exposure concentration and w is the exposure period duration.

total atmospheric sulphur was assessed using the pSO_4^{2-} to SO_2 plus pSO_4^{2-} ratio (F_s expressed as percent). We also evaluated whether this ratio may be used as a means to estimate pSO_4^{2-} from observations of SO_2. The sulphur concentration ratio (F_s) was calculated following Grosjean and Friedlander (1975):

$$F_s = \frac{[pSO_4^{2-}]}{[SO_2] + [pSO_4^{2-}]} \times 100$$

where [pSO_4^{2-}] is the sea-salt corrected particulate sulphate concentration, expressed as S (µg/m³), and [SO_2] is the average gaseous SO_2 concentration expressed as S (µg/m³). The measured F_s ratios were compared to the modelled F_s ratios to evaluate model performance. It should be noted that the measured F_s represent a small number of daily observations (max = 20) compared with modelled F_s based on annual data. Further, the modelled F_s do not include 'background' atmospheric sulphur contributions.

3.1.2.3 *Data we collected: modelling methods*

We performed CALPUFF modelling for three scenarios: actual emissions (varying by month), 35 tpd, and 42 tpd (permitted rate). As part of this analysis, we gathered SO_2 emission rate information from the smelter (using sulphur mass balance) to accurately estimate monthly average SO_2 emission rates from each emission source (electrolysis gas treatment centre and potline roof vents, anode baking furnace, fume treatment centre, and calciner). This same actual emissions dataset was used to update the 35 tpd and 42 tpd scenario to more accurately model the distribution of the SO_2 emissions among the sources at the smelter. In addition, we collected as-built source and building information for the new model analysis. Atmospheric Appendix Section 3.1.5 provides the monthly SO_2 emission rates and source parameters, and Section 1.3 describes the historic SO_2 emission rates from the smelter.

Data sets collected from local meteorological stations were also used in the CALPUFF model analysis. Complete details of all data inputs to the CALPUFF model system are included in Atmospheric Appendix Section 3.1.5 and 3.1.9.

3.1.2.4 *CALPUFF modelling analysis methods*

We conducted 2016–2018 CALPUFF modelling following a detailed model plan and B.C. Air Quality Dispersion Modelling Guideline (B.C. Ministry of Environment and Climate Change Strategy 2015), submitted to ENV May 13, 2019 and approved May 31, 2019. The model plan and approval are included in Atmospheric Appendix Section 3.1.9.

About dispersion models methods

Dispersion models serve as a tool to predict or estimate ambient air concentrations and deposition rates due to industrial or other anthropogenic sources of emissions. Dispersion models are most commonly used to predict air concentrations from industrial sources that have not yet been constructed. Predictions available from dispersion models allow stakeholders to gain an understanding of the changes to ambient air due to emissions changes from a project *before* the project begins operation. Most applications of source-oriented dispersion models compare modelled air concentrations or deposition rates to screening thresholds, air quality objectives, or air quality standards. It is rare to use these model outputs as inputs to other models.

Dispersion models are designed to be conservative, because their most common purpose is to provide a worst case estimate of air quality after a project to ensure the project will not result in violations of air quality requirements or detrimental impacts to human health or the environment. Typical levels of conservatism range from 50 percent over-prediction, up to over-predicting by a factor of four (400 percent over-prediction) when using maximum (permitted) emission rates. When model evaluations are performed using hourly actual emission rates and other methods to minimize reducible uncertainty, model accuracy is typically within about a factor of two (i.e., models often estimate between 50% and 200% of monitored concentrations).[11] The uncommon use of air dispersion model output as inputs to additional models (e.g., critical load models) causes uncertainties in each model to compound. The most commonly used dispersion models for predicting air pollutant concentrations from industrial sources are AERSCREEN, AERMOD, and CALPUFF.

About the CALPUFF dispersion model

While the CALPUFF model is more complex and technically challenging than its relatives, it offers several advantages. The modelling analysis presented in this report applies the CALPUFF dispersion model for a number of reasons, including the need to:

- determine long-range impacts (AERSCREEN and AERMOD are not recommended for distances over 50 kilometres);
- represent complex terrain conditions in the Kitimat area (AERMOD assumes winds do not change direction across the entire domain for each time step, while AERSCREEN does not consider wind direction at all);
- represent the influence of the land/sea boundary (e.g., land-sea breeze circulation and onshore fumigation); and
- represent calm wind conditions (AERMOD ignores hours with "calm" winds).

The CALPUFF model is a useful tool to inform decisions and generally errs on the conservative side.

The main components of the CALPUFF modelling system are the CALMET, CALPUFF, and CALPOST models. CALMET is the meteorological model that generates hourly three-dimensional meteorological fields such as wind and temperature. CALPUFF simulates the non-steady state transport, dispersion, and chemical transformation of air pollutants emitted from a source in "puffs". CALPUFF calculates hourly concentrations of specified pollutants at specified receptors in a modelling domain. CALPOST is the post-processor for CALPUFF that computes concentration and deposition from emissions sources based on the pollutant concentrations and deposition that are output by CALPUFF.

CALPUFF dispersion modelling methods summary methods

For the new 2016–2018 CALPUFF model analysis, we used model methods consistent with the methodologies used for the STAR dated April 2013, with the exception of some key changes:

[11] U.S. Environmental Protection Agency. Guideline on Air Quality Models (40 CFR 51, Appendix W): *The "irreducible" uncertainty associated with Gaussian plume models may be responsible for variation in concentrations of as much as +/- 50 percent. "Reducible" uncertainties can be on a similar scale.*

- As-built source and building parameters are used, including flow and temperature based on actual source test data where available.
- Meteorological years 2016–2018 are used.
- The regional-scale analysis used meteorological data processed using Weather Research and Forecasting (WRF)[12] data developed by Trinity rather than fifth-generation mesoscale regional weather model used in the STAR.
    - The CALMET model was run in the hybrid mode with WRF and local observation data consistent with the STAR approach. Note this approach is different from the CALMET method proposed in the original model plan. The hybrid approach yields improved model performance as detailed in a technical memorandum to ENV, included in Atmospheric Appendix Section 3.1.9.
- The initial domain for this meteorological data is nearly identical to the domain used in the STAR protocol but extended south 24 km to include better coverage of the final STAR receptor grid, which was also extended south.
    - The domain was expanded to the southwest as further described in the section below.
- The local-scale analysis uses meteorological data processed using only surface station data (also known as Obs-Only mode).
    - That is, the local scale analysis does not use WRF for gridded input.
    - However, a pseudo upper air station from WRF output is used to represent the upper air data because no upper air data are available within the Kitimat Valley. The location of the pseudo upper station is from the WRF grid cell closest to the Terrace Airport. This location is different from the location proposed in the original model plan (initially proposed the WRF cell closest to the gas treatment centre stacks). Using the new pseudo upper air station location yields improved model performance as detailed in a technical memorandum to ENV, included in Atmospheric Appendix Section 3.1.9.
- The UTM coordinate system, WGS 84 ellipsoid is used as opposed to the UTM NAD 27 used in the STAR approach, which will allow Qualified Professionals (QPs), ENV, and the public to better understand model inputs and outputs using readily available tools such as Google Earth.
- Hourly precipitation data are obtained from the Haul Road and Lakelse Lake wet deposition stations.
- SO_2 concentrations measured at the Terrace Skeena Middle School station, representing SO_2 background, are added to model results to predict total ambient SO_2 concentrations for effect assessments.
    - 1-hour, 99th percentile daily peak SO_2 for 2016, 2017 and 2018: 4.6, 5.9 and 6.1 ppb respectively, are added to each corresponding year for the actual emission scenario. 3-year average results and future scenarios use the average of three years: 5.53 ppb.
    - Annual average SO_2 for 2016, 2017 and 2018: 0.5, 0.5, and 0.4 ppb respectively, are added to each corresponding year for the actual emission scenario. 3-year average results and future scenarios use the average of three years: 0.47 ppb.

[12] WRF is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications (https://www.mmm.ucar.edu/weather-research-and-forecasting-model).

    - This approach of adding background concentrations based on Terrace monitoring is expected to over-predict SO_2 concentrations in non-populated areas because emissions of SO_2 from non-modelled sources (such as diesel burning engines) are much lower in non-populated areas. This approach would also double count any smelter emissions contributing to SO_2 at the Terrace monitor (however, smelter contribution of SO_2 at Terrace is expected to be very low).
- For model performance evaluation, more realistic background values are used based on Williams Lake SO_2 monitoring data: Based on 2017 and 2018 data, the Williams Lake background concentrations are:
    - 1-hour, 99th percentile daily peak SO_2: 1.8 ppb; and
    - Annual average SO_2: 0.26 ppb.

The regional-scale model S deposition outputs serve as input for CL modelling for terrestrial and aquatic ecosystems. The regional-scale model SO_2 concentration outputs (considered in conjunction with other information including measured SO_2) are used to evaluate the risk of direct injury to vegetation. The local-scale model results are used for the local monitoring network evaluation.

We evaluated model performance by comparing the actual scenario results to SO_2 monitoring data. This included comparing hourly data at the continuous monitoring stations and monthly data at the passive sampling sites. The primary purpose of the comparison to SO_2 passive sampling is to evaluate the spatial SO_2 gradient produced by CALPUFF to verify that it aligns with observations.

The initial model runs (actual scenario) following the original model plan resulted in an unexpected spatial distribution of the concentrations and deposition rates. The initial results did not align with expectations based on terrain and monitoring data. Therefore, we evaluated model improvement options, proposed updates to the model plan to ENV, and compared initial and updated CALPUFF results for the actual scenario to observations. The change made to the regional scale model was to run the regional CALMET model in the hybrid mode, rather than no-observations mode as originally proposed. The change made to the local scale-model was to use a different location to extract WRF data for the pseudo upper air station. Both these changes reduced the influence of WRF data and increased the influence of local observation data near the smelter. Both changes resulted in clear improvement in model performance (i.e., model concentrations align more closely with observations when using the updated methods). Copies of the model evaluation and proposed model plan updates provided to ENV and associated ENV approval are provided in Atmospheric Appendix Section 3.1.9.

Regional CALPUFF domain: All cases of industrial air emissions begin with relative high air concentrations at the point of release (e.g., at the top of the stack). Meteorological and terrain influences cause the emissions to disperse as the plume travels downwind. At some point downwind, ground level concentrations reach a dispersion level so dilute that concentrations are below levels of interest. The emissions from the smelter disperse to a level equivalent to half of the CAAQS (< 2.5 ppb on annual averaging period and < 35 for the 1-hour averaging period) approximately 30 km to the north and approximately 15 km to the southwest. The model domain proposed in the detail model plan adequately captures this level. The level of interest for total sulphur deposition is 7.5 kg SO_4^{2-}/ha/yr. The proposed model domain in the detail model plan did not include all areas with predicted deposition equal to or above 7.5 kg SO_4^{2-}/ha/yr. Therefore, the domain was extended to the southwest as shown in Figure 1-3.

3.1.3 What did we learn, and did we make any adjustments to the EEM Program?

3.1.3.1 *Overview of EEM monitoring program results – continuous SO_2 network*

The continuous SO_2 network provided valuable information to answer STAR question A1 (answered in the following sub-section) and to understand the overall spatial and temporal trends in the Kitimat area. The four monitoring locations provide limited spatial variability information but do confirm that the residential areas of Kitimat and Kitamaat Village continue to experience generally low concentrations of SO_2, while the area near the fenceline to the north of the smelter (represented by the Haul Road monitor) remains higher than residential areas. The passive SO_2 network results discussed in the next Section 3.1.3.2 provide more information on spatial variability. As presented in Figure 3-2 and Figure 3-3, the temporal trends of the continuous SO_2 monthly average data indicate the Haul Road (fenceline) concentrations have generally increased with increasing SO_2 emissions from the smelter, while SO_2 concentrations in residential areas do not show a noticeable trend of higher monthly SO_2 concentrations associated with the higher SO_2 emissions.. In particular, the charts show residential concentrations are similar or lower during the 2016 – 2018 post-KMP period than during the 2013 to 2015 period with lower SO_2 emissions. In contrast, the highest Haul Road monthly SO_2 concentrations in 2013 – 2015 are approximately 3 ppb and increase to 8 ppb during post-KMP. This difference may be influenced by residential areas being influenced more by meteorological conditions than at the Haul Road station. Figure 3-3 shows only the residential SO_2 monitoring data alongside the SO_2 emission rate data to see the changes (or lack thereof) more clearly for these relatively low concentrations.

- Riverlodge recorded the highest monthly average of 1.0 ppb in August 2013 (during low SO_2 emissions) compared to 0.80 ppb in July 2017.
- Kitamaat Village recorded the highest monthly average of 0.60 ppb and 0.56 ppb in August 2013 (during low SO_2 emissions) compared to 0.67 ppb in February 2016 (and below 0.5 ppb for all other 2016 – 2018 months).
- The Whitesail monitor was not operational for most of 2013 – 2015; however, it generally shows trends of relatively low post-KMP concentrations consistent with Riverlodge.

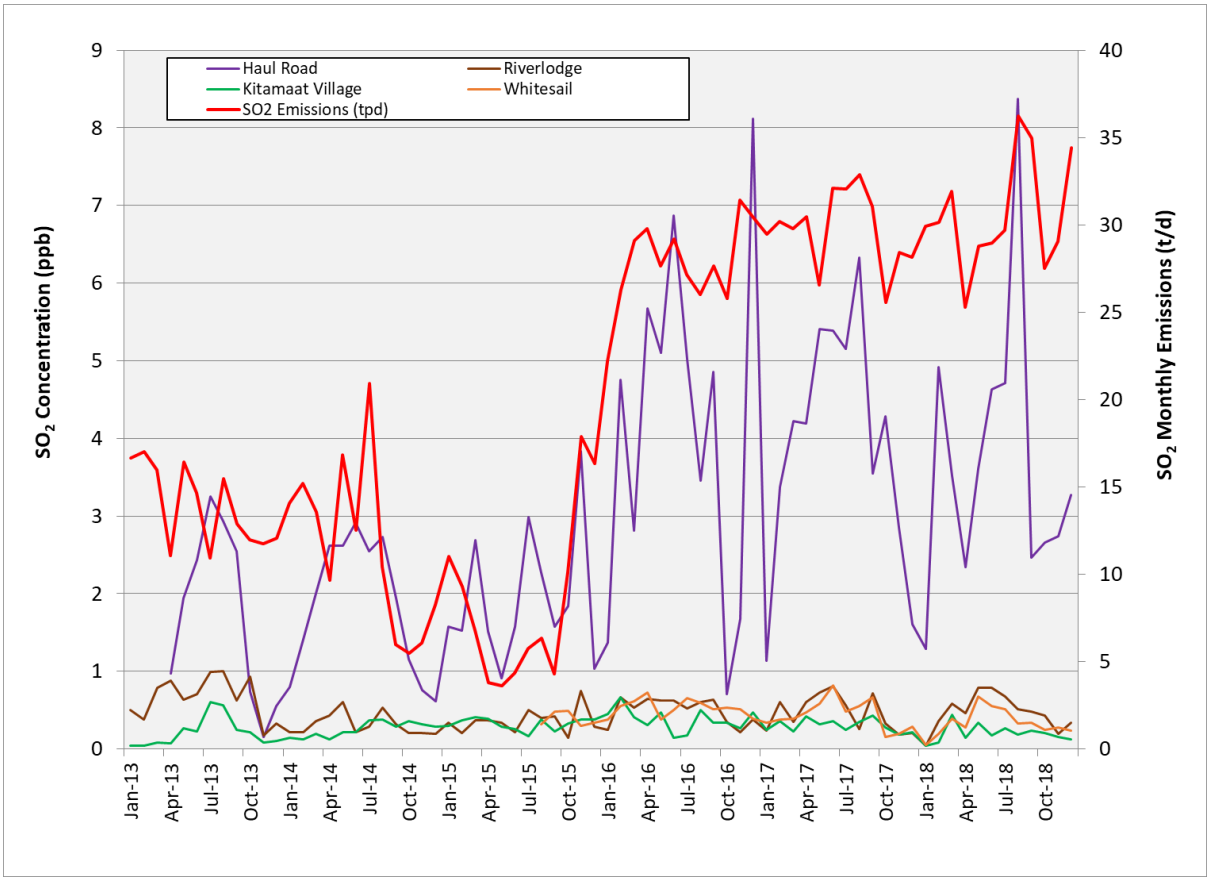


Figure 3-2. Monthly SO_2 emissions (red line) and monthly average ambient SO_2 concentrations at the four continuous monitoring stations (purple, brown, green and orange lines) for 2013 to 2018.

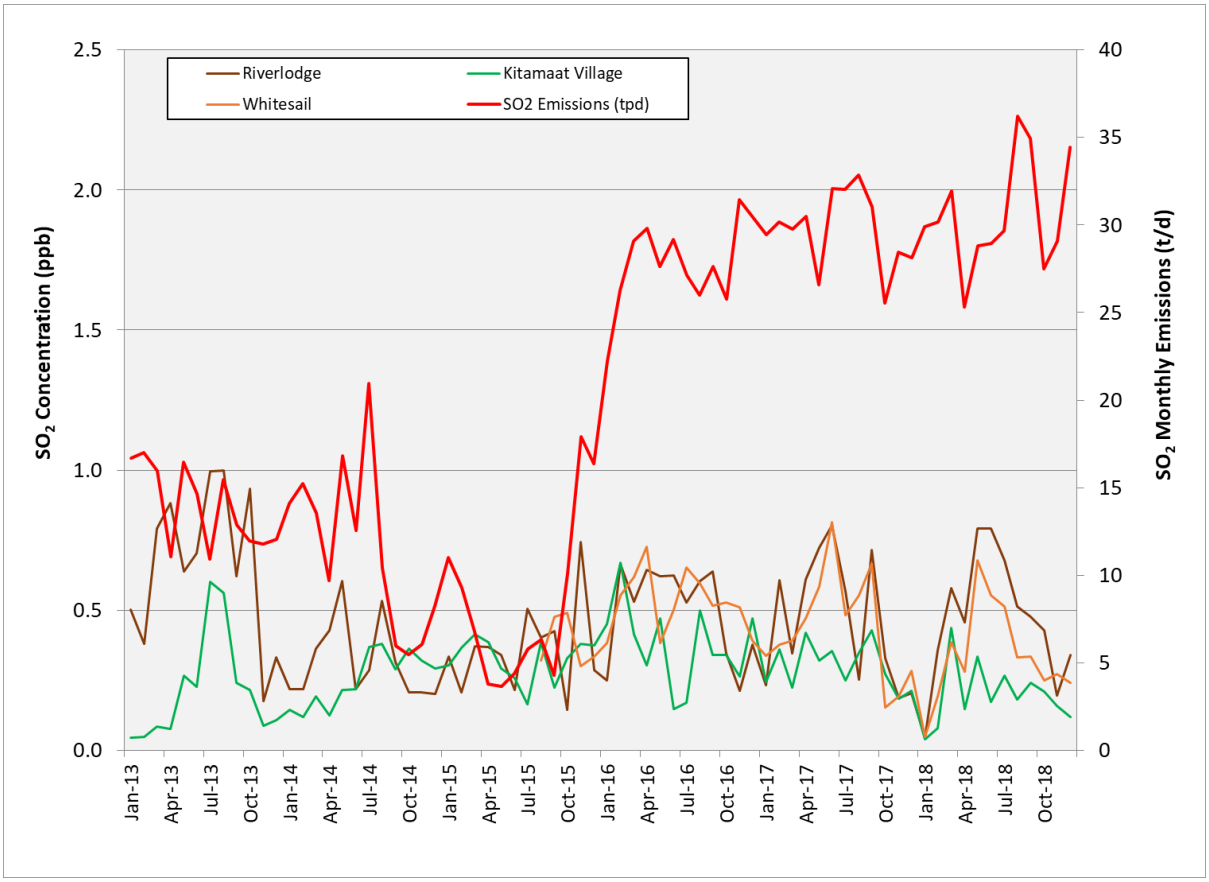


Figure 3-3. Monthly SO_2 emissions (red line) and monthly average ambient SO_2 concentrations at three residential continuous monitoring stations (brown, green and orange lines) for 2013 to 2018.

Charts of the residential annual averaging SO_2 and 1-hour SO_2 (99th percentile of daily 1-hour peak) in Figure 3-4 and Figure 3-5 show similar temporal trends. The residential concentrations remain relatively unaffected by the changes in SO_2 emissions; however, some increasing trend is noticeable for the 1-hour results in Figure 3-5. The Haul Road monitor is not shown in the CAAQS-comparison charts below because the CAAQS are not intended to be used for fenceline reporting.[13] Consistent with model results, these trends indicate that the post-KMP SO_2 plume infrequently affects the residential areas of Kitimat. In addition, as illustrated by comparison to the CAAQS air management levels on the chart background, the residential concentrations have remained in the "keep green areas green" management category under the Canadian Council of Ministers of the Environment (CCME) and well below the 2020 CAAQS levels indicated by the red management level (for "Reduce ambient pollutants below the CAAQS").[14]

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[13] ENV Air Quality Management System Information Sheet: New National Air Quality Standards for SO_2. November 2016. (https://www2.gov.bc.ca/assets/gov/environment/air-land-water/air/reports-pub/fs_so2_caaqs.pdf).
While the CAAQS are not intended to be used for fenceline reporting, these standards will be used to characterize air quality and potential air quality impacts in areas where people live or where other sensitive receptors are likely to be found.

[14] https://www.ccme.ca/en/resources/air/air/sulphur-dioxide.html

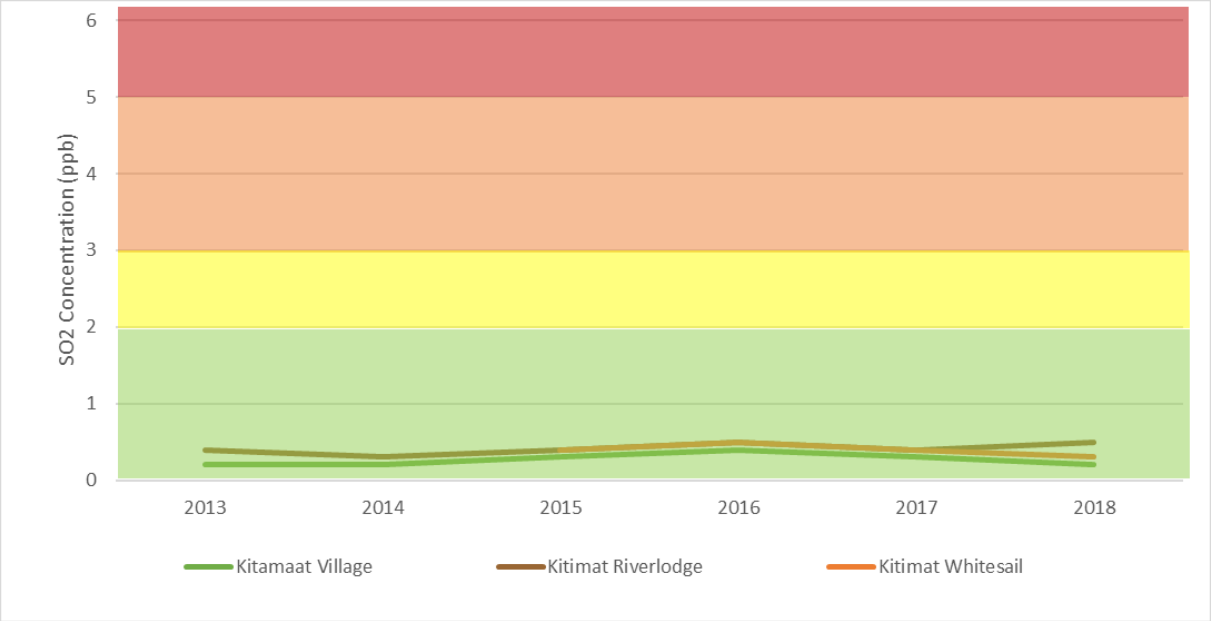


Figure 3-4. Annual average ambient SO_2 concentrations at the four continuous monitoring stations (purple, brown, green and orange lines) for 2013 to 2018. SO_2 CAAQS and CCME management levels shown in background: Red = Reduce below the CAAQS, Orange = Prevent CAAQS exceedance, Yellow = Prevent air quality deterioration, Green = Keep clean areas clean.

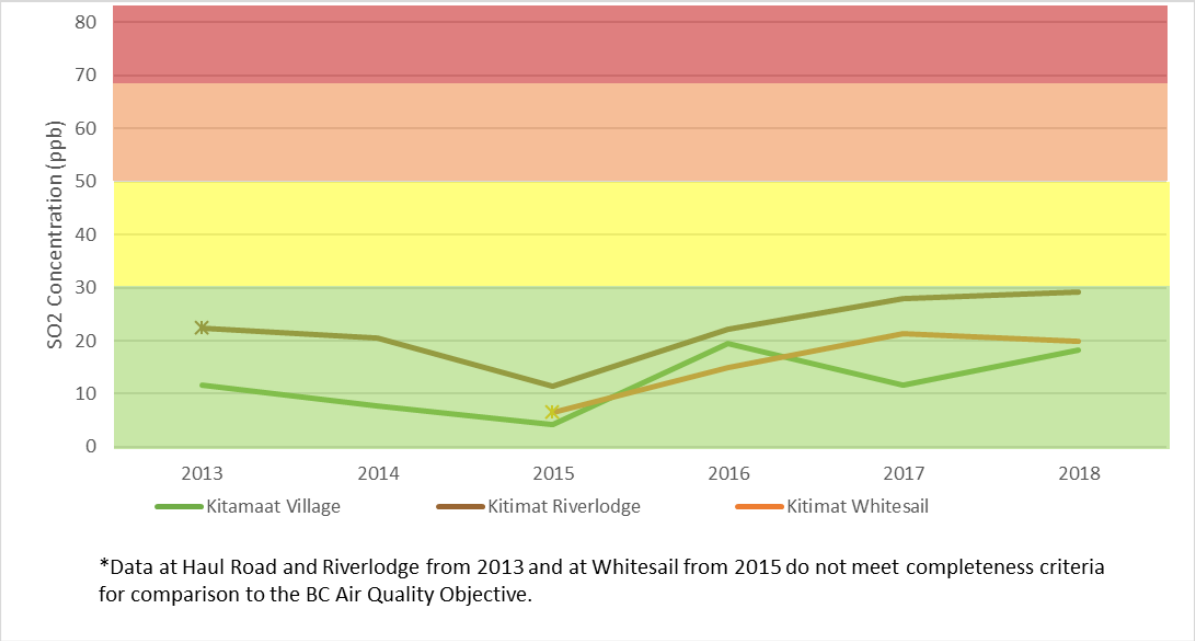


Figure 3-5. 99th percentile of daily 1-hour peak ambient SO_2 concentrations at the four continuous monitoring stations (purple, brown, green and orange lines) for 2013 to 2018. SO_2 CAAQS and CCME management levels shown in background: Red = Reduce below the CAAQS, Orange = Prevent CAAQS exceedance, Yellow = Prevent air quality deterioration, Green = Keep clean areas clean.

STAR question A1: Does the CALPUFF model accurately predict post-KMP SO_2 air concentrations?

As detailed in the annual EEM reports and summarized in Figure 3-6 below, comparisons performed each year between continuous SO_2 monitoring data and CALPUFF model results showed that the actual measured SO_2 concentrations were substantially lower than model predictions of post-KMP SO_2 concentrations from the STAR at most locations and near model predictions at Haul Road (most years the model slightly under-predicted at Haul Road when scaling STAR results using actual emission rates). Figure 3-7 comparing the 99th percentile of daily 1-hour peak also shows that the STAR model over-predicted concentrations at all three residential monitors and slightly under-predicted at Haul Road. This comparison confirmed expectations based on the STAR CALPUFF model comparison of pre-KMP model results to pre-KMP monitoring data (2006, 2008, 2009): that the STAR SO_2 predictions generally over-predicted concentrations, particularly in residential areas. In other words, the continuous SO_2 monitoring has provided the data needed to answer the question whether CALPUFF accurately represents post-KMP SO_2 concentrations: CALPUFF over-predicted post-KMP concentrations at most locations.

The continuous SO_2 data set also provides information for new CALPUFF model performance evaluation (see Section 3.1.3.5), which will answer the related question of how accurately the new CALPUFF model predicts post-KMP concentrations.

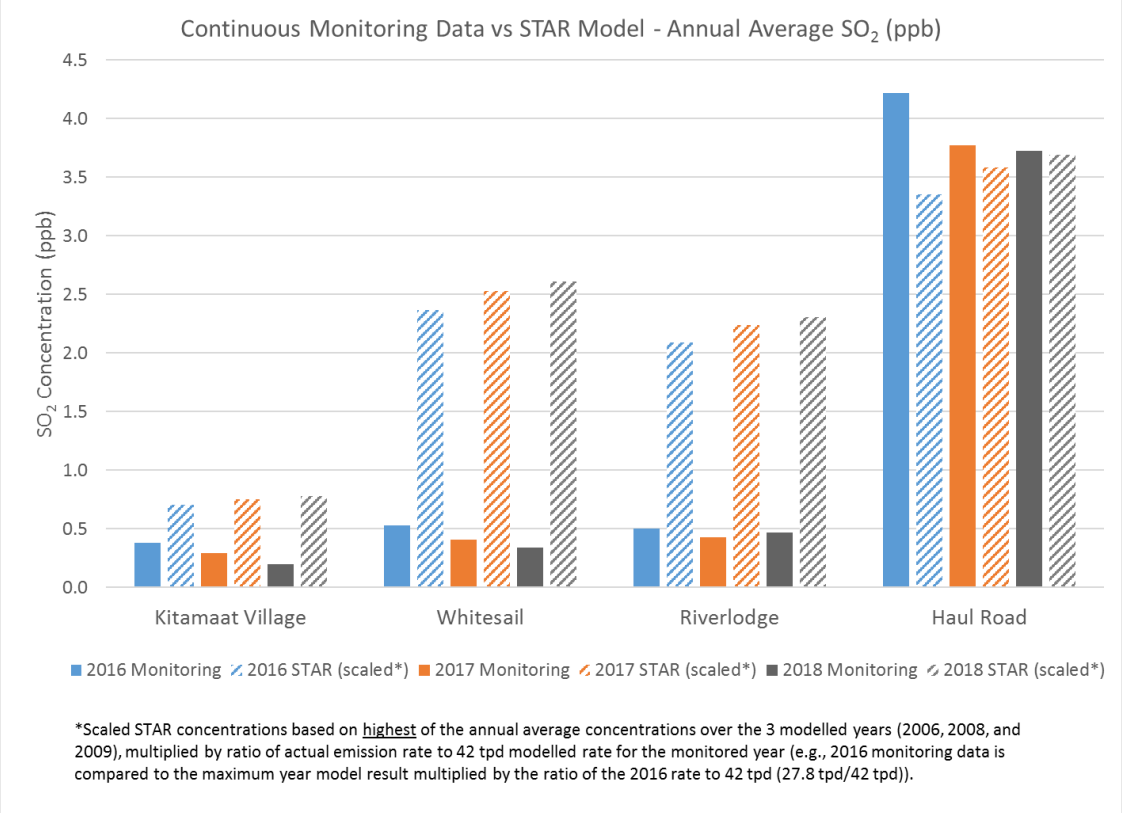


Figure 3-6. Continuous SO_2 monitoring concentration compared to scaled STAR model concentrations, annual average (background of 0.4 ppb used in STAR included).

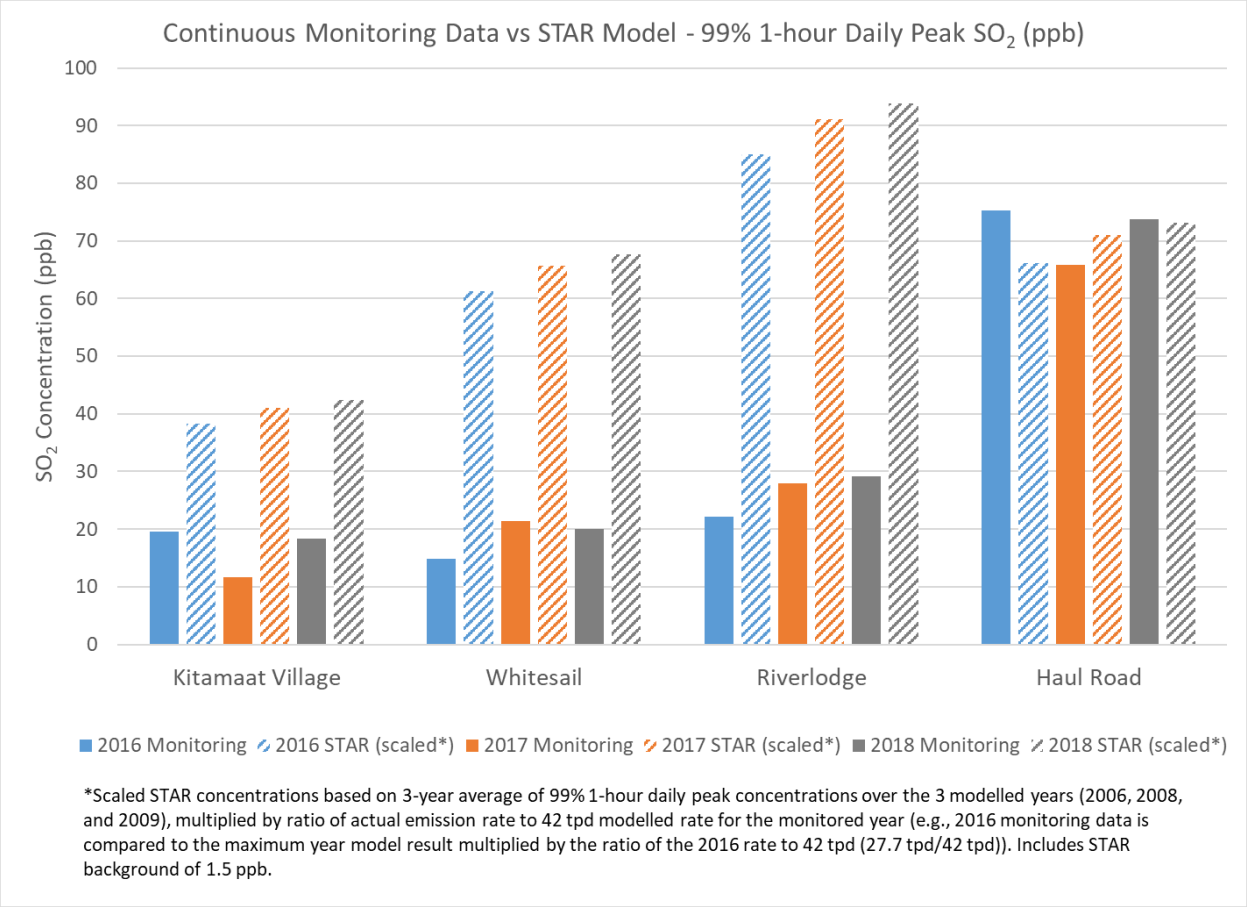


Figure 3-7. Continuous SO_2 monitoring concentration compared to scaled STAR model concentrations, 99th percentile of daily 1-hour peak (background of 1.5 ppb used in STAR included).

3.1.3.2 *Overview of EEM monitoring program results – passive SO_2 network*

During 2016–2018 (three years), there were 240 passive samplers deployed in the Kitimat Valley network, which included 50 duplicate exposures (>25% of sampler exposures were duplicates). The average percent difference between duplicate samplers was ~15% (median ~11%). There was a strong linear agreement between passive (individual monthly exposures) and continuous SO_2 observations (averaged over the same exposure period) in both the valley (coefficient of determination (R^2) of 0.90) and urban (R^2 = 0.67) networks; although, deployments at the continuous station in the valley network showed stronger statistical agreement than the agreement at the urban continuous stations (Figure 3-8). In general, passive samplers underestimated air concentrations compared with the continuous analyzers; as such all passive data were calibrated to the continuous analyzers based on the best fit lines shown in Figure 3-8 (see Atmospheric Appendix Section 3.1.4 for details on the calibration). All Valley sampler results

are calibrated using the best fit line for the Haul Road and Smeltersite (Figure 3-8(A) [15]) and all Urban sampler results apply the best fit for Whitesail and Riverlodge (Figure 3-8(B)).

The passive sampler SO_2 concentrations are reported in units of micrograms per meter cubed ($\mu g/m^3$). However, this chapter also frequently presents SO_2 results in units of parts per billion (ppb) in order to stay consistent with the continuous analyzer monitoring data and the CAAQS. It is possible to move between ppb and $\mu g/m^3$ by a factor of 2.614 $(\mu g/m^3)/(ppb)$.[16]

The average yearly Spring–Autumn (June–October) SO_2 concentrations ranged from 1.38 $\mu g/m^3$ (0.53 ppb) (A04: Lakelse Lake during 2016) to 13.51 $\mu g/m^3$ (5.17 ppb) (V11: Bish Road during 2017) in the valley network (Table 3-1). The highest SO_2 concentrations were generally observed close to and south of the smelter (Figure 3-9 and Table 3-1). In general, SO_2 concentrations in the valley followed a logarithmic decay with distance from the smelter (Figure 3-10). This spatial pattern was consistent between the three years of observations, with an average coefficient of variation < 20% (Table 3-1) ranging from 4.1% (Bish Road at Chevron) to 31.6% (Sandhill).

We also used the passive sampling measurements to evaluate the 2016–2018 CALPUFF model performance (see Section 3.1.3.5). The accuracy of spatial SO_2 dispersion patterns predicted in the STAR cannot be entirely assessed based on the coverage of the continuous SO_2 analyzers. As such, the passive sampling network implemented mid-way through the EEM program provided valuable information in locations where continuous SO_2 analyzers are not located. It is important to note that passive samplers provide a measure of average air concentration during their exposure, they cannot provide information on maximum concentrations (see Atmospheric Appendix Section 3.1.2). Nonetheless, they provide important information on the spatial variation in SO_2 air concentrations.

[15] Kitimat Valley network: Calibrated SO_2 $(\mu g/m^3)$ = uncalibrated SO_2 $(\mu g/m^3)$ × 1.034 + 0.749

[16] The 2.614 $(\mu g/m^3)/(ppb)$ factor converts from a mass concentration basis to a volume concentration basis of SO_2 based on the molecular weight of SO_2 and standard atmospheric conditions. In this case, standard conditions are 1 atm and approximately 25 C, precisely corresponding to the 1-hour SO_2 B.C. AQO levels listed of 70 ppb and 183 $\mu g/m^3$ (https://www2.gov.bc.ca/assets/gov/environment/air-land-water/air/reports-pub/aqotable.pdf).

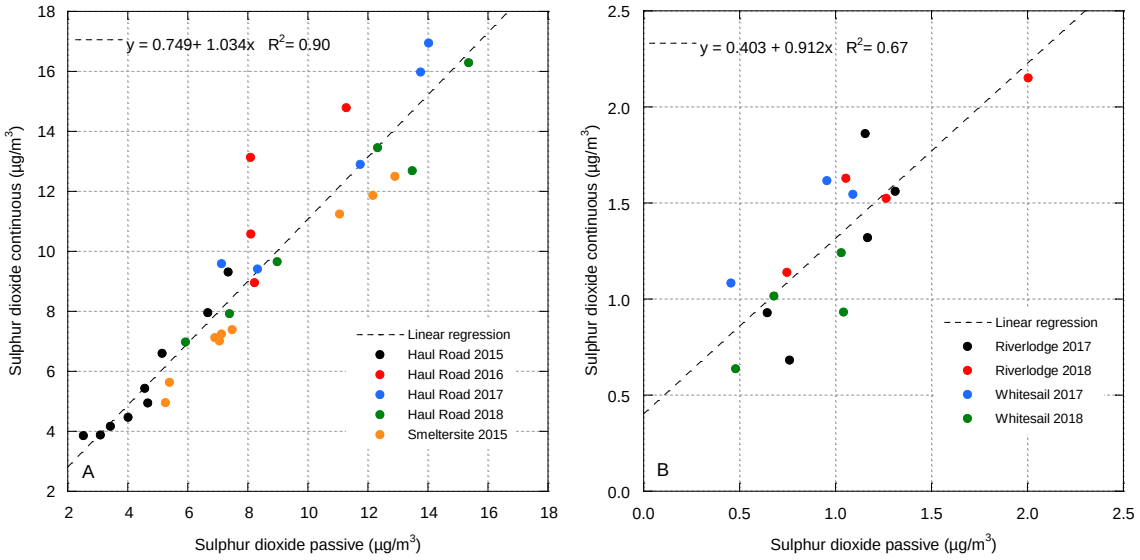


Figure 3-8. Concentration (µg/m³) of sulphur dioxide (SO_2) measured with passive samplers (monthly exposures) against average SO_2 from the continuous analyzers during the same exposure period in the (A) Valley and (B) Urban Kitimat networks. The best-fit linear regression between passive and continuous is also shown (as a dashed line). See Atmospheric Appendix Section 3.1.4 for details on the calibration of passive samplers to the continuous analyzers.

Table 3-1. Passive sulphur dioxide (SO_2) monitoring sites (Figure 3-9 for site locations), location (latitude, longitude), distance from smelter, number of exposures (N_{exp}), three-year average SO_2 (June–October), the coefficient of variation (CV) and yearly Spring–Autumn (June–October) average during 2016, 2017 and 2018. Passive samplers were calibrated against continuous SO_2 data (Figure 3-8).

Site¥	Latitude	Longitude	Distance §	N_{exp}	SO_2 2016 – 2018	SO_2 2016 – 2018	CV	SO_2 2016	SO_2 2017	SO_2 2018
			km	n	µg/m³	ppb	%	µg/m³	µg/m³	µg/m³
A01	54.02931	–128.70192	1.82	13	11.71	4.48	13.7	9.85	11.91	12.96
A04	54.37721	–128.57734	41.35	12	1.50	0.57	6.8	1.38	1.54	1.57
V01	54.30437	–128.61655	32.91	11	2.74	1.05	4.2	2.62	2.74	2.85
V02	54.28593	–128.64471	30.61	10	2.39	0.91	10.4	2.27	2.18	2.65
V03	54.23226	–128.67892	24.45	9	3.90	1.49	22.3	3.88	5.14	3.36
V04	54.18131	–128.68178	18.78	11	2.12	0.81	26.3	1.71	2.87	2.12
V05	54.14140	–128.68559	14.33	11	5.22	2.00	18.9	4.03	5.78	5.64
V06	54.11443	–128.67961	11.38	11	4.16	1.59	24.4	3.13	4.07	5.13
V07	54.09294	–128.67343	9.09	9	2.30	0.88	24.3	2.14	2.72	1.66
V08	54.07872	–128.69531	7.33	9	6.40	2.45	23.4	4.82	6.80	7.79
V09	54.05111	–128.71008	4.27	11	8.30	3.17	31.6	5.65	8.00	10.80
V10	54.01693	–128.70958	0.66	10	10.61	4.06	20.1	8.19	11.53	12.19
V11	53.96473	–128.70387	5.37	11	11.83	4.53	21.5	8.77	13.51	12.41
V12	53.94320	–128.72061	7.86	11	7.80	2.98	19.2	5.98	8.31	8.71
V13	53.93831	–128.75015	8.89	7	8.29	3.17	4.1		8.51	8.03
V14	54.05997	–128.68704	5.32	10	3.90	1.49	20.4	2.91	4.03	4.39

¥ A represents ambient stations, and V represents the valley network sites; A01 is Haul Road and A04 is Lakelse Lake.
§ Based on a smelter location of 54.01300, –128.70200

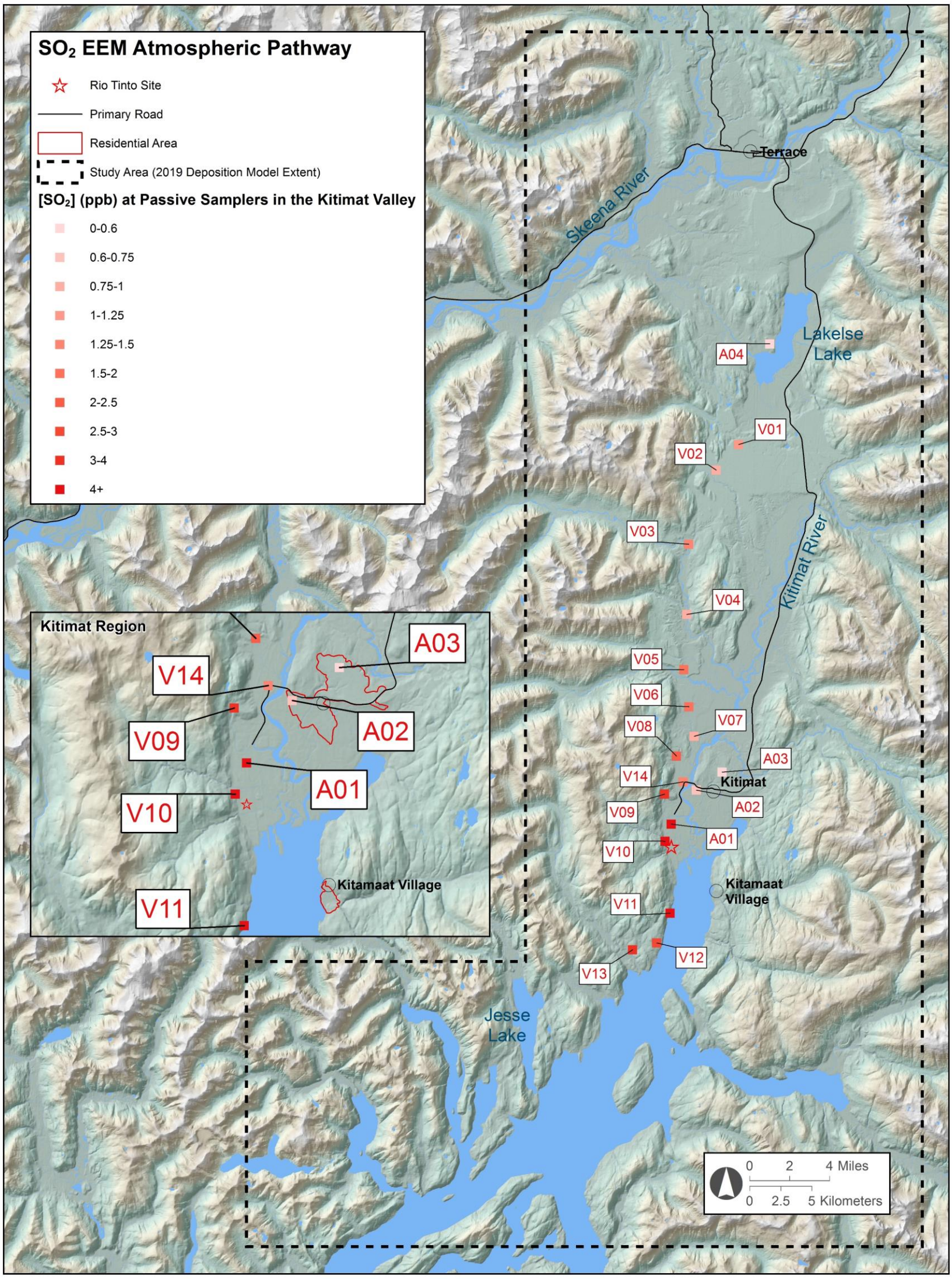


Figure 3-9. Average (2016–2018) sulphur dioxide (SO_2) concentrations at the passive sample sites during the June to October exposures. The site ID is also shown (see Table 3-1 for details on location). Passive samplers were calibrated against continuous SO_2 data (see Figure 3-8).

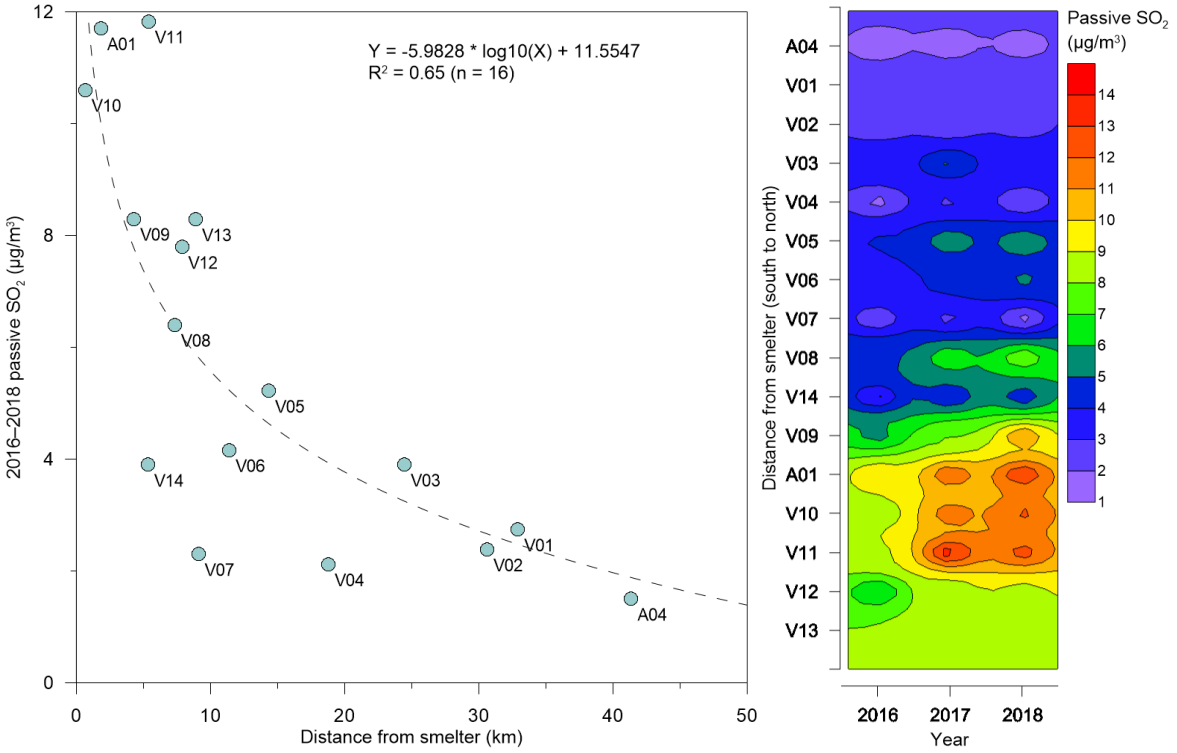


Figure 3-10. Left panel: average (2016–2018) passive sulphur dioxide (SO_2) concentrations observed in the valley network against their geographic (straight-line) distance from the smelter (km). The best-fit log regression line is also shown. Right panel: space-time plot showing the Spring–Autumn (June–October) passive SO_2 concentrations during 2016, 2017 and 2018 at each location in the Kitimat valley network ordered by distance (south to north) from smelter (see Figure 3-9 for exact site locations). Passive samplers were calibrated against continuous SO_2 data (see Figure 3-8).

The number of sites in the urban passive sampler network ranged from 15–16 during 2017–2016 and expanded to 20 during 2018. The 15 sites with consistent deployments during 2016–2018 (June–October) are described herein (Figure 3-11 and Table 3-2). There were 140 passive samplers deployed during the three years in the urban network; however, the hours of exposure at each site varied greatly (2924–9348 hrs), primarily due to physical disturbance of samplers (and that some sites only operated for two of the three years).

The average yearly Spring–Autumn (June–October) SO_2 concentrations ranged from 0.69 µg/m³ (0.26 ppb) (U05: Cable Car during 2016) to 1.53 µg/m³ (0.59 ppb) (A02: Riverlodge during 2018) in the urban network (Table 3-2). The highest Spring–Autumn (June–October) SO_2 concentrations were always observed at A02: Riverlodge (Figure 3-11 and Table 3-2). During 2016–2018 (three years), the next highest SO_2 concentration was observed at U06: Kitimat General Hospital, and the lowest at U05: Cable Car (Figure 3-11 and Table 3-2). Nonetheless, there was very little variation across all the stations; the average for all sites was 1.09 µg/m³ (0.42 ppb). In contrast, the average for the Valley Network for the same period was 5.82 µg/m³ (2.23 ppb). (Table 3-1). The spatial pattern in the urban network was consistent between the three years of observations (Figure

3-11), with an average coefficient of variation < 12% (Table 3-2), ranging from 3.2% (U13: St. Anthony's Elementary) to 20.8% (U9: Fulmar Street), although the latter is likely influenced by the low number of exposures.

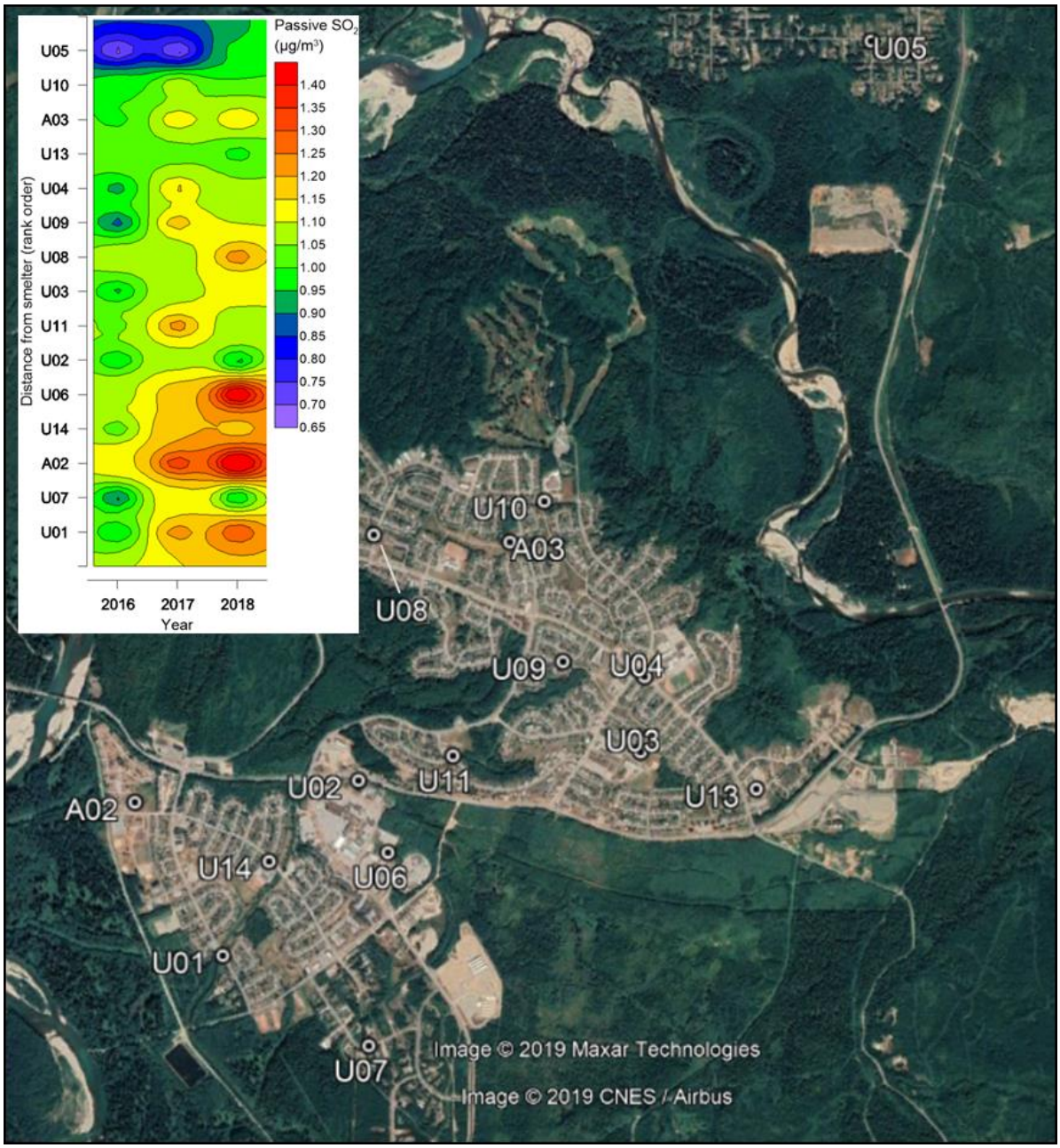


Figure 3-11. Location of passive sampler sites in the urban Kitimat network with monthly exposures during June–October between 2016 to 2018 (see Table 3-2 for exact site locations). Inset: space-time plot showing the Spring–Autumn (June–October) passive sulphur dioxide (SO_2) concentrations during 2016, 2017 and 2018 at each location in the Kitimat urban network ordered by distance from smelter. Passive samplers were calibrated against continuous SO_2 data (see Figure 3-8).

Table 3-2. Passive sulphur dioxide (SO_2) monitoring sites (Figure 3-12 for site locations), location (latitude, longitude), total hours and number of exposures, three-year average SO_2 (June–October), the coefficient of variation (CV) and yearly Spring–Autumn (June–October) average during 2016, 2017 and 2018. Passive samplers were calibrated against continuous SO_2 data (see Figure 3-8).

Site¥	Latitude	Longitude	Exposure		SO_2 2016–2018	SO_2 2016–2018	CV	SO_2 2016	SO_2 2017	SO_2 2018
			Hrs	n	µg/m³	ppb	%	µg/m³	µg/m³	µg/m³
A02	54.05396	-128.67101	9348	13	1.36	0.52	14.4	1.14	1.34	1.53
A03	54.06695	-128.63910	8192	11	1.09	0.42	7.7	0.99	1.14	1.14
U01	54.04629	-128.66356	7462	10	1.18	0.45	15.1	0.96	1.22	1.29
U02	54.05507	-128.65199	5757	8	1.00	0.38	8.1	0.95	1.08	0.93
U03	54.05655	-128.62810	7458	10	1.06	0.41	9.2	0.94	1.09	1.11
U04	54.06028	-128.62775	7457	10	1.05	0.40	11.3	0.93	1.16	1.05
U05	54.09192	-128.60854	6708	9	0.82	0.31	20.2	0.69	0.69	0.96
U06	54.05146	-128.64951	7460	10	1.29	0.49	17.0	1.08	1.19	1.49
U07	54.04179	-128.65115	7462	10	0.99	0.38	12.4	0.89	1.13	0.95
U08	54.06731	-128.65057	7456	10	1.15	0.44	7.3	1.09	1.08	1.23
U09	54.06102	-128.63463	2924	4	1.10	0.42	20.8	0.88	1.18	
U10	54.06897	-128.63620	4268	6	1.04	0.40	7.4	0.98	1.09	
U11	54.05635	-128.64391	7457	10	1.11	0.42	9.2	1.04	1.23	1.07
U13	54.05471	-128.61835	6568	9	1.01	0.39	3.2	1.02	1.04	0.98
U14	54.05101	-128.65961	7460	10	1.14	0.44	9.0	1.02	1.20	1.18

¥ A represents ambient stations, and U represents the urban network sites; A02 is Riverlodge and A03 is Whitesail.

3.1.3.3 *Overview of EEM monitoring program results – filter pack pSO_4^{2-} network*

The filter packs were deployed at nine locations; seven of these sites were part of the passive sampler Valley Network or co-located with continuous samplers. In total there were 56 discrete (24–48 hour) exposures at these seven sites between June 2017 and July 2018 (Table 3-3). There was strong linear agreement between the concentration of SO_2 measured with the filter pack (individual exposures) and the continuous SO_2 observations (averaged over the same exposure period) with an R^2 = 0.98 (Figure 3-12). The filter pack SO_2 concentrations were lower than continuous samplers; however, it is the relative concentrations of particulate to gaseous sulphur that is primarily of interest. The average pSO_4^{2-} [17] ranged from 0.4 (A04: Lakeslse Lake) to 0.19 (A05) µg S/m³. In comparison, average SO_2 ranged from 0.28 (A04) to 3.38 (A01: Haul Road) µg S/m³. On average, SO_2 is 10 times higher than pSO_4^{2-} across the measurement sites (Table 3-3).

[17] Conversion of units. Particulate sulphate: pSO_4^{2-}-S (µg S/m³) = pSO_4^{2-} (µg/m³) × $MW_{sulphur}$ / $MW_{sulphate}$ where MW is the molecular weight of sulphur (32.065 g/mol) and sulphate (96.06 g/mol); Gaseous sulphur dioxide: SO_2-S (µg S/m³) = SO_2 (µg/m³) × $MW_{sulphur}$ / $MW_{sulphur\ dioxide}$ where MW is the molecular weight of sulphur dioxide (64.066 g/mol).

The calibrated SO_2 from the filter packs (Table 3-3) is generally consistent with the longer-term (June–October) exposures for the passive samplers (Table 3-1 and Table 3-2) despite the limited duration of exposures.

The average F_s ratio of pSO_4^{2-} to total atmospheric sulphur was 8.7% and ranged from 4.1% (A01) to 18.2% (A02). In contrast, the average F_s estimated from CALPUFF was 1.4% (for the same sites). The CALPUFF estimates do not include background contributions and represent a full year; nonetheless the modelled and measured data both indicate that pSO_4^{2-} is a minor component of atmospheric sulphur in the Kitimat Valley. Moreover, a low F_s is expected because the rate of transformation of SO_2 to SO_4^{2-} in the atmosphere occurs on a longer timescale than transportation and dispersion (Warneck 1999); and these measurements corroborate this expectation. The relationship between SO_2 and F_s may provide a means to scale these observations to sites without pSO_4^{2-} measurements, albeit a minor component of atmospheric sulphur.

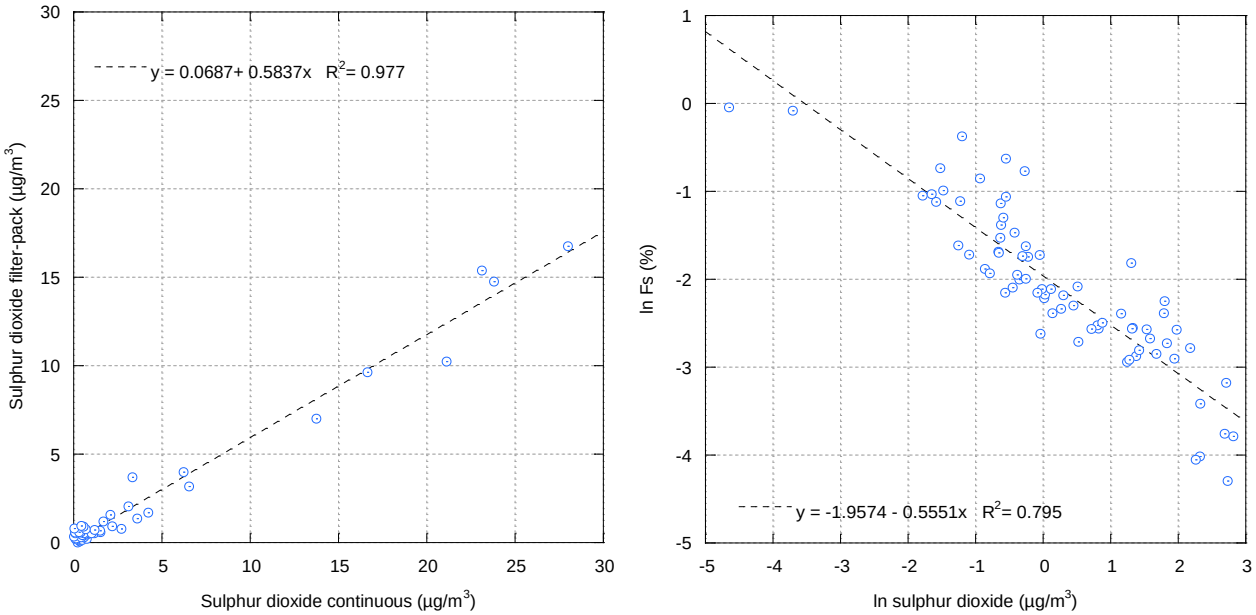


Figure 3-12. Left: concentration (µg/m³) of sulphur dioxide (SO_2) measured with filter pack samplers (24–48 hour exposures) against average SO_2 from the continuous analyzers during the same exposure period (both uncalibrated). The best-fit linear regression between filter-pack and continuous is also shown (as a dashed line). Right: Comparison of natural-log transformed SO_2 (µg/m³) and F_s (%) measured via filter pack sampler during sampling campaigns one through four. The line of best fit (dashed line) and corresponding linear equation is also shown.

Table 3-3. Average (uncalibrated) atmospheric concentrations (µg S/m³) of particulate sulphate (pSO_4^{2-}) and sulphur dioxide (SO_2) from the filter pack network during 2017–2018 across all exposures, average ratio (Fs expressed as a percentage) of pSO_4^{2-} to total ambient sulphur (SO_2 and pSO_4^{2-} as S), and calibrated SO_2 for comparison to passive samplers observations (Table 3-1 and Table 3-2).

Site ID ¥	Latitude	Longitude	Elevation	Exposures	pSO_4^{2-}-S	SO_2-S	SO_2 calibrated §	F_S
	decimal degrees		m	n	µg/m³	µg/m³	µg/m³	%
A01	54.0293	-128.7019	11	15	0.15	3.38	11.3	4.1
A02	54.0540	-128.6710	18	19	0.08	0.35	1.2	18.2
A04	54.3773	-128.5776	111	16	0.04	0.28	0.9	12.4
V03	54.2360	-128.6871	127	4	0.18	1.47	4.9	10.9
V05	54.1408	-128.6859	114	7	0.19	1.66	5.5	10.5
V08	54.0786	-128.6955	68	7	0.16	2.16	7.2	6.8
V12	53.9432	-128.7206	114	3	0.17	0.87	2.9	16.3
Average					0.14	1.45	4.83	8.7
Median					0.15	1.46	4.86	9.4

¥ A represents ambient stations, and V represents the valley network sites; A01 is Haul Road A02 is Riverlodge and A04 is Lakelse Lake.
§ Calibrated SO_2 (µg/m³) = 1.674 × filter-pack SO_2 (µg/m³) – 0.026 where filter-pack SO_2 (µg/m³) = filter-pack SO_2-S (µg S/m³) / $MW_{sulphur}$ × $MW_{sulphur\ dioxide}$ where MW is the molecular weight of sulphur (32.065 g/mol) and sulphur dioxide (64.066 g/mol).

3.1.3.4 *Summary of 2016-2018 CALPUFF model results*

The primary purpose of the new CALPUFF analysis is to provide updated SO_2 air concentrations and sulphur deposition rates for updated vegetation, soil, and aquatic ecosystem effects assessments.

For general information, the SO_2 model results are also presented in the form of the B.C. IAQOs for the 42 tpd scenario. As shown in Figure 3-13 through Figure 3-16, the areas exceeding the B.C. IAQOs are limited to areas close to the smelter. While viewing results in the form of the B.C. IAQOs provides helpful illustration short-term and annual average spatial distribution, model results compared to the B.C. IAQOs are not used for any effects assessments. This section focuses on the regional-scale model annual average SO_2 concentrations because the regional-scale annual average (and 3-year average) model results are used for assessing the risk of impacts on vegetation, soil, and aquatic ecosystems. The vegetation assessment also uses shorter-term averaging periods (also regional-scale), but the most stringent vegetation impact thresholds are assessed for annual averaging period. The human health assessment uses monitoring data (not model data). The local-scale model will be used for evaluating the ambient monitoring network, which will conclude in a separate future report. Atmospheric Appendix Section 3.1.8 provides additional figures for the actual and 35 tpd scenarios, individual years, and exceedance maps, and also provides tables of concentrations at locations of interest.

SO_2 concentration results are calculated by CALPUFF in units of micrograms per meter cubed ($\mu g/m^3$). However, this chapter generally presents SO_2 results in units of parts per billion (ppb) in order to stay consistent with the monitoring data and the CAAQS. It is possible to move between ppb and $\mu g/m^3$ by a factor of 2.614 $(\mu g/m^3)/(ppb)$.[18]

[18] The 2.614 $(\mu g/m^3)/(ppb)$ factor converts from a mass concentration basis to a volume concentration basis of SO_2 based on the molecular weight of SO_2 and standard atmospheric conditions. In this case, standard conditions are 1 atm and approximately 25 C, precisely corresponding to the 1-hour SO_2 B.C. IAQO levels listed of 70 ppb and 183 $\mu g/m^3$ (https://www2.gov.bc.ca/assets/gov/environment/air-land-water/air/reports-pub/aqotable.pdf).

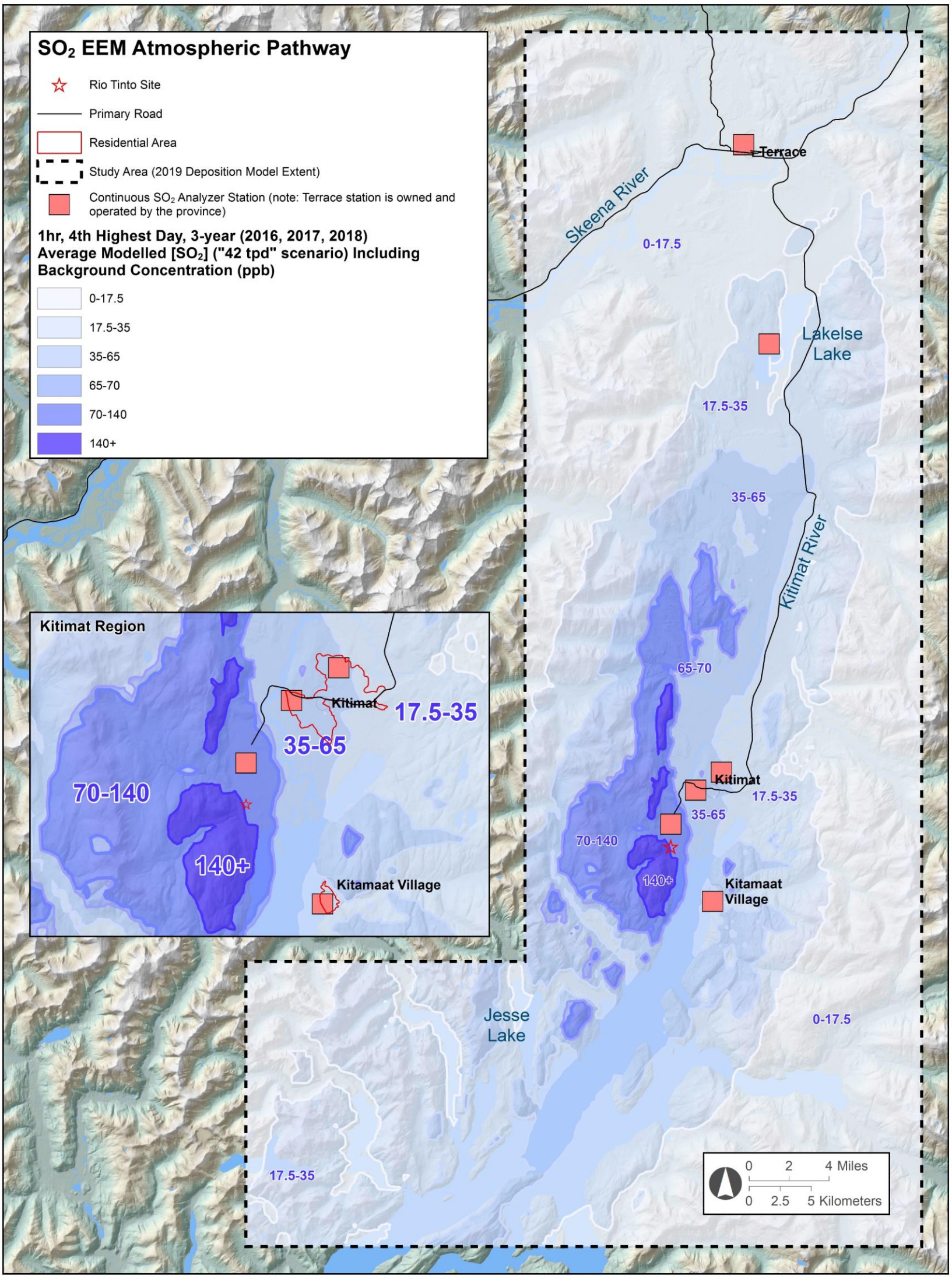


Figure 3-13. Modelled SO_2 concentrations (new 2016–2018 CALPUFF), 42 tpd, 99th percentile of daily 1-hour peak, 3-year average, regional (units of ppb, including background of 5.53 ppb).

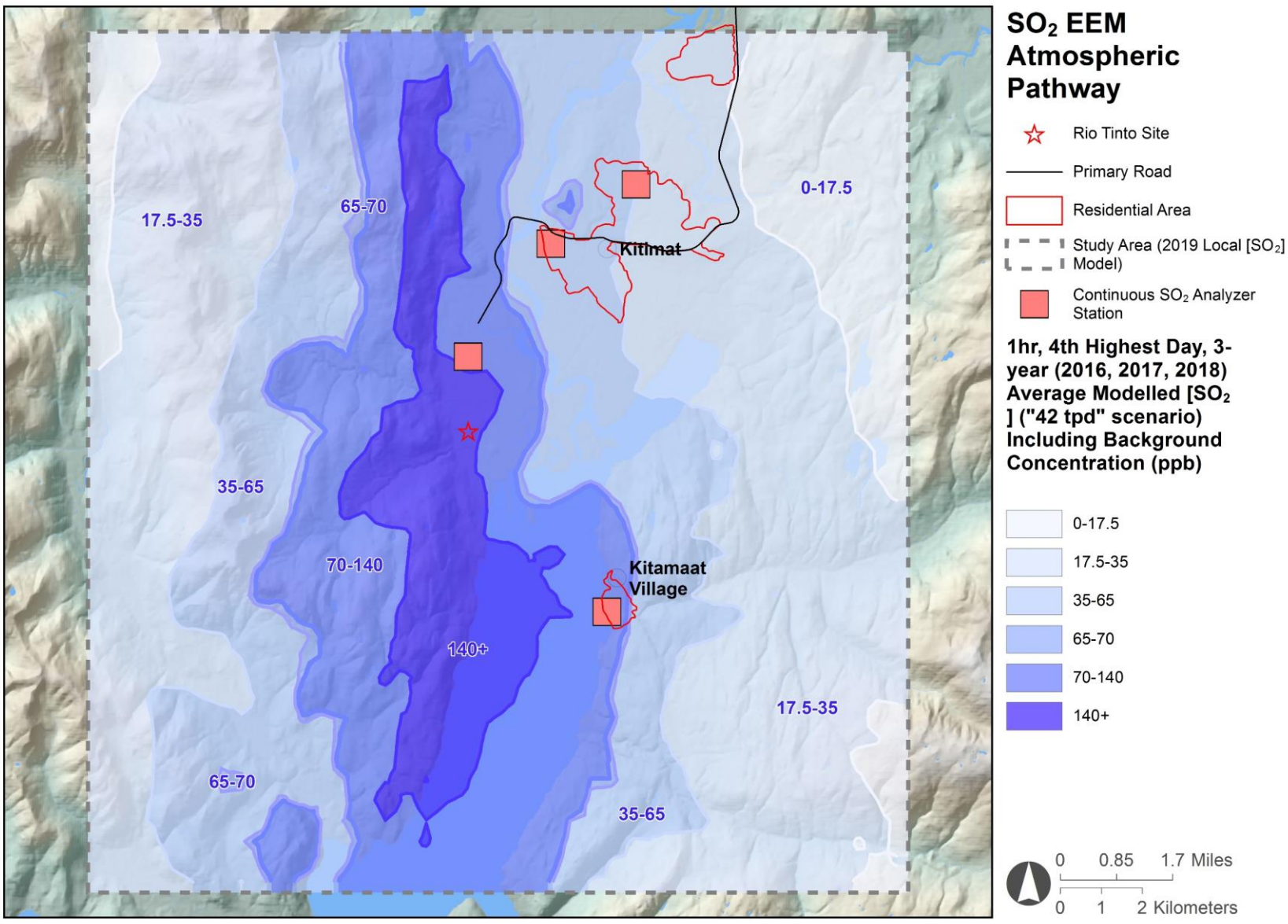


Figure 3-14. Modelled SO_2 concentrations (new 2016–2018 CALPUFF), 42 tpd, 99th percentile of daily 1-hour peak, 3-year average, local-scale (units of ppb, including background of 5.53 ppb).

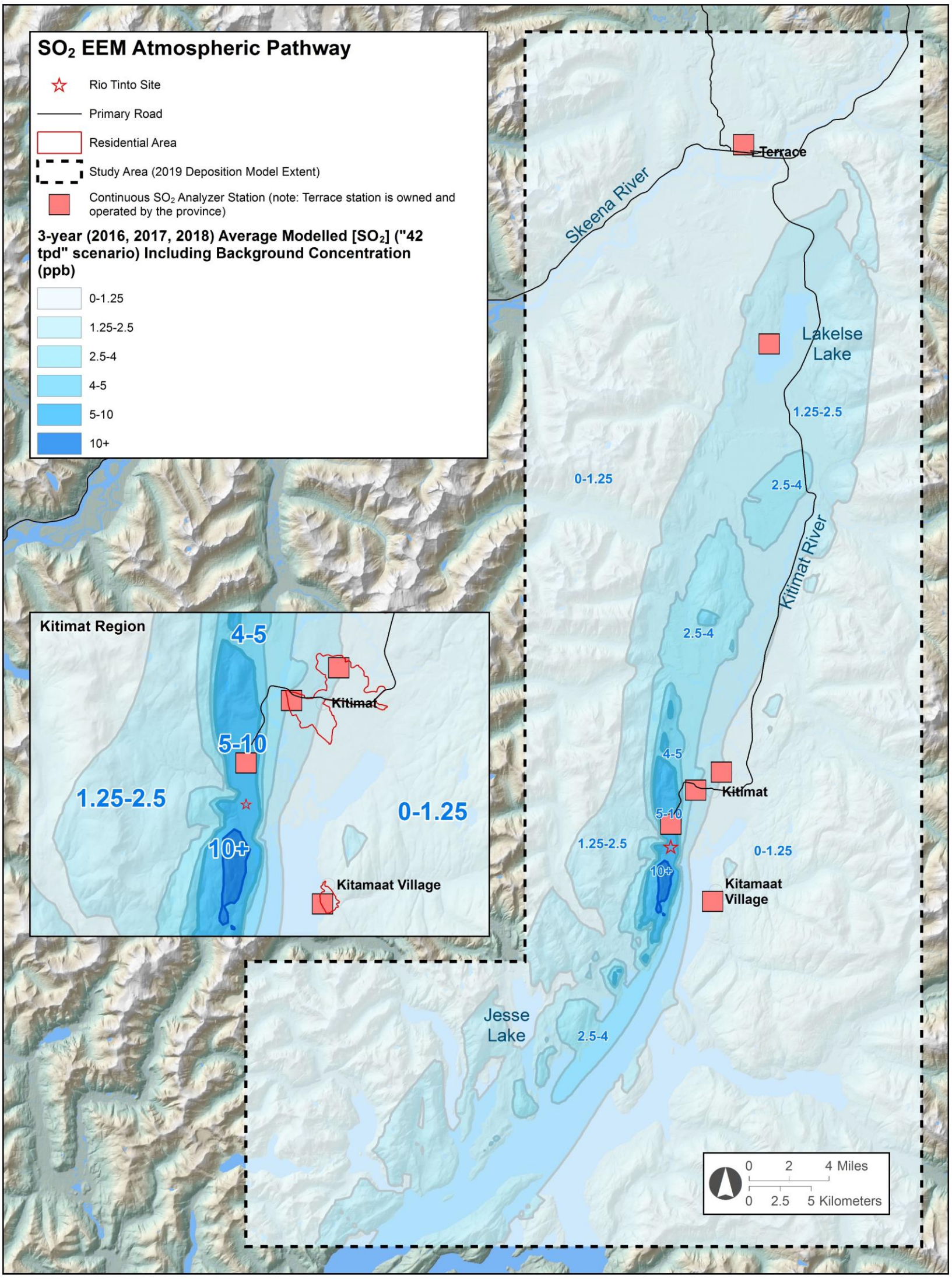


Figure 3-15. Modelled SO_2 concentrations (new 2016–2018 CALPUFF), 42 tpd, 3-year average, regional (units of ppb, including background of 0.47 ppb).

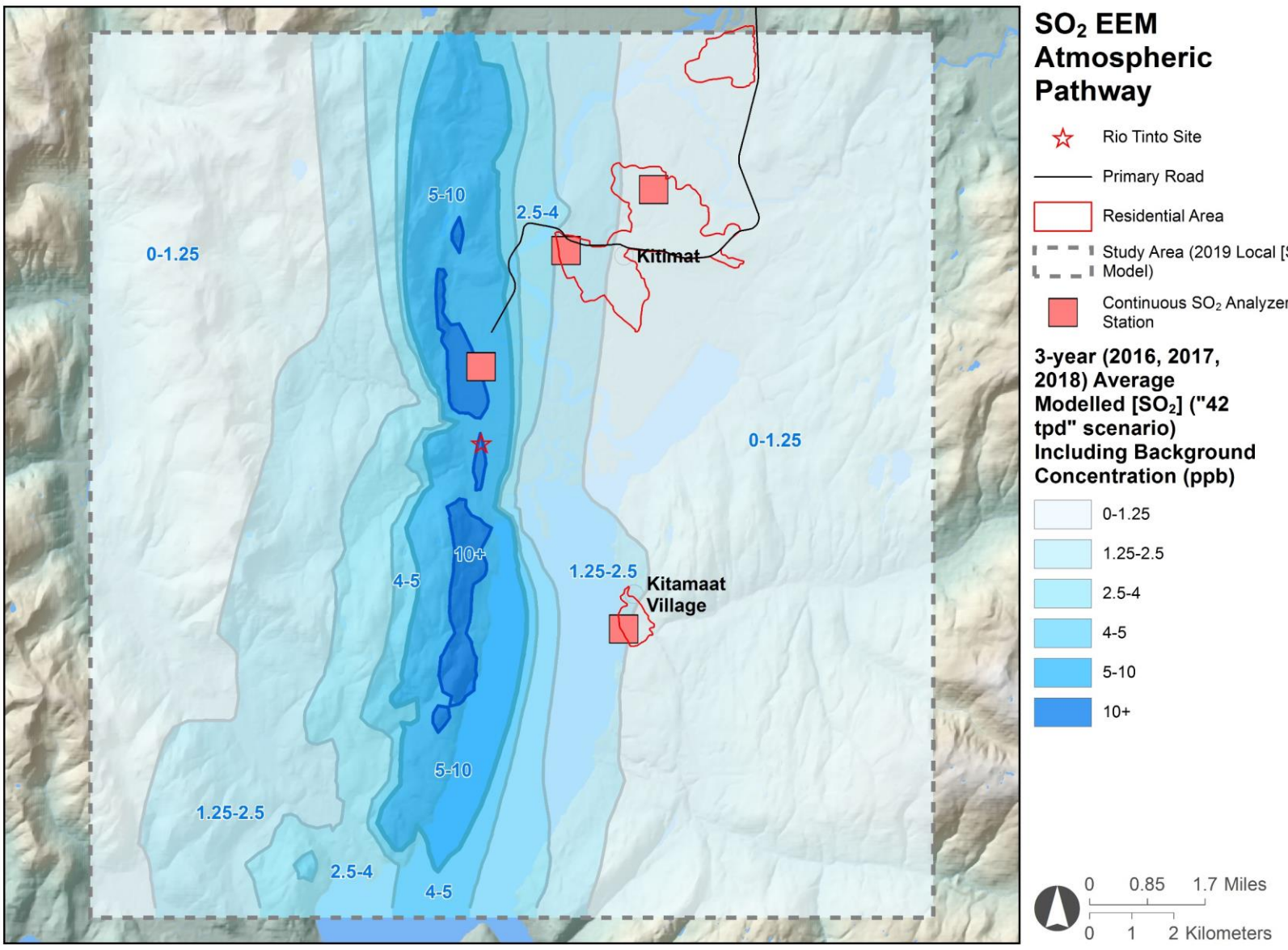


Figure 3-16. Modelled SO_2 concentrations (new 2016–2018 CALPUFF), 42 tpd, 3-year average, local (units of ppb, including background of 0.47 ppb).

The annual average concentration maps show a consistent spatial distribution for each of the modelled years (2016, 2017, and 2018, Atmospheric Appendix Section 3.1.8), with a slightly smaller extent for 2016 and slightly larger extent for 2018 (most notably to the south for the 2.5 ppb isopleth). The 1-hour SO_2 (99th percentile of daily 1-hour peak) plots show slightly more variation year to year, but all years show highest peak concentrations directly to the south and north-northwest of the smelter (Atmospheric Appendix Section 3.1.8). Modelled concentrations remain well below the CAAQS in Kitimat for all three years with a consistent distribution in the area. In contrast, the predicted concentrations near Kitamaat Village vary noticeably year to year and between the regional-scale model and local-scale model. Based on the regional-scale model, SO_2 concentrations remain below the CAAQS within the residential area with the 2016 and 2017 models predicting 1-hour concentrations exceeding 70 ppb directly to the north of Kitamaat Village, while 2018 shows concentrations below 65 ppb in the same area. The local-scale model shows even greater year-to-year variation of 1-hour results in Kitamaat Village, ranging from less than 65 ppb in 2018 to over 140 ppb in 2016 (Atmospheric Appendix pages 83-85).[19] Consistent with the annual average trends, 2018 shows the highest concentrations near the smelter (most noticeable directly to the north-northwest) and the farthest extent of the 17.5 ppb isopleth to the north. Table 3-4 also shows consistent year-to-year maximum concentrations in the form of the CAAQS, with slightly lower maximum concentrations in 2016. These year-to-year comparisons use the same 42 tpd SO_2 emissions and parameters for all years, so the variation is solely due to changes in the meteorological data used in the model.

[19] Based on the local-scale CALPUFF performance evaluation (Atmospheric Appendix Section 3.1.7), the local-scale model over-predicted SO_2 concentrations at Kitamaat Village more-so than at other locations and more-so than the regional-scale model, particularly in 2016 (1-hr, 99th% daily peak concentration of 157 ppb modelled compared to 20 ppb measured).

Table 3-4. Summary of New CALPUFF Regional-scale Model 42 tpd Maximum SO_2 Concentrations (ppb).

Year	Max Offsite [1] (SO_2 ppb)	Max Residential [2] (SO_2 ppb)
	1-hr, 99th% Daily Peak Concentration [3] (ppb)	
2016	599	43
2017	628	54
2018	834	53
3-Year Average	645	45
Objective [4]	70	70
	Annual Average Concentration [3] (ppb)	
2016	18.7	1.7
2017	19.1	1.7
2018	20.3	1.9
3-Year Average	19.0	1.7
Objective [4]	5.0	5.0

[1] Maximum offsite includes all receptors outside Rio Tinto's modelled fenceline (see Atmospheric Appendix Section 3.1.5 for figure).
[2] Maximum residential results include all results in Kitimat, Cable Car, and Kitamaat Village (see Atmospheric Appendix Section 3.1.9, detailed model plan for figure).
[3] Background concentrations are included based on average SO_2 concentrations measured at the Terrace Skeena Middle School station in 2016, 2017 & 2018. The background concentration applied for the annual averaging period is 0.47 ppb, while the background concentration for the 1-hr averaging period is 5.53 ppb. Model results are converted to ppb based on the ratio of [70 ppb]/[183 µg/m^3] per the 1-hr SO_2 British Columbia air quality objective.
[4] Objectives are based on British Columbia air quality objectives. Where both Interim Provincial IAQO and CAAQS are in place, the more stringent 2020 CAAQS is listed in this table.

While annual average spatial distribution is consistent among years, the position of the plume has shifted to predict higher concentrations to the south and extend a shorter distance to the north compared to the STAR model (Figure 3-17). The deposition spatial distribution shift from STAR results to the new model is similar (see Figure 3-29). As detailed further in Section 3.1.3.5 below and Atmospheric Appendix Section 3.1.6, this shift in plume position and extent from the north to the south aligns more closely with passive sampling measurements, which have recorded higher concentrations to the south.

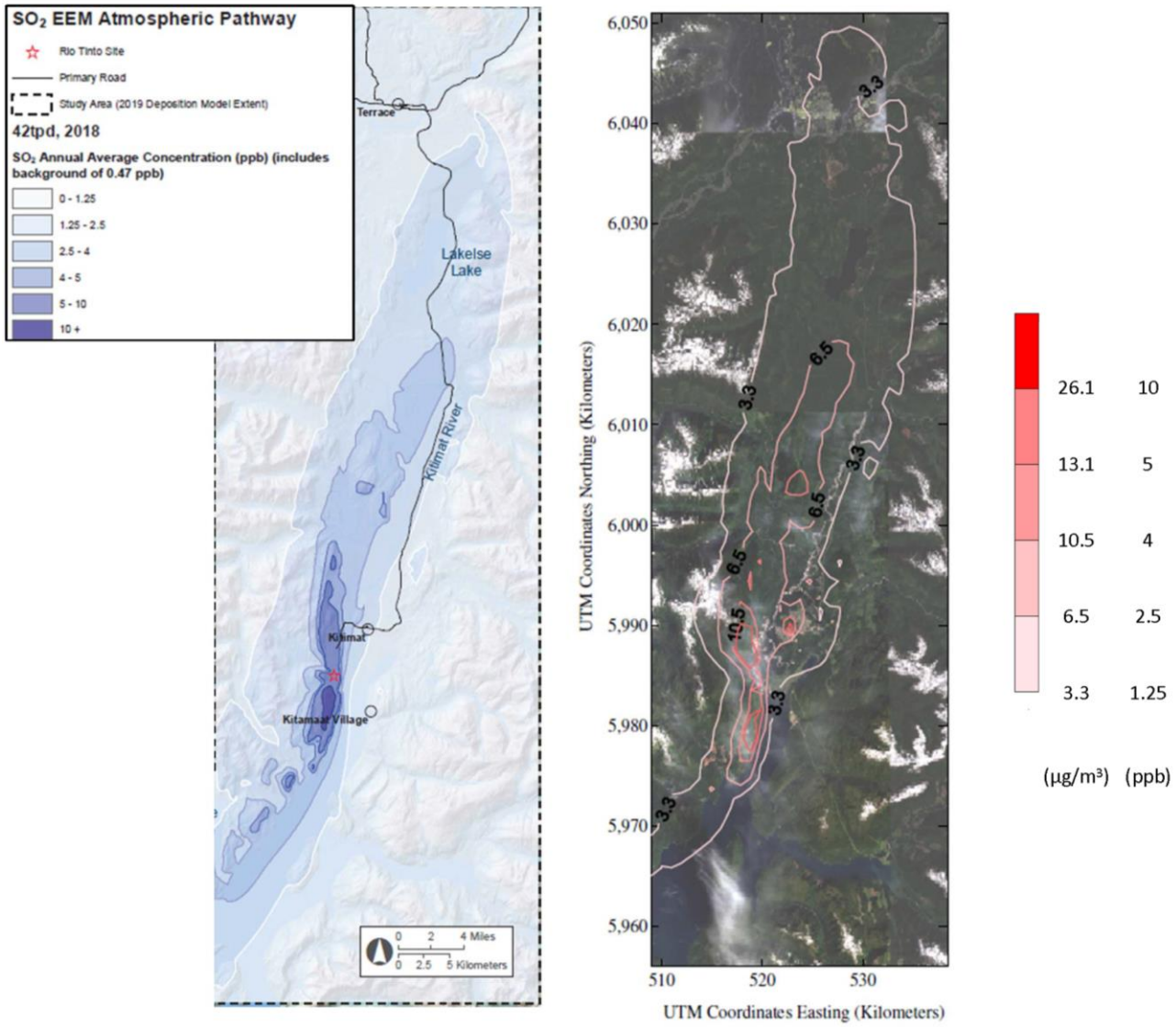


Figure 3-17. Modelled annual average SO_2 concentrations for new CALPUFF (left panel) versus STAR (right panel), 42 tpd, max year (2018 and 2006), regional-scale. New CALPUFF in units of ppb (including background of 0.47 ppb); STAR in units of µg/m³ with ppb equivalent scale, STAR scale set to identical levels (e.g., lowest for both is 1.25 ppb), including STAR background of 0.40 ppb.

3.1.3.5 *Summary of regional-scale CALPUFF model performance for SO_2 air concentrations*

The updated 2016–2018 CALPUFF modelling reduces uncertainty in post-KMP model predictions by using as-built source parameters and actual 2016–2018 SO_2 emission rates from the smelter combined with corresponding 2016–2018 meteorological data to evaluate the model performance. As detailed in Atmospheric Appendix Section 3.1.6, the regional-scale CALPUFF model shows good performance overall. The most important metric to evaluate for this

comprehensive review is the regional-scale model annual average SO_2 concentration because the regional-scale annual average (or 3-year average) model results are used for assessing the risk of impacts on vegetation, soil, and aquatic ecosystems. The vegetation assessment also uses shorter-term averaging periods, but the most stringent vegetation impact thresholds are assessed for annual averaging period. The human health assessment uses monitoring data (not model data). The local-scale model will be used for evaluating the ambient monitoring network, which will conclude in a separate future report.[20]

Model performance evaluation primarily relies on comparing modelled SO_2 to measured SO_2 taken at the continuous SO_2 monitoring stations and to measurements from the passive samplers. Table 3-5 shows the 2016–2018 CALPUFF model estimates compared to the monitoring data at each station; while Figure 3-18 illustrates the comparison and also includes the comparable STAR model results.

Table 3-5. Summary of New CALPUFF Model Comparison to Continuous Monitoring Data, Annual Average SO_2 (ppb).

	Monitoring Data [1] (SO_2 ppb)	New CALPUFF [2] (SO_2 ppb)	Monitoring Data [1] (SO_2 ppb)	New CALPUFF [2] (SO_2 ppb)	Monitoring Data [1] (SO_2 ppb)	New CALPUFF [2] (SO_2 ppb)
	2016		2017		2018	
Kitamaat Village	0.38	0.58	0.29	0.52	0.20	0.53
Haul Road	4.22	7.12	3.77	7.33	3.73	7.02
Riverlodge	0.50	1.49	0.43	1.54	0.47	1.69
Whitesail	0.53	0.82	0.41	0.86	0.34	0.99

[1] Monitoring data annual average for 2016, 2017, 2018.

[2] New CALPUFF results for actual scenario, regional-scale using actual smelter emission rates from 2016 to 2018, varying monthly. Model results for performance evaluation apply a background based on Williams Lake (0.26 ppb), which is more appropriate to represent realistic results because we expect minimal contribution from non-smelter SO_2 for 2016 – 2018 actual conditions. Results with a higher background are used for new model future 35 and 42 tpd effect assessment in order to be cautious in risk assessments. The annual average background concentration used for the new 2016 -2018 model is 0.47 ppb based on monitoring at Terrace-Skeena Middle School.

[20] Since the local-scale model results are not used directly in conclusions of the EEM comprehensive review, the local-scale model evaluation is included only in Atmospheric Appendix Section 3.1.7.

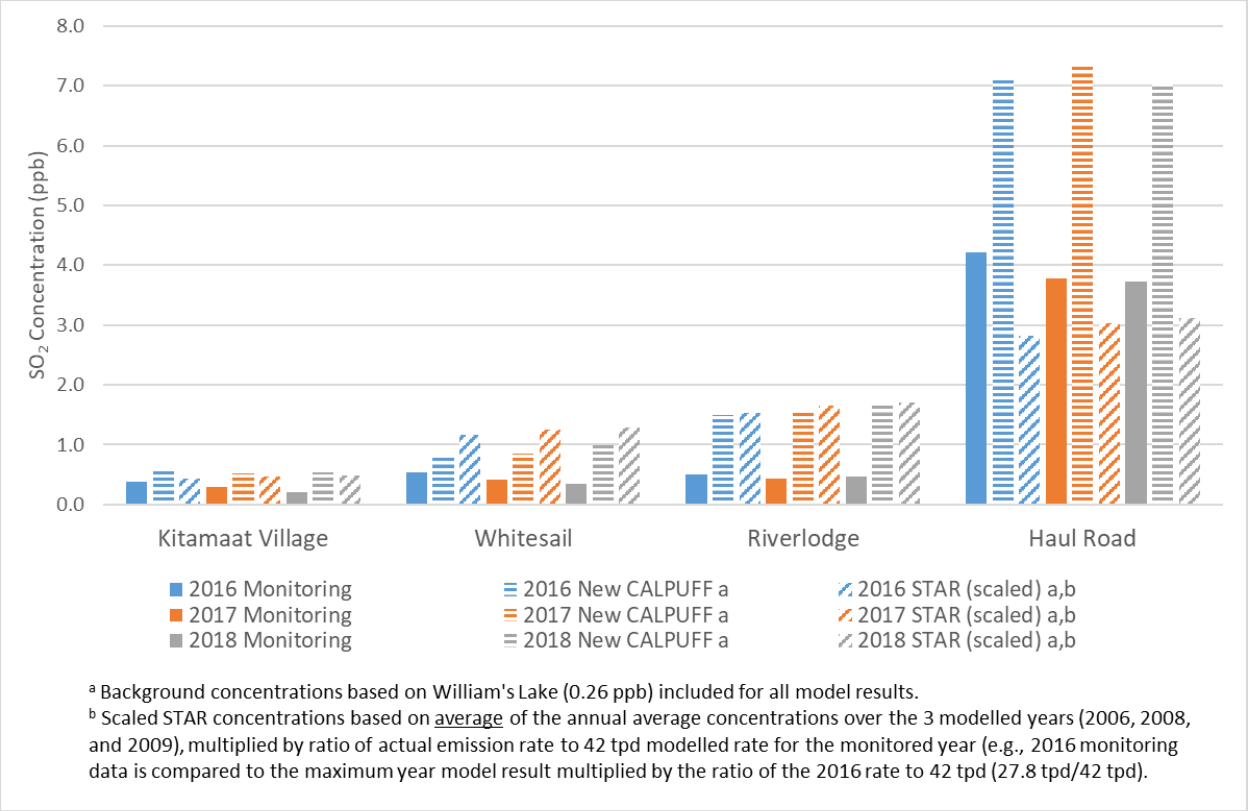


Figure 3-18. Continuous SO_2 (ppb) monitoring concentrations compared to new CALPUFF model results and scaled STAR model concentrations, annual average (Williams Lake annual background of 0.26 ppb applied).[21]

As shown in Figure 3-18 and summarized in Table 3-6, the 2016–2018 regional-scale CALPUFF model is more accurate overall than the STAR model. In particular, the new 2016–2018 model aligns with observations better than the STAR model at all residential monitors. In addition, the STAR model under-predicted slightly at the Haul Road monitor, while the new model over-predicts at the Haul Road monitor by 1.8 times.

[21] Comparable STAR model results for model performance comparisons use 3-year average STAR results with Williams Lake background for model performance purposes. Figure 3-6 shows a similar comparison, but the STAR results show the maximum annual average over the three model years with STAR background for purposes of comparing model predictions used for impact assessment to monitored concentrations.

Table 3-6. Summary of new CALPUFF model comparison to continuous monitoring data, 3-year Average SO_2 (ppb).

Monitoring Station	Monitoring Data [1] (SO_2 ppb)	STAR CALPUFF, Scaled [2] (SO_2 ppb)	2016-018 CALPUFF [3] (SO_2 ppb)	Comment on comparisons to model results without background (values in parentheses)
Kitamaat Village	0.29	0.46	0.54	STAR and new CALPUFF over-predict very slightly (by less than the background value).
Whitesail	0.43	1.23	0.89	STAR over-predicted by nearly triple. New CALPUFF over-predicts by slightly more than double.
Riverlodge	0.47	1.63	1.57	STAR and new CALPUFF over-predict at similar levels: 3.5 and 3.4, respectively.
Haul Road	3.91	2.99	7.16	STAR slightly under-predicted. New CALPUFF over-predicts by 1.8 times.

[1] Monitoring data average over 2016-2018.
[2] STAR CALPUFF results are scaled to be comparable to actual 2016 – 2018 conditions by multiplying by the ratio of actual smelter emission rates in 2016–2018 (29.3 tpd) to permitted (modelled) emission rates of 29.3 tpd / 42 tpd or 69.8%. Model results for performance evaluation apply a background based on Williams Lake (0.26 ppb), which is more appropriate to represent realistic results because we expect minimal contribution from non-smelter SO_2 for 2016 – 2018 actual conditions. Results with a higher background were used for STAR effects assessment in order to be cautious in assessments (the annual average STAR background concentration was 0.40 ppb based on monitoring at Whitesail).
[3] New CALPUFF results for actual scenario, using actual smelter emission rates from 2016 to 2018, varying monthly. Model results for performance evaluation apply a background based on Williams Lake (0.26 ppb), which is more appropriate to represent realistic results because we expect minimal contribution from non-smelter SO_2 for 2016 – 2018 actual conditions. Results with a higher background are used for new model future 35 and 42 tpd effects assessment in order to be cautious in assessments. The annual average background concentration used for the new 2016 -2018 model is 0.47 ppb based on monitoring at Terrace-Skeena Middle School.

Figure 3-19 and Figure 3-20 show comparison between the hourly regional-scale model results and monitoring data over the three modelled years at each monitoring station. Figure 3-19 illustrates the comparison paired in time (max hour each day from 2016 to 2018 for visualizing), while Figure 3-20 compares the hourly model data (all hours from 2016 to 2018) versus monitoring data sorted highest to lowest (known as a quantile-quantile plot or Q-Q plot). The comparisons illustrate that the model predicts concentrations and distribution similar to monitoring data at each station (e.g., Kitamaat Village concentrations are low (below 10 ppb) most days with a few (5 to 10) occurrences of 1-hour peaks in the 20 – 30 ppb range for both datasets). However, while the model's overall predictions compare closely to the monitored concentrations, the model results do not generally predict the peaks on the same day or hour. For example, the Kitamaat Village monitor measured two peak concentrations in February 2016 (22.3 and 21.2 ppb on February 22nd and 27th), and the model predicted two peak concentration shortly after (18.3 ppb and 22.8 ppb on March 2nd and 6th), but the model did not predict the peaks on the same days. This outcome (i.e., the model resembling the monitor when comparing overall results (as in the Q-Q plots in Figure 3-20) and not agreeing perfectly when paired hour by hour) is expected for all air dispersion models. This expectation leads to common practice of placing more

emphasis on using Q-Q plots for model performance evaluation rather than on comparisons paired in time.[22]

[22] While expected to reveal lower agreement, comparisons paired in time are also valuable. The model performance statistics presented in Atmospheric Appendix Section 3.1.6 summarize the model result compared to monitor results paired in space and time using root mean squared error, mean bias error, and mean absolute error.

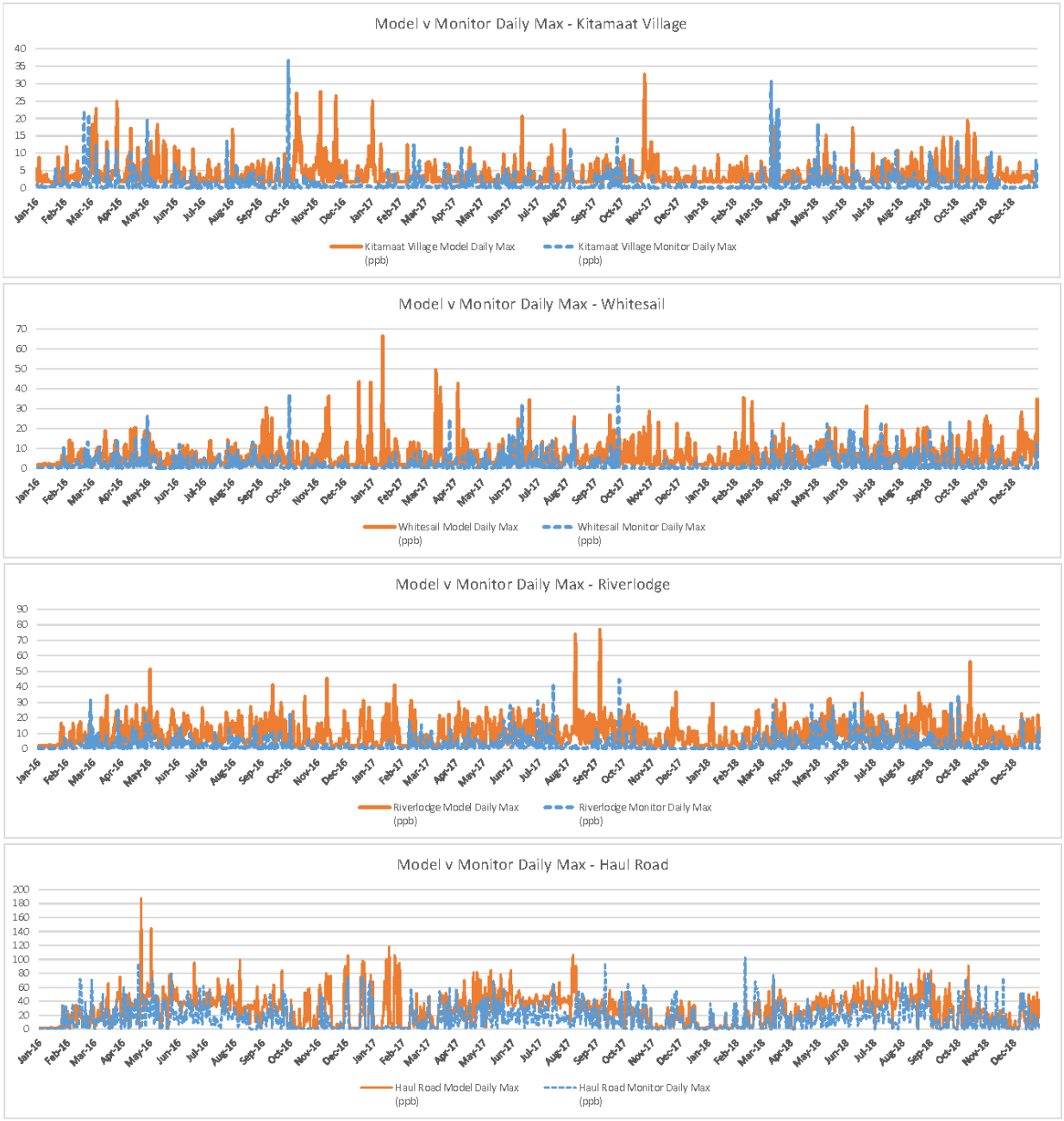


Figure 3-19. Comparison of modelled SO_2 concentrations (actual scenario) against continuous monitoring network SO_2., 2016-2018, timeseries (paired in time). The model data include the 1-hour background concentration (1.80 ppb).

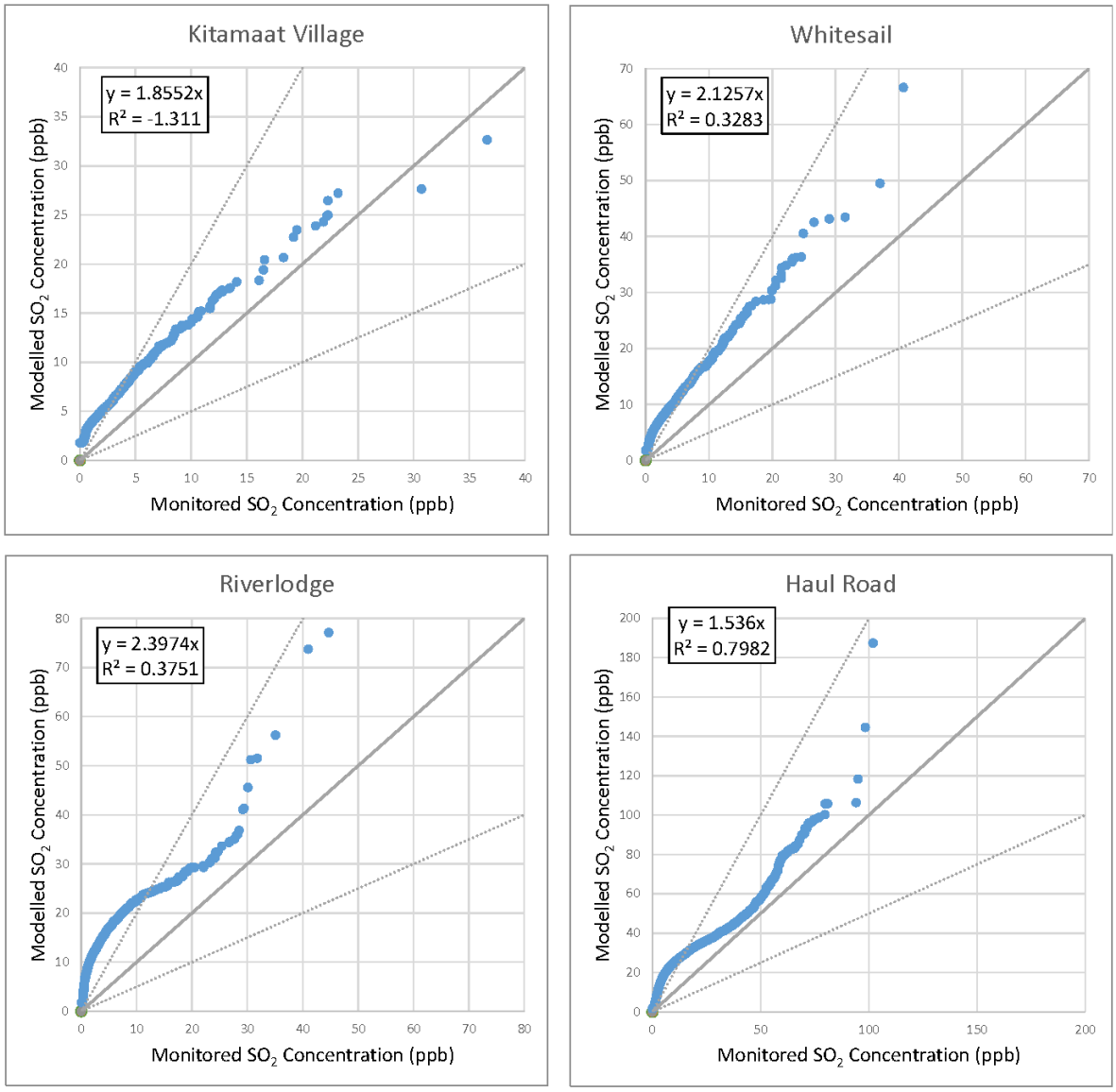


Figure 3-20. Comparison of modelled SO_2 concentrations (actual scenario) against continuous monitoring network SO_2, 2016-2018, Q-Q plot (ordered by rank). The 1-to-1 line (solid) and 2-to-1 lines (dashed) are shown. Best fit linear regression equation and R^2 value shown for 0 intercept. The model data include the model performance 1-hour background concentration (1.80 ppb at Williams Lake).

The Q-Q plots in Figure 3-20 illustrate that the model generally predicts concentrations between 100% and 200% of the monitored concentrations, with the exception of slight under-prediction at Kitamaat Village for the two highest hours over three years and some over-prediction above 200% at the lowest quantile concentrations, particularly for Riverlodge and Haul Road.

Additional model performance evaluation data are included in Atmospheric Appendix Sections 3.1.6 and 3.1.7, including comparison of 1-hour model results in the form of the objective (99th percentile of the daily peak) and model performance statistics (comparing the model versus

monitor paired for each hour). The regional-scale model also over-predicts 1-hour 99th percentile concentrations at all continuous monitoring sites, with a ratio of model to monitor ranging from 1.18 at Kitamaat Village to 1.81 at Whitesail.

We also used the passive sampling measurements to evaluate the 2016–2018 CALPUFF model performance (Figure 3-21). There was strong linear agreement between the modelled and measured SO_2 concentrations; however, there was a different relationship to the north and south of the smelter (Figure 3-21). While the 2016–2018 model over-predicted by approximately 2.2 times at sites to the north, the over-prediction is consistent, indicating good model spatial performance to the north (R^2= 0.86). In contrast, the 2016–2018 CALPUFF model under-predicted SO_2 concentrations at sites to the south of the smelter (model results average 58% of passive sampler results). The confidence in this level and uniformity of under-prediction of concentrations to the south is limited by the fewer number of monitoring sites to the south (R^2 = 0.19 for n=4). Atmospheric Appendix Section 3.1.6 also includes tables and maps for each year comparing the regional scale CALPUFF model results to the passive sampling results.

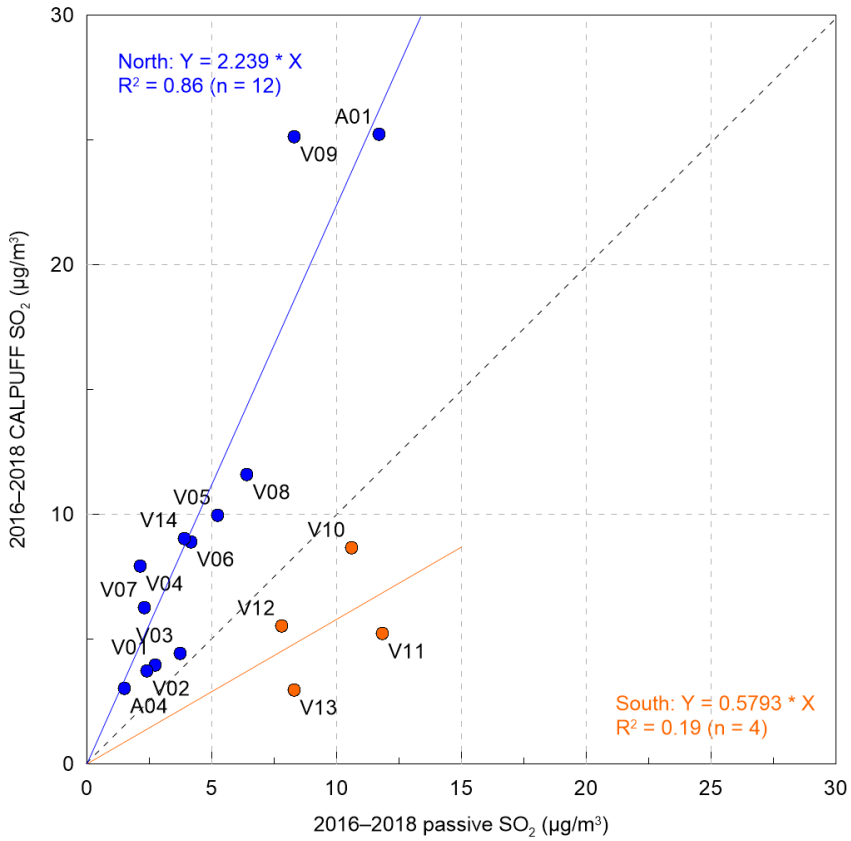


Figure 3-21. Comparison of modelled SO_2 concentrations (actual scenario) against average (2016–2018) passive sample data in the valley network. The 1-to-1 line is shown (dashed line), and best-fit linear regression for sites north and south of the smelter. Passive samplers were calibrated against continuous SO_2 data (see Figure 3-8). Note: the modelled data do not include estimates for residual background concentrations (1.21 µg/m³).

3.1.3.6 *Summary of regional-scale CALPUFF uncertainty*

As discussed in Section 3.1.2.4, dispersion models such as CALPUFF are generally accurate within about a factor of two (actual concentrations can be 50% to 200% of model results). The model performance evaluation described in the previous section also provides valuable information for quantifying the accuracy and uncertainty of the model data. A review of the annual average comparison at each continuous SO_2 monitoring station for each year allows a view of year-to-year and location-to-location variability in model over-prediction (or under-prediction). Table 3-5 (previous section) shows the 2016–2018 annual average CALPUFF model estimates compared to the monitoring data at each station. The model results at the four continuous SO_2 monitors range from 35% to 72% over-prediction of annual average SO_2 concentrations.[23] Based on this comparison, actual concentrations in the areas near the continuous SO_2 monitors are expected to have an uncertainty of approximately -75% to -25% (actual annual concentrations are expected to be 25% to 75% lower than modelled concentrations). However, this evaluation is limited to only four continuous monitoring locations. When also considering the comparison to passive sampling data (Figure 3-21), we can conclude more broadly that the actual annual average concentrations will likely be slightly lower to approximately half of CALPUFF results (actual concentrations likely 50% - 100% of model results) at any location north of the smelter or near Kitamaat Village, while actual concentrations south of the smelter along the western shores of the Douglas Channel are likely slightly higher to double those of CALPUFF results.

3.1.3.7 *SO_2 monitoring network evaluation results*

The local-scale CALPUFF model is used to evaluate the continuous SO_2 monitoring network (preliminary Phase 2 results). As detailed in Section 3.1.2.2, the CALPUFF results are used in the network evaluation by ranking receptors, giving equal weight to the receptor's highest concentration (99^{th} % 1-hour daily maximum concentration, form of the CAAQS) and to the frequency that the highest concentration occurs at that receptor compared to all receptors in the area of evaluation. As shown in Figure 3-22, the new CALPUFF results indicate that the Riverlodge monitor site is near the highest ranked locations within the town of Kitimat. The Whitesail monitor is not located near the highest rank locations; however, it may be located in the nearest site to the 9^{th} ranked location that meets siting criteria.

Note that the spatial SO_2 dispersion patterns predicted in the STAR within residential areas of Kitimat showed some higher concentrations that were suspected to be artifacts of the model's treatment of wind data from two different sources. Subsequent modelling and passive sampling (described in Phase 1 Network Evaluation in Atmospheric Appendix Section 3.1.9) showed spatial patterns consistent with the new model results – the highest concentrations within Kitimat are along the western boundary near Riverlodge.

Additionally, as shown in Figure 3-23, the model prediction of the most suitable location for measuring the highest concentrations within Kitamaat Village is along the western shoreline of

[23] Percentage under-prediction or over-prediction calculated as the difference between the CALPUFF result and observation, as a percent of the CALPUFF result. STAR results on the same basis (using Williams Lake background, STAR results vs. continuous monitors, Figure 3-18) gives an uncertainty of under-predicting by 50% to over-predicting by 74%.

Kitamaat Village. Additional maps showing individual years and individual metrics are included in Atmospheric Appendix Section 3.1.3.

The analysis in this section is preliminary, based on new CALPUFF results only. The formal conclusions for the continuous SO_2 monitoring network evaluation and optimization will be made in the Phase 2 monitoring network optimization report.

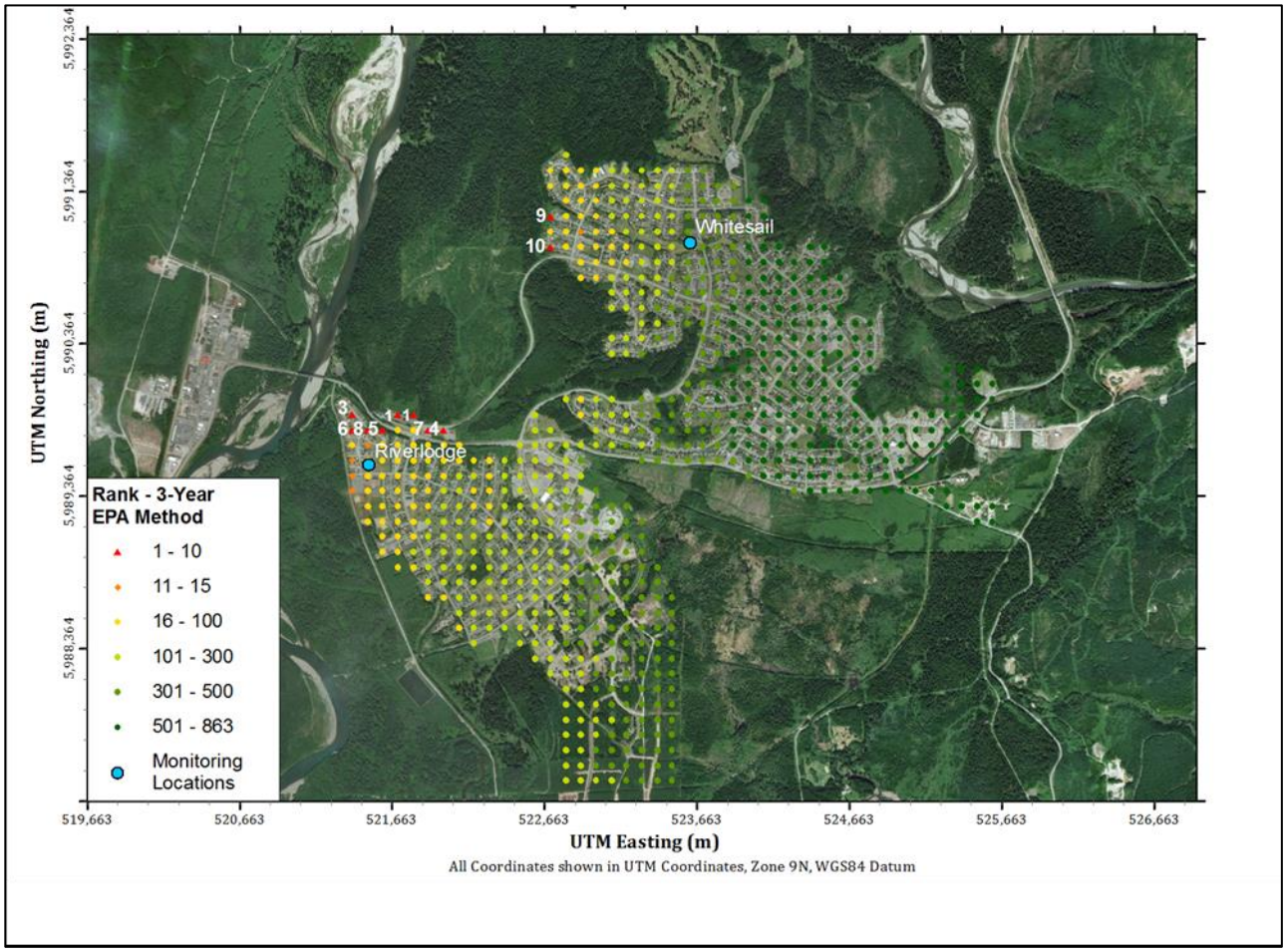


Figure 3-22. Network evaluation results, 2016-2018 met data for Kitimat, 42 tpd scenario, local-scale CALPUFF, considering equal weighting to 99% daily 1-hour peak concentration and frequency at which the location is the highest among receptors.

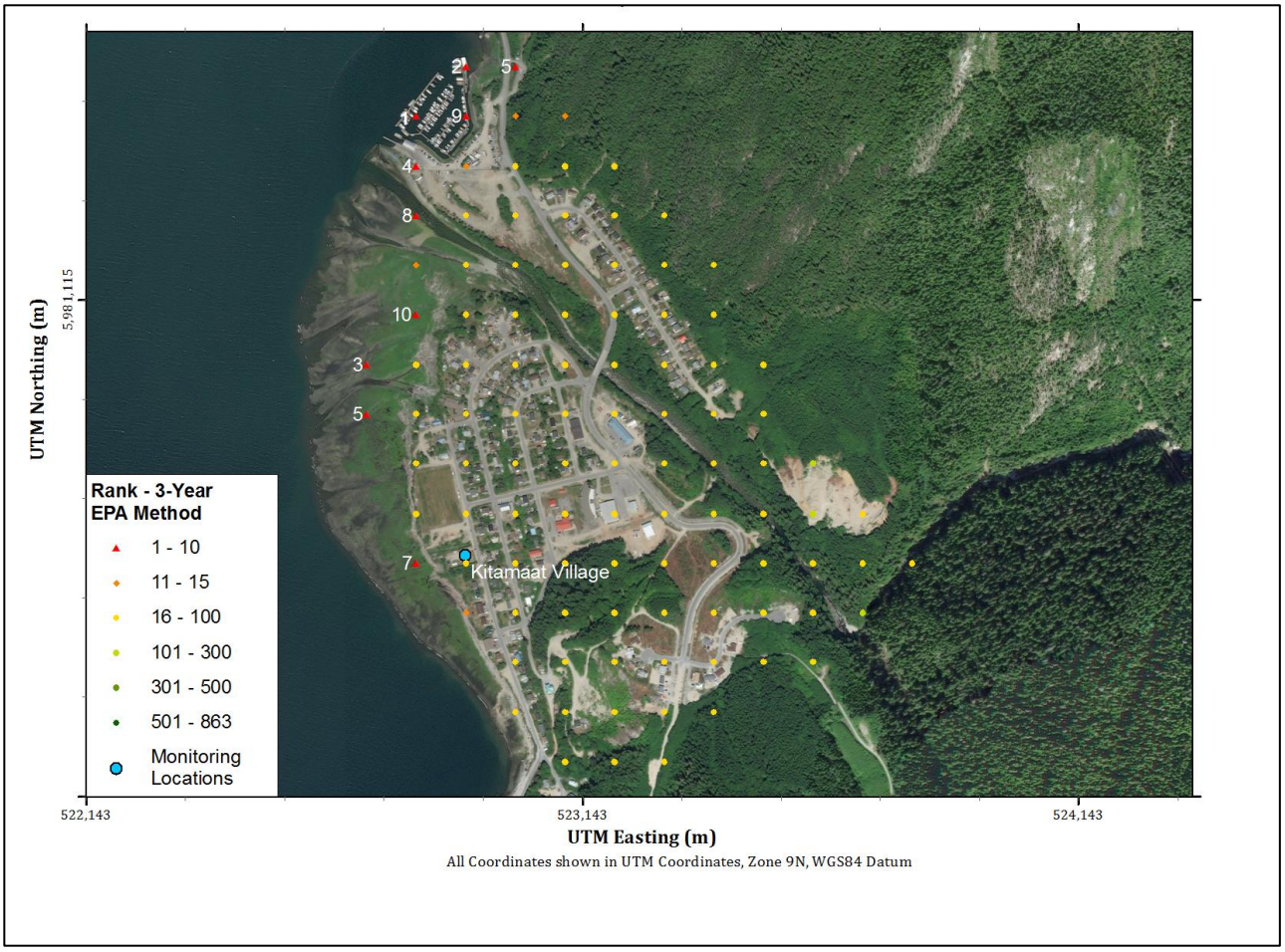


Figure 3-23. Network evaluation results for Kitamaat Village, 2016-2018 met data, 42 tpd scenario, local-scale CALPUFF, considering equal weighting to 99% daily 1-hour peak concentration and frequency at which the location is the highest among receptors.

3.2 Atmospheric Deposition

3.2.1 What did we set out to learn?

The STAR identified two uncertainties within the atmospheric deposition pathway, framed as questions to be addressed through the EEM program:

- STAR question D1: *Does the CALPUFF accurately predict post-KMP total sulphur deposition?*
- STAR question D2: *What are the base cation deposition values in the study region?*

As described in Section 3.1.1, the CALPUFF dispersion model used in the STAR predicted post-KMP SO_2 concentrations and total sulphur deposition throughout the Kitimat Valley. These atmospheric SO_2 and total sulphur deposition predictions were used to complete receptor-specific effects assessments along the four lines of evidence. In this comprehensive review, we set out to learn how accurate the STAR model predictions were and to understand the base cation deposition levels in the study region. We also set out to develop more accurate model predictions of current and future post-KMP atmospheric SO_2 and total sulphur deposition using a new CALPUFF model analysis. The new CALPUFF results are used to complete updated receptor-specific effects assessments to vegetation, and terrestrial and aquatic ecosystems.

The new CALPUFF model, in combination with the 2012-2018 atmospheric monitoring data, provides information to understand the spatial and temporal variability of post-KMP SO_2 concentrations and total sulphur deposition.

3.2.1.1 *EEM informative indicators*

We use the atmospheric deposition results to assess risk of impacts on vegetation, terrestrial, and aquatic ecosystems in Section 5, Section 6, and Section 7, respectively. Since the effects from sulphur deposition on receptors are assessed in receptor-specific evaluations, there are no KPIs for atmospheric deposition. The atmospheric pathway has two atmospheric deposition informative indicators: *atmospheric sulphur deposition* and *base cation deposition*.

We also added two new informative indicators to the EEM Program: *contribution of particulate sulphate to dry sulphur deposition* and *contribution of dry deposition to total deposition*. These indicators are not used to assess effects due to sulphur deposition, but provide valuable information to understand the factors that could lead to variation in deposition rates.

3.2.2 What methods did we use?

Sulphur dioxide is primarily removed from the atmosphere by two mechanisms. During dry periods, SO_2 and pSO_4^{2-} are removed through settling, impaction, and adsorption, termed as 'dry deposition'. SO_2 is also readily taken up by moisture in the air and becomes incorporated into rainfall along with pSO_4^{2-}; this removal mechanism is termed 'wet deposition'. Under the SO_2 EEM program, both wet and dry deposition were measured (modelled) to provide an estimate of total sulphur deposition, which was compared with CALPUFF modelled total sulphur deposition. It is difficult to directly measure dry deposition, as such it is generally estimated using a modelled dry deposition velocity. Therefore, although based on observations of air concentrations (of SO_2 and pSO_4^{2-}), dry deposition is modelled.

3.2.2.1 *Data we collected: wet deposition*

Sulphur wet deposition is measured by collecting samples of precipitation, including both rain and snow. Weekly major ion precipitation chemistry was measured at two stations within the Kitimat Valley. Both stations were incorporated into the National Atmospheric Deposition Program (NADP), which provided standardised equipment (electronic recording rain gauge and a wet deposition collector) and monitoring / measurement protocols. The wet deposition monitoring station at Haul Road (NADP site BC22) was established in September 2012, and the Lakelse Lake station (BC23) in March 2013.

3.2.2.2 *Analyses we conducted with these data: wet deposition*

Quality controlled monthly major ion precipitation chemistry and annual deposition data for Haul Road and Lakelse Lake were obtained directly for the NADP website (URL: nadp.slh.wisc.edu). Data quality and rainfall amount were evaluated for each station. The annual seasonality and long-term temporal trend between the two three-year periods 2013–2015 and 2016–2018 were evaluated. The changes in sulphate (SO_4^{2-}) deposition were compared with other NADP stations (BC24, WA19 and AK02). The monitoring data were also used to evaluate non-sea salt and non-anthropogenic base cation deposition, which is a required input for critical loads of acidity for soils.

3.2.2.3 *Data we collected: dry deposition*

Dry deposition measurements are difficult to make 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 modeling techniques, i.e., 'inferential' models (Vet et al. 2014).

$$F_{dry} = C \times V_d$$

where F_{dry} 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 three stations in the Kitimat Valley (Haul Road, Whitesail and Terrace Airport [YXT]). The V_d model required meteorological forcing variables on an hourly resolution for the period of interest (2015–2018). The data sources for the big-leaf dry deposition velocity model at three stations are shown in Table 3-7. The model also required 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).

Table 3-7. Data sources for meteorological variables required to model deposition velocity at Haul Road, Whitesail and Terrace Airport.

Variable	Kitimat: Haul Road	Kitimat: Whitesail	Terrace Airport
Temperature	Haul Road hourly	Whitesail hourly	Terrace Airport hourly
Wind speed	Haul Road hourly	Whitesail hourly	Terrace Airport hourly
Relative humidity	Whitesail hourly	Whitesail hourly	Terrace Airport hourly
Solar irradiance	Modelled from maximum and minimum daily temperature using Hargreaves method	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	NADP Haul Road	Terrace Airport daily data, disaggregated by NADP Lakelse Lake hourly data
Surface pressure	2015 & 2016: estimated from Terrace A hourly data. 2017 & 2018: Haul Road	2015 & 2016: estimated from Terrace A hourly data. 2017 & 2018: Haul Road	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
Cloud fraction	3-hourly Terrace Airport	3-hourly Terrace Airport	3-hourly Terrace Airport

3.2.2.4 *Analyses we conducted with these data: dry deposition*

We estimated hourly dry deposition velocities for a range of atmospheric gaseous species and particle size classes (including SO_2 and pSO_4^{2-}). We evaluated the influence of meteorological variables on deposition velocity to assess the potential error in using multiple data sources for a single station (Table 3-7). We estimated dry deposition for SO_2 using modelled hourly dry deposition velocities.

3.2.2.5 *Analyses we conducted with these data: total deposition*

We produced observation-based estimates of total sulphur deposition at Haul Road and Lakelse Lake by combining:

- measured wet S deposition (obtained from the NADP precipitation),
- estimated dry SO_2 deposition (based on hourly modelled deposition velocity and air concentrations from continuous analyzers[24]), and
- estimated dry deposition of pSO_4^{2-} (based on the relationship in Figure 3-12).

3.2.2.6 *CALPUFF modelling methods*

We used the new 2016-2018 CALPUFF model described in Section 3.1.2.4 to update predictions of deposition rates throughout the Kitimat Valley for the three model scenarios (actual, 35 ptd,

[24] SO_2 concentrations at Haul Road are obtained directly from the Haul Road station analyzer from 2016-2018. At Lakelse Lake, SO_2 concentrations were obtained from passive sampling during June to October, which was scaled to annual concentrations using the ratio in air concentrations observed at Haul Road.

and 42 tpd). The resolution of the deposition results was 1 km spacing for the STAR, which has been refined to 0.5 km spacing for the current effort. Section 3.1.2.4 summarizes the model methods, and Atmospheric Appendix Section 3.1.5 describes the methods in more detail.

3.2.3 What did we learn, and did we make any adjustments to the EEM Program?

3.2.3.1 *Overview of EEM monitoring program results – wet deposition network*

The long-term (2014–2018) average annual rainfall volume at Haul Road (2408 mm) is approximately 1.7 times Lakelse lake (1423 mm). The pattern is generally consistent for every year of observations (Figure 3-24). The monthly ion balance for stations indicates an anion deficit (Figure 3-24), which is notably larger at Haul Road, this may be driven by missing anions (e.g., fluoride or organic ions) or by removal of outliers in monthly summaries. Only two of the major ions in deposition chemistry showed any large change between the periods 2013–2015 and 2016–2018 (both three-year periods). SO_4^{2-} and hydrogen ion (H^+) concentration in precipitation increased at both Haul Road and Lakelse Lake between these periods; sulphate (mg/L) increased by 63% at Haul Road and 72% at Lakelse Lake, and H^+ increased by 26% and 48%, respectively. We compared changes in sulphur deposition for the same period against three other NADP stations (one in B.C., one in Alaska and one in Washington state; (Table 3-8); there was an observed decrease in sulphur deposition at the other stations compared with the increase at BC22 and BC23 in the Kitimat Valley (Table 3-8). There was a decrease in sulphate deposition at Haul Road and Lakelse Lake in 2018 compared with 2017 (Table 3-8), this was caused by the low precipitation volume (Figure 3-25). Focusing on sulphur and pH (hydrogen ion concentration), sulphur did not show a consistent seasonal pattern between stations; in contrast, pH at Haul Road and Lakelse Lake showed minima during June–July (Figure 3-24). The long-term time-series for Haul Road and Lakelse Lake show a step change (increase) in the deposition of sulphur from 2013–2015 compared with 2016–2018 (Figure 3-24 and Figure 3-25; note that the scale for Haul Road is a factor of 10 higher than Lakelse Lake). The long-term time-series for pH showed a similar decrease (Figure 3-24; note a decrease in pH is equivalent to an increase in H^+ concentration). However, at Haul Road the pH of rainfall increased during the period 2013–2015, and subsequently decreased during 2016–2018.

STAR question D2: *What are the base cation deposition values in the study region?*

Base cation deposition is a required input for the determination of critical loads of acidity for terrestrial ecosystems (soils). Base cation deposition should be corrected for sea salts and excluded anthropogenic inputs, i.e., it should reflect ambient 'background' deposition of base cations. We evaluated annual base cation (BC = Ca^{2+} (calcium) + Mg^{2+} (magnesium) + K^+ (potassium) + Na^+ (sodium)) precipitation chemistry at three NADP stations, Haul Road [BC22], Lakelse Lake [BC23] and Port Edward [BC24] during the period 2014–2018 (2013–2018 for BC22). Following correction for sea salts, Mg^{2+} and Na^+ were zero, i.e., they had no non-sea salt sources at both stations. Long-term $Ca^{2+}$and K^+ in precipitation were almost equal at Lakelse Lake and Port Edward (, i.e., Ca^{2+} was 0.71 µeq/L at both sites, and K^+ was 0.09–0.10 µeq/L at Port Edward–Lakelse). In contrast, the precipitation concentrations at Haul Road were 1.5 (K^+) to >2 (Ca^{2+}) times larger than the other two sites. It was assumed that precipitation chemistry at Haul Road was influenced by anthropogenic sources; as such, regional base cation precipitation was set to the average for Lakelse Lake and Port Edward. Regional base cation deposition was estimated by multiplying mapped rainfall volume by average 'background' base cation precipitation = 0.8 µeq/L (Ca^{2+} = 0.71 µeq/L and K^+ = 0.09 µeq/L). See Terrestrial Ecosystems (Soils) Appendix 6.6 for a map of base cation deposition across the Kitimat Valley.

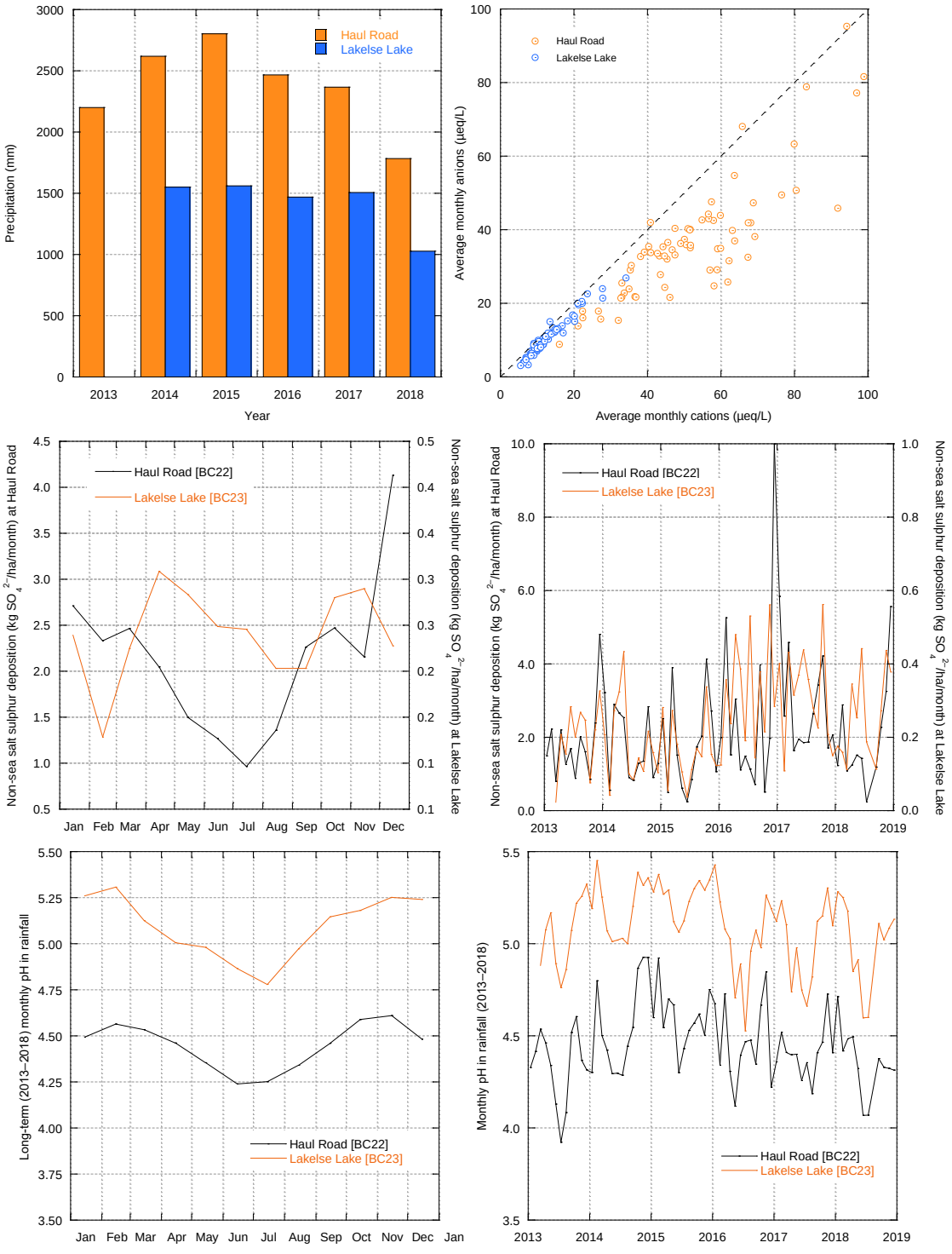


Figure 3-24. Comparison of precipitation chemistry at Haul Road and Lakelse Lake. Top row: Rainfall volume and ion balance. Middle row: Seasonal and long-term monthly non-sea salt sulphur deposition (kg SO_4^{2-}/ha/month); note different axis for Haul Road and Lakelse Lake. Bottom row: Seasonal and long-term monthly pH (see Atmospheric Appendix 3.2.1 for larger version).

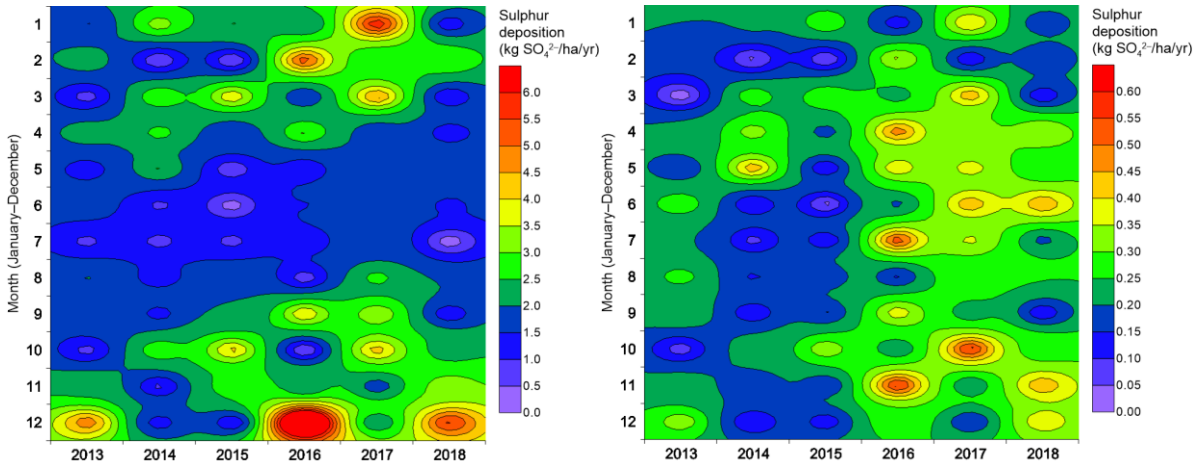


Figure 3-25. Year-month maps showing monthly deposition of non-marine sulphate at Haul Road (left) and Lakelse Lake (right) during the period 2013–2018 (six-years).

Table 3-8. Annual non-sea-salt (excess) sulphur deposition (kg SO_4^{2-}/ha/year) at wet-only monitoring stations within the National Atmospheric Deposition Program (NADP) network during 2013 to 2018. Also shown is the ratio between the two periods 2013–2015 and 2016–2018.

Station	Haul Road	Lakelse Lake	Port Edward	North Cascades	Juneau
Year	BC22	BC23	BC24	WA19	AK02
2013	21.83	2.38*	—	3.01	2.90
2014	20.41	1.95	3.65	2.81	2.55
2015	21.03	1.82	3.46	1.78	2.26
2016	32.38	3.37	2.45	2.30	1.89
2017	33.64	3.68	2.93	1.59	1.87
2018	21.17	3.00	2.33	1.72	1.91
Ratio ($^{16\text{-}18}/_{13\text{-}15}$)	1.38	1.63	0.72	0.74	0.74

* The 2013 annual average was based on 10 months of observations.

3.2.3.2 *Overview of EEM monitoring program results – dry deposition*

Annual modelled dry deposition velocity (V_d) for SO_2 during 2016–2018 ranged 0.49 cm/s at Haul Road (0.47–0.51 cm/s) to 0.83 cm/s at Terrace Airport (0.74–0.91 cm/s). The V_d for SO_2 is generally higher than other gases (e.g. nitrogen dioxide (NO_2) and ozone (O_3)) and particles ($PM_{2.5}$) within the Kitimat Valley (Table 3-9). The V_d for pSO_4^{2-} was assumed to be equivalent to $PM_{2.5}$, which is about one-third of the V_d for SO_2 (and lower than other gases and particles; Table 3-9). Daily V_d for SO_2 was highly variable within and between months (Figure 3-26) with no clear seasonal pattern across the three sites. Overall, modelled V_d for SO_2 were highest at Terrace Airport and lowest at Haul Road (Figure 3-18, also true for other gases and particles see Table 3-9). The monthly average V_d for SO_2 showed lower variation between summer exposure months

(Table 3-10; June to October exposure period for passive samplers); the average coefficient of variation was 20%, which ranged from 8.3% (2017 at Haul Road) to 30.3% (2016 at Haul Road). The average V_d at Haul Road is very similar to Whitesail during 2016–2018, i.e., 0.53 cm/s compared with 0.56 cm/s, respectively.

A one-at-a-time sensitivity analysis was carried out to assess the influence of input variables on modelled V_d. Gaining an understanding of which variable most influences V_d is valuable because a number of input variables were estimated or taken from nearby stations (Table 3-7) rather than those variables originating directly from observations at the same site. Temperature had the greatest influence, i.e., ±30% change in temperature resulted in a 56% decrease in V_d for SO_2 (a 30% increase in temperature resulted in a 56% decrease in V_d and a 30% decrease in temperature resulted in a 106% increase in V_d). Windspeed and relative humidity were the next sensitive (with windspeed being the most sensitive) and had a similar magnitude and direction of effect; i.e., a 30% increase resulted in a 20% increase in V_d and a 30% decrease resulted in a 20% decrease in V_d. A ±30% change in solar irradiance, precipitation, surface pressure, snow depth and cloud fraction had negligible influence on modelled V_d for SO_2. In the current study, temperature and windspeed were site-specific measurements; the only sensitive parameter that was infilled at Haul Road was relative humidity, which was taken from Whitesail (Table 3-7).

Given the low observed atmospheric concentration of pSO_4^{2-} compared with SO_2 (factor of 10 lower; see Table 3-3) and the lower V_d for pSO_4^{2-} compared with SO_2 (approximately one-third of the value, see Table 3-9), the estimated dry deposition of pSO_4^{2-} makes up a small fraction of total (pSO_4^{2-} + SO_2) dry deposition, and an even smaller fraction of total (wet plus dry) sulphur deposition.

Table 3-9. Annual average (hourly) dry deposition velocity of four common gases (sulphur dioxide, nitrogen dioxide, ozone, ammonia) and two particle size classes at three climate monitoring stations during 2016–2018. The deposition velocities assume coniferous landcover.

Station	Year	SO_2	NO_2	O_3	NH_3	$PM_{2.5}$	$PM_{2.5-10}$
		cm/s	cm/s	cm/s	cm/s	cm/s	cm/s
Haul Road	2016	0.48	0.27	0.30	0.55	0.13	0.49
Haul Road	2017	0.51	0.28	0.31	0.58	0.14	0.51
Haul Road	2018	0.47	0.25	0.27	0.54	0.14	0.51
Whitesail	2016	0.47	0.22	0.25	0.50	0.14	0.49
Whitesail	2017	0.56	0.28	0.32	0.61	0.17	0.51
Whitesail	2018	0.58	0.29	0.33	0.65	0.18	0.51
Terrace YXT	2016	0.91	0.51	0.59	0.99	0.33	1.62
Terrace YXT	2017	0.85	0.48	0.55	0.93	0.32	1.58
Terrace YXT	2018	0.74	0.43	0.49	0.81	0.29	1.41

Table 3-10. Monthly (June–October) average (hourly) dry deposition velocity (cm/s) for sulphur dioxide at three climate monitoring stations during 2016–2018. The five-month (June–October) average and variation between months (as coefficient of variation [CV]) is also shown.

Station	Year	Monthly Dry Deposition Velocity (cm/s)					Average	CV
		June	July	August	September	October	cm/s	%
Haul Road	2016	0.63	0.63	0.45	0.61	0.27	0.52	30.3
Haul Road	2017	0.62	0.59	0.64	0.52	0.64	0.60	8.3
Haul Road	2018	0.63	0.42	0.48	0.41	0.43	0.47	19.1
Whitesail	2016	0.50	0.53	0.43	0.56	0.29	0.46	23.1
Whitesail	2017	0.43	0.68	0.73	0.60	0.78	0.64	21.3
Whitesail	2018	0.73	0.52	0.60	0.54	0.52	0.58	15.3
Terrace YXT	2016	0.96	0.93	0.72	0.98	0.97	0.91	12.0
Terrace YXT	2017	0.85	0.78	0.86	0.77	1.00	0.85	10.6
Terrace YXT	2018	0.88	0.58	0.64	0.79	0.78	0.73	17.0

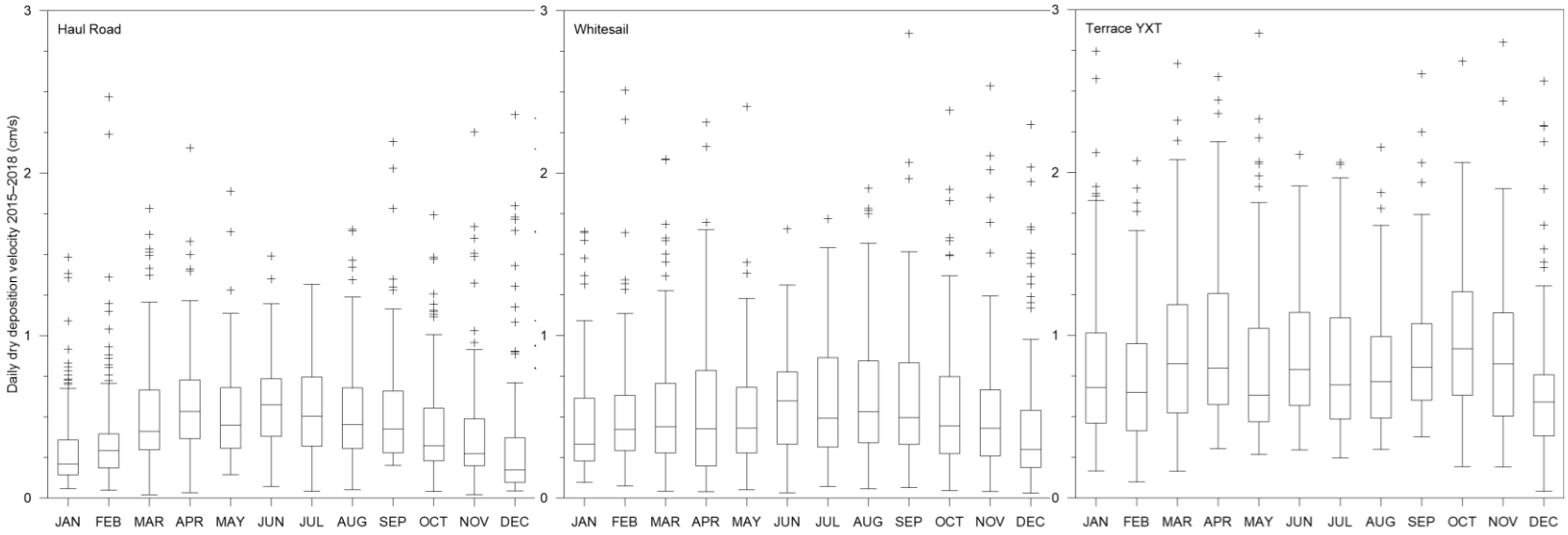


Figure 3-26. Box-plot showing the variation in daily dry deposition velocity (cm/s) for sulphur dioxide each month during the period 2015–2018 (four years) at Haul Road, Whitesail and Terrace airport.

3.2.3.3 *Summary of CALPUFF model results for total sulphur deposition*

Figure 3-27 and Figure 3-28 present the new 2016-2018 CALPUFF model deposition results. The model outputs deposition of total sulphur from SO_2 and SO_4^{2-} wet and dry deposition, which is presented in units of kg SO_4^{2-} /ha/yr. The new 2016–2018 CALPUFF model predicts a similar spatial distribution of deposition as was predicted in the STAR; however, some differences are notable. As shown in Figure 3-29, which compares the new CALPUFF deposition and the STAR CALPUFF deposition results, the 7.5 kg SO_4^{2-} /ha/yr isopleth extends farther to the southwest and does not extend as far to the north. The new CALPUFF model predicts a smaller area within the 7.5 kg SO_4^{2-} /ha/yr isopleth compared to STAR due to the change in extent to the north (Table 3-12).

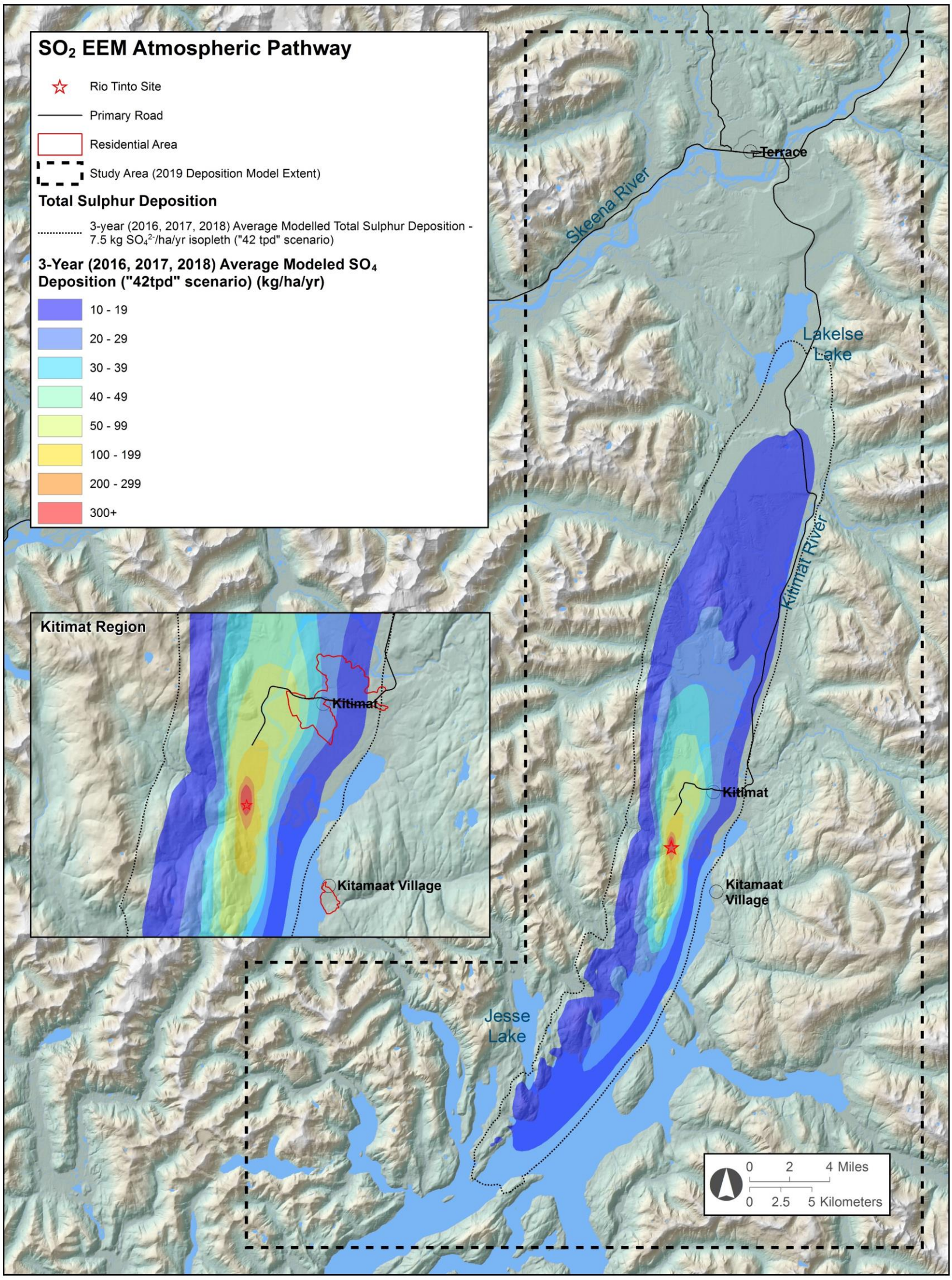


Figure 3-27. Modelled total sulphur deposition as SO_4^{2-} (kg/ha/yr SO_4^{2-}), 42 tpd scenario, 3-year average, regional (not including background).

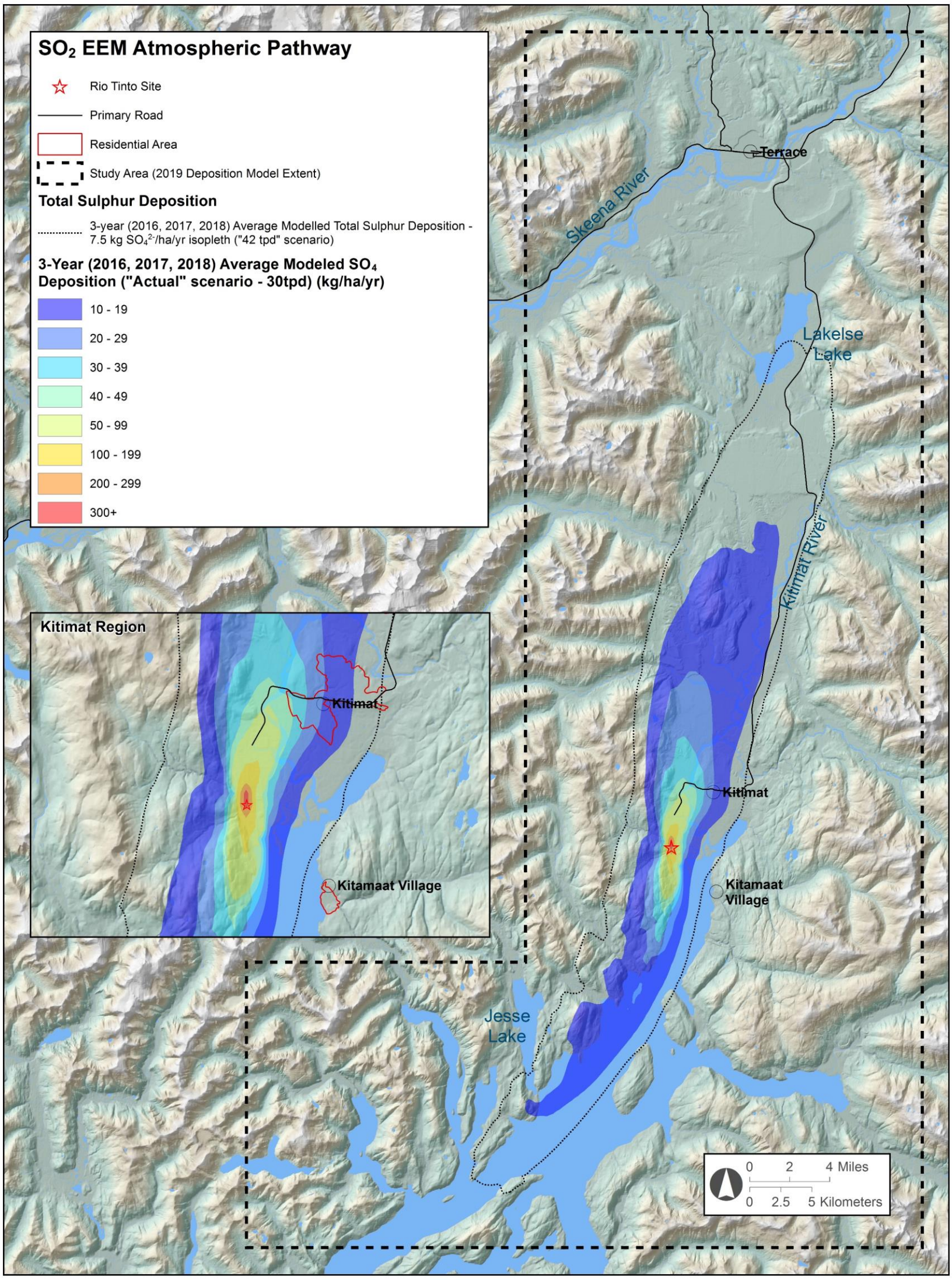


Figure 3-28. Modelled total sulphur deposition as SO_4^{2-} (kg/ha/yr SO_4^{2-}), actual scenario (29.3 tpd), 3-year average, regional (not including background).

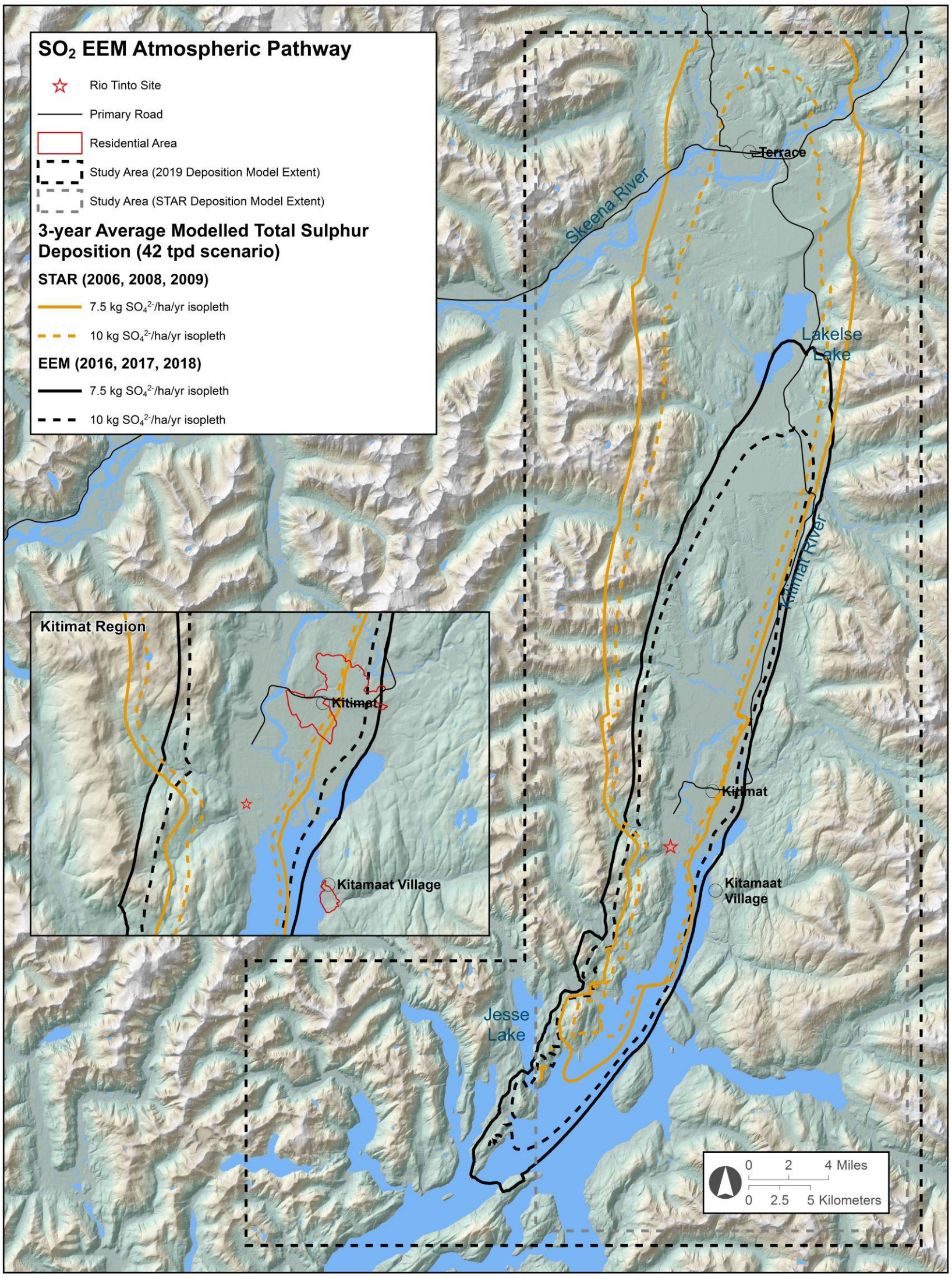


Figure 3-29. Modelled total sulphur deposition as SO_4^{2-} (kg/ha/yr SO_4^{2-}) for new CALPUFF versus STAR, 42 tpd scenario, 3-year average, regional (not including background).

Only a small fraction of SO_2 emitted from the smelter is deposited through wet or dry deposition within the study area (Table 3-11). This fraction is 8.1% for the 42 tpd scenario based on the 3-year average new 2016–2018 CALPUFF model results. The remaining SO_2 stays in the atmosphere and eventually exits the model domain. Deposition rates beyond the CALPUFF domain are well below levels we use to define the area within which deposition impacts may occur (7.5 kg/ha/yr).

Table 3-11. Percentage of SO_2 emitted from the smelter that is deposited through wet or dry deposition within the study area as predicted by CALPUFF (based on 42 tpd scenario).

Year	Deposited (ton/day (as SO_2))	Deposited (as % of emitted)	Not Deposited (as % of emitted)
2016	3.47	8.3	91.7
2017	3.55	8.4	91.6
2018	3.13	7.5	92.5
3-year Average	3.38	8.1	91.9

* Note that the amount 'deposited' is based on wet and dry deposition of total sulphur SO_2 and SO_4^{2-}. The number shown is total S deposited as SO_2, so it can be compared to the sulphur emitted.

Table 3-12. Sulphur deposition boundary area of new CALPUFF model compared to STAR CALPUFF model.

	Area of Plume (km^2)	
Deposition Scenario:	7.5 kg/ha/yr SO_4^{2-}	10 kg/ha/yr SO_4^{2-}
3-year average SO_4^{2-} deposition for 2006, 2008, 2009 - Post-KMP (STAR) - 42 tpd Scenario	1,012*	722
3-year average modelled SO_4^{2-} deposition for 2016, 2017, and 2018 (New CALPUFF) - 42 tpd Scenario	578	418
Difference	*-433*	*-304*
* The STAR "Post-KMP" deposition (7.5 kg/ha/yr SO_4^{2-}) is cut-off at the north end, leading to a restricted estimate of its area.		

3.2.3.4 *Summary of regional-scale CALPUFF model performance for total sulphur deposition*

STAR question D1: Does the CALPUFF accurately predict post-KMP total sulphur deposition?

Table 3-13 compares the annual and 3-year average wet, dry, and total deposition at the two NADP stations. Similar to the STAR model, the new CALPUFF model predicts that wet deposition dominates the total sulphur deposition; however wet deposition observations combined with the big-leaf model dry deposition estimates indicate that wet and dry deposition contribute approximately equal amounts, with dry contributing a slightly higher fraction than wet at Haul

Road, and wet contributing a slightly higher fraction than dry at Lakelse Lake. Overall, the new CALPUFF model predictions of total sulphur deposition compare well to the monitor results. When considering that the model results do not include background deposition (which may be up to 3.6 kg SO_4^{2-}/ha/yr; see Terrestrial Ecosystems (Soils) Appendix 6.7, the new model over-estimates actual deposition rates at Haul Road by 24% to 29% (3-year average comparison of observed to modelled without background and to modelled with maximum background), and predicts actual deposition at Lakelse Lake from 16% under-estimation to 47% over-estimation (3-year average comparison of observed to modelled without background and to modelled with maximum background).

Table 3-13. Annual and three-year average wet, dry and total observation-based deposition and CALPUFF modelled sulphur deposition (kg SO_4^{2-}/ha/yr) at Haul Road and Lakelse Lake during 2016 to 2018.

Station	Year	Observation			Model		
		wet	dry	total	wet	dry	total
Haul Road	2016	32.38	42.88	75.26	75.83	15.36	91.20
	2017	33.64	39.44	73.08	82.69	14.58	97.26
	2018	21.17	34.45	55.62	50.46	14.98	65.45
	Average	29.06	38.92	67.99	69.66	14.97	84.63
Lakelse Lake	2016	3.37	2.67	6.04	2.81	2.41	5.22
	2017	3.68	2.66	6.34	2.62	2.51	5.14
	2018	3.00	2.14	5.14	2.00	2.47	4.47
	Average	3.35	2.49	5.84	2.48	2.47	4.94

* Note: wet deposition is a direct measurement obtained from the NADP station; in contrast, dry deposition is estimated from measurements of atmospheric SO_2 and modelled deposition velocity (using the big-leaf model).

Under the STAR, observation-based estimates of total (wet and dry) sulphur deposition were compared with pre-KMP modelled total deposition (ESSA et al. 2013). CALPUFF total sulphur deposition at Haul Road under pre-KMP was ~93 kg SO_4^{2-} ha/yr. In comparison, the observation-based estimate of total deposition was ~65 kg SO_4^{2-} ha/yr during the period 2007–2011 (5-year annual average), composed of ~35 kg SO_4^{2-} ha/yr wet deposition and ~30 kg SO_4^{2-} ha/yr dry deposition. The pre-KMP comparison suggested that STAR CALPUFF simulations overestimated total sulphur deposition at Haul Road (consistent with the current study); however, both showed approximately the same proportion of dry deposition (42% CALPUFF and 46% observed data). Under the current study, observation-based estimates show a similar but higher proportion of dry deposition at 57% likely owing to the inclusion of site-specific high temporal resolution V_d and the low rainfall volume during 2018. In contrast, the 2016-2018 CALPUFF predicts a much lower proportion of dry deposition at 18% (compared with 42% under the STAR),

3.3 What do we recommend for the EEM Program going forward?

Overall, we recommend continuing the atmospheric monitoring within the EEM program with relatively few changes to the core monitoring programs (SO_2 continuous monitoring and Valley Network passive sampling).

We recommend continuing SO_2 continuous monitoring at all or most of the current sites. The Phase 1 monitoring network evaluation indicated that the Riverlodge monitor site is in the most suitable location for measuring the highest concentrations within the town of Kitimat, and that the Kitamaat Village monitoring station is in the best location for Kitamaat Village. The preliminary Phase 2 network evaluation does not contradict these conclusions, but the Phase 2 evaluation should be completed before making final conclusions. Therefore, final continuous network recommendations will be made as part of the Phase 2 network optimization report. In the interim, the continuous SO_2 monitoring should continue at the current sites pending the Phase 2 network evaluation completion.

We also recommend continuing the passive sampling network in the Kitimat Valley because it adds value for understanding the spatial distribution of SO_2. In particular, the passive sampling network added substantial value for evaluating CALPUFF model performance. Accurate CALPUFF prediction of SO_2 (and SO_4^{2-} deposition) reduces uncertainty when using the CALPUFF output for evaluating risk of impacts to vegetation, terrestrial, and aquatic ecosystems. However, the number of sites and frequency of monitoring should be reviewed. For example, in order to gain a better understanding of the plume position and extent in the east-west direction, we recommend adding passive sampling sites to the east and west of current sites located to the north of the smelter, where possible based on access, and in locations that meet the B.C. air monitoring site selection guidelines for passive sampling. The current north to south network could be reduced to accommodate the proposed east to west expansion. Two or three cross sections over two to three years will be sufficient for model evaluation needs. Additionally, we recommend evaluating whether additional passive sampling sites can be established in locations south of the smelter. Lastly, the passive sampling site locations should be assessed for whether some sites could be moved to align with the proposed biodiversity plots (or vice versa).

Note that the passive sampling urban network study has been successful in confirming the entire Kitimat urban area has low SO_2 concentrations. There are no plans to continue the study beyond October 2019, and no benefit in continuing the study has been identified through the comprehensive review. Similarly, the short study of particulate sulphate sampling using filter packs was successful in confirming that only a very small fraction of total sulphur in the atmosphere is particulate sulphate. There are no plans to continue particulate sulphate study, and no benefit in continuing the study has been identified through the comprehensive review.

For the deposition monitoring program, we recommend continuing the Lakelse Lake monitor and considering discontinuing the Haul Road wet deposition monitor. The monitoring of wet deposition at Haul Road provides no ecological value (i.e., for the assessment of impacts) owing to its fence line location, and it provides limited value for model (CALPUFF) evaluation.

4 Review Results for Human Health

4.1 What Did We Set Out to Learn?

4.1.1 How is the Human Health Receptor evaluated in the SO_2 EEM Program?

The purpose of the SO_2 EEM Program for human health is to characterize the levels of SO_2 in the ambient air in residential areas in the Kitimat area and to compare those levels with KPIs related to human health.

The human health aspects of the SO_2 EEM program are unique with respect to the role of the STAR (ESSA et al. 2013). When the STAR was prepared, the Province of British Columbia did not have an Air Quality Objective for sulphur dioxide that was based on recent human health evidence. As a result, the STAR included predictions of the annual number of restricted airway events based on the ambient air concentrations in residential areas. The ambient air concentrations were predicted by the air dispersion modelling that was conducted as part of the STAR, similar in structure to the modelling described in Section 3 of this report.

As part of the original SO_2 EEM Program, informed by the STAR, a performance indicator was included based on updated predictions of the annual number of restricted airway events based on each future year's actual emissions and meteorological observations. In the EEM, this indicator was described as an "informative" rather than a "key" indicator.

In the time between the preparation of the STAR and this comprehensive review, the Province of British Columbia adopted an IAQO and has modified the SO_2 EEM Program to apply the IAQO as a KPI. The KPI is based on measurements at residential monitoring stations. Starting with the year 2020, the B.C. IAQO for SO_2 becomes equivalent to the CAAQS adopted by the CCME.

This section primarily addresses the KPI which is based on the observations of the levels of SO_2 at residential monitoring stations in comparison to the levels specified in the B.C. IAQOs. The locations of the residential monitors ("Riverlodge" in Lower Kitimat, "Whitesail" in Upper Kitimat, and "Kitamaat Village") are shown in Figure 4-1.

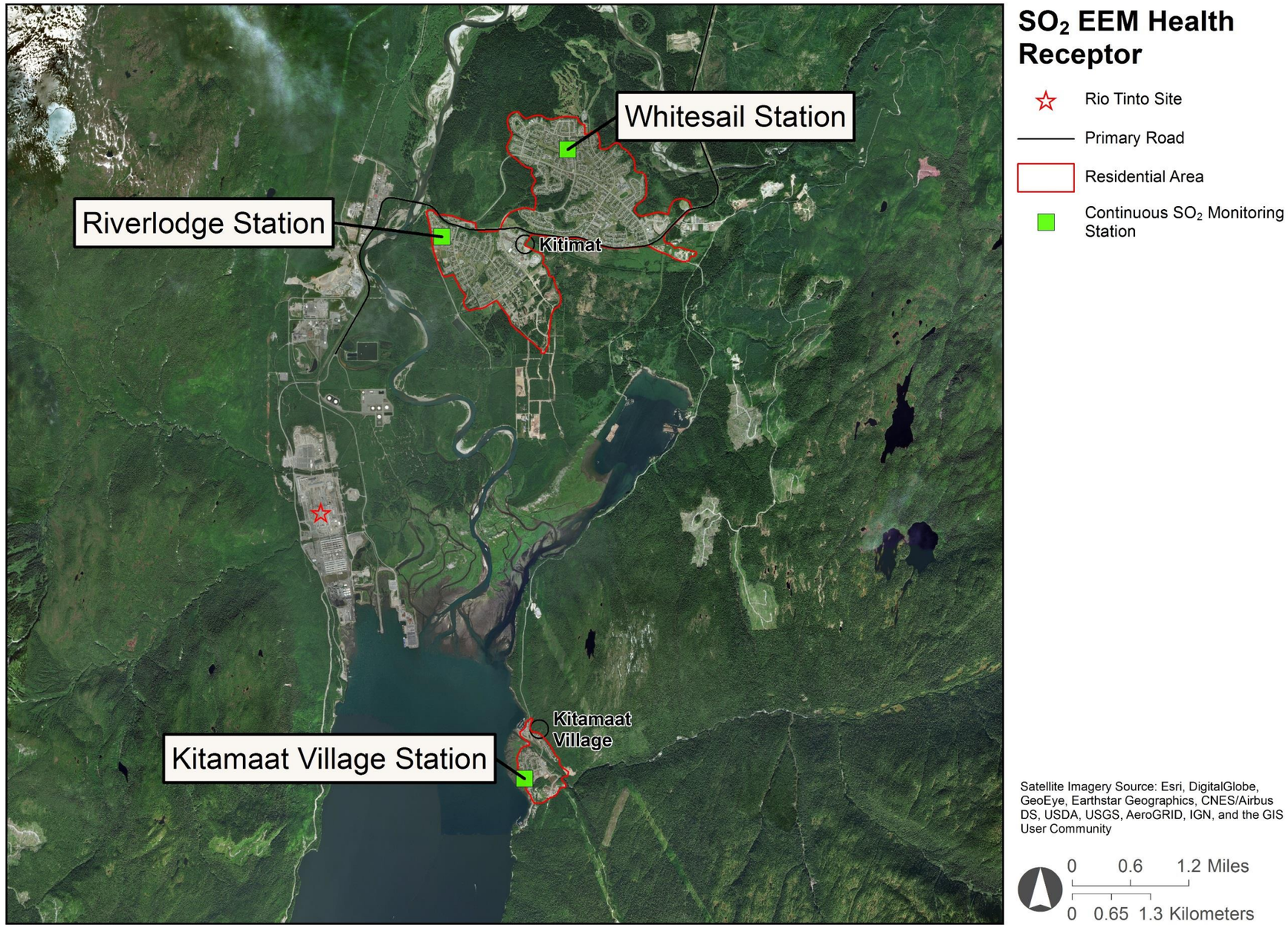


Figure 4-1. Locations of residential continuous SO_2 monitoring stations in the Kitimat region.

4.1.2 What is the basis for the B.C. IAQOs and the CAAQS?

The CAAQS constitute a set of pollutant-specific standards that place limits on and establish goals for the levels of pollutants in the air. The CAAQS values for SO_2 were announced in October, 2016[25]. They establish a specific SO_2 concentration limit (70 ppb) starting in 2020, and a lower limit starting in 2025 (65 ppb). A specific statistic of the observed air pollutant levels is employed to compare to the limit values ("The three-year average of the annual 99th percentile of the SO_2 daily-maximum of 1-hour-averaged concentrations.").

The CAAQS values of 70 ppb and 65 ppb, for 1-hour averaged concentrations, are compatible with, but not identical to, a value of 67 ppb derived by Health Canada (2016) for 10 minute averaged concentrations. Health Canada's report (2016), *Human Health Risk Assessment of Sulphur Dioxide: Analysis of Ambient Exposure to and Health Effects of Sulphur Dioxide in the Canadian Population,* describes the process of deriving an exposure limit, which Health Canada labels a Reference Concentration (RfC), for SO_2. The process is summarized below:

1. Causal analysis of relationships between various types and durations of exposure to SO_2 and human health effects. This answers the question: How likely is it that SO_2 causes each possible human health effect?
2. Selection of a Lowest Observed Adverse Effect Concentration (LOAEC) from human studies related to those health effects identified as known to be causally linked to SO_2 exposure. This answers the question: What is the lowest concentration of SO_2 at which the identified human health effects have been observed in studies of appropriate quality?
3. Downward adjustment of the LOAEC to account for human variability and uncertainties.
4. The result of this process (identifying the LOAEC and downward adjustment) is the RfC, which is understood to be an exposure level below which human health effects are not expected or would be very infrequent even in vulnerable populations.

In Health Canada's judgement, based on a weight-of-evidence approach, the human health effect which is known to be caused by SO_2 is the exacerbation of airway restriction events among asthmatics. This is based on clear evidence from highly controlled human studies in which asthmatics are exposed to specific concentrations (e.g. 100 ppb, 200 ppb, 400 ppb) of SO_2 while

[25] Canadian Ambient Air Quality Standards for SO_2. CCME, 2016.

exercising. The studies are conducted on exercising asthmatics in order to ensure some observed airway restrictions since these are considerably less likely for asthmatics breathing normally.

Health Canada selected a LOAEC of 400 ppb based on statistically significant increases in measurements of airway restriction and lung function among exercising asthmatics. The extent of downward adjustment of the LOAEC was described as being based on the following considerations:

1. That some exercising asthmatics responded below 400 ppb, even if the finding was not statistically significant
2. That some asthmatics may be more sensitive than the relatively healthy volunteers who participated in the controlled human studies
3. That it is possible that there are other health effects other than restricted airway events
4. That the controlled studies are done using indoor and room temperature air and there is evidence of increased incidence of restricted airway events in the presence of cold, dry air as might be experienced frequently in Canada

With these considerations, Health Canada selected an overall downward adjustment factor of 6. This is used to reduce the observed threshold value (the LOAEC) by a factor of 6 from 400 ppb down to 67 ppb. The resulting RfC is therefore 67 ppb. Specifically, Health Canada indicates "To account for the uncertainties mentioned above and considering the supporting evidence from the epidemiology, an uncertainty factor of 6 was applied to result in a 10-minute RfC of 67 ppb, which is expected to be protective of human health, including sensitive subpopulations like asthmatics."

The Health Canada approach is based on standard practice in regulatory toxicology that is applied in deriving exposure guideline values across multiple human exposure pathways (i.e., in air, water, soil, food and consumer products). This practice includes the weight-of-evidence evaluation, the selection of a lowest observed effect concentration, and the assignment of additional adjustment factors to account for uncertainties and human variability in response to SO_2 (i.e., those people who may be even more sensitive than those who participated in the controlled studies). By establishing an exposure threshold level that is deliberately chosen to be protective of the sub-population who is known to be most vulnerable to SO_2 effects, the understanding is that the rest of the population may be presumed to be protected.

Recently, the U.S. Environmental Protection Agency reaffirmed its standard of 75 ppb for SO_2 (US EPA 2019). This value is applied to the three-year average of the 99th percentile of the distribution of daily 1-hour maxima.

4.2 What Methods Did We Use?

In 2017, the indicators for the Human Health component of the SO_2 EEM Component permit were amended. The amendment added a KPI based on the newly adopted B.C. IAQOs. The B.C. IAQOs were formally adopted on December 15, 2016.

The B.C. IAQO of 75 ppb was applied in a phased approach within the EEM. As such, the percentile of comparison was increased gradually through the interim period. The resulting requirements and updated KPIs are captured in Table 4-1. For comparison, the CAAQS values, which will be adopted as the B.C. Air Quality Objectives as of 2020 are described in the last two rows of Table 4-1. Note that the CAAQS values are made more stringent (lowered to 65 ppb) starting in 2025.

Table 4-1. Characterization of the phased approach to the KPI for SO_2 for human health.

Exposure Year	KPI Threshold	KPI Percentile	KPI Averaging Time	"Plain language" KPI
2017	75 ppb	97th	3 years	The average of the 1-hour daily maximum on the 11th worst day in each of 2015, 2016, 2017
2018	75 ppb	97.5th	3 years	The average of the 1-hour daily maximum on the 10th worst day in each of each of 2016, 2017, 2018
2019	75 ppb	98th	3 years	The average of the 1-hour daily maximum on the 8th worst day in each of 2017, 2018, 2019
CAAQS 2020-2024	70 ppb	99th	3 years	The average of the 1-hour daily maximum on the 4th worst day in each of three consecutive years
CAAQS 2025+	65 ppb	99th	3 years	The average of the 1-hour daily maximum on the 4th worst day in each of three consecutive years

4.2.1 What levels of SO2 did we observe at residential air monitors?

The levels of SO_2 in the residential areas of Kitimat and Kitamaat Village change on an hourly basis. Despite being variable, the levels of SO_2 are below 1 ppb in more than half of the hours of each year, at all three sites. Even when considering *only the worst hour of each day*, the average concentration in that worst hour is less than 1 ppb in more than half of the days at each site in each year.

Due to the nature of meteorological conditions and other variables, there are relatively infrequent excursions of the SO_2 concentration above 10 ppb. For the period 2016-2018, the maximum hourly averaged concentration for all stations (44.7 ppb) occurred at Riverlodge Station (Lower Kitimat) in 2017.

The series of figures below (Figure 4-2 to Figure 4-7) show selected histograms of the hourly averaged concentrations at the three residential monitoring stations. For each station, the histograms are shown below for the most recent year (2018). Each histogram is first shown at the full scale, followed by the same histogram with a "zoomed in" view with y-axis, to allow a clearer view of the infrequent values above 1 ppb. The same types of histograms for the three stations for the years 2016 and 2017 are provided in Human Health Appendix 4.

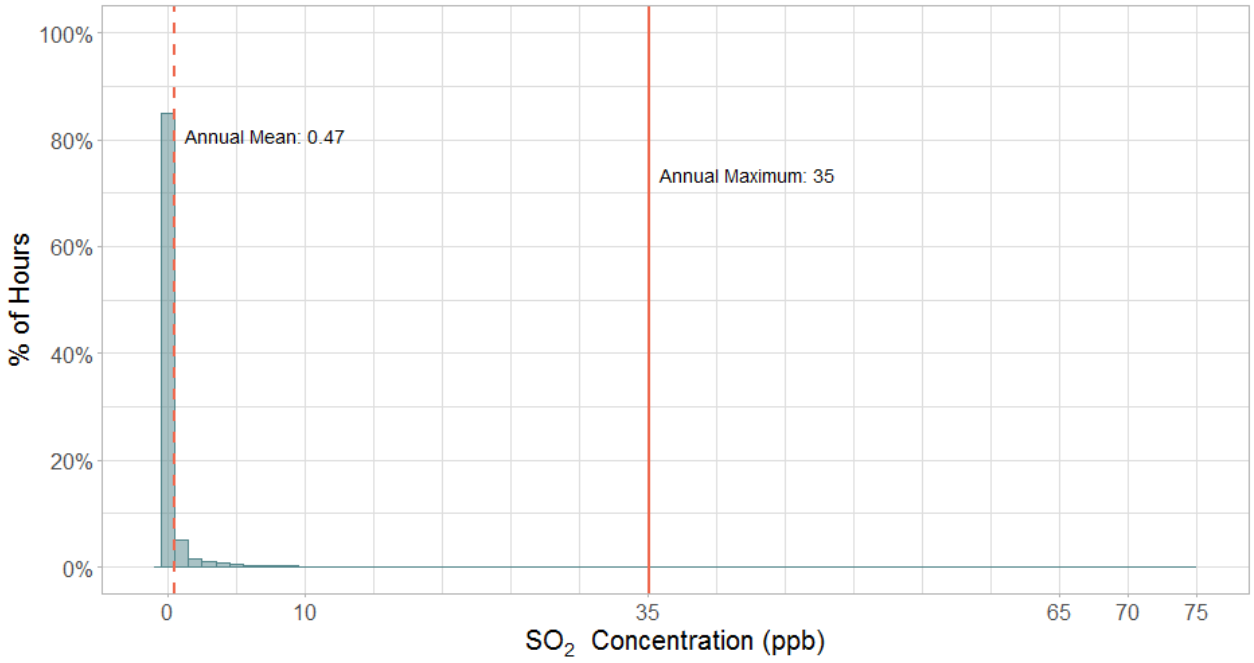


Figure 4-2. Histogram of hourly averaged SO_2 concentrations (Riverlodge, 2018).

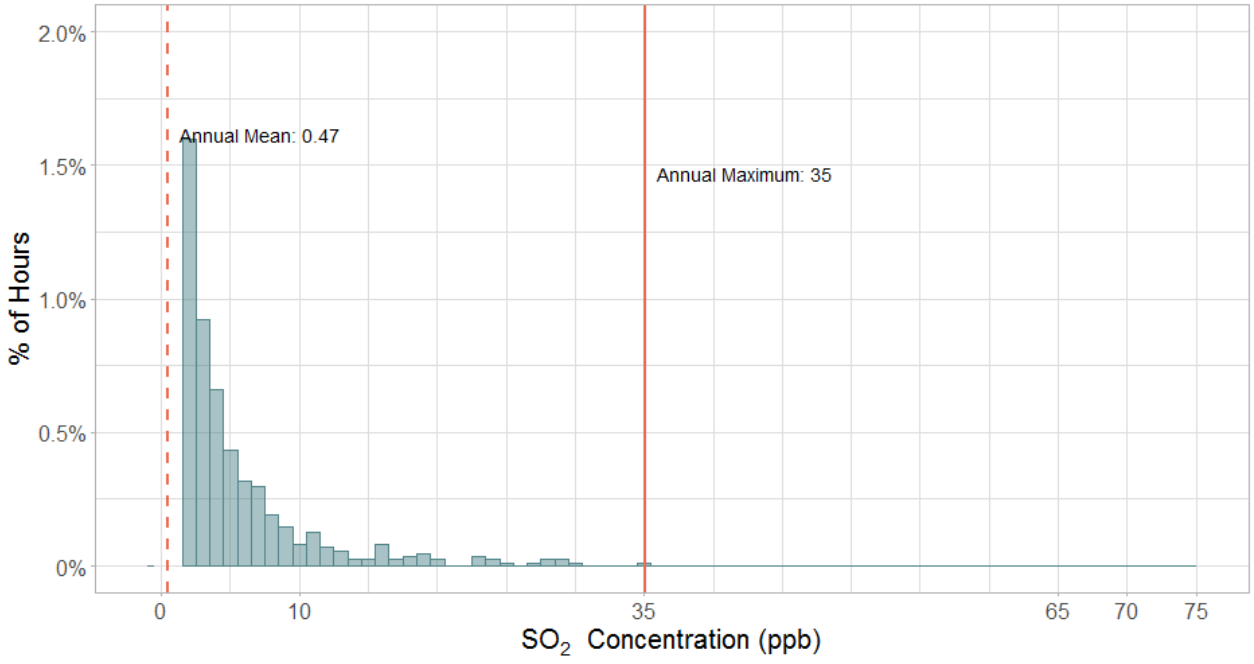


Figure 4-3. Histogram of hourly SO_2 concentrations with y-axis cut off at 2% (Riverlodge, 2018). Note: The first two histogram bars are not shown because they exceed the limit of the y-axis.

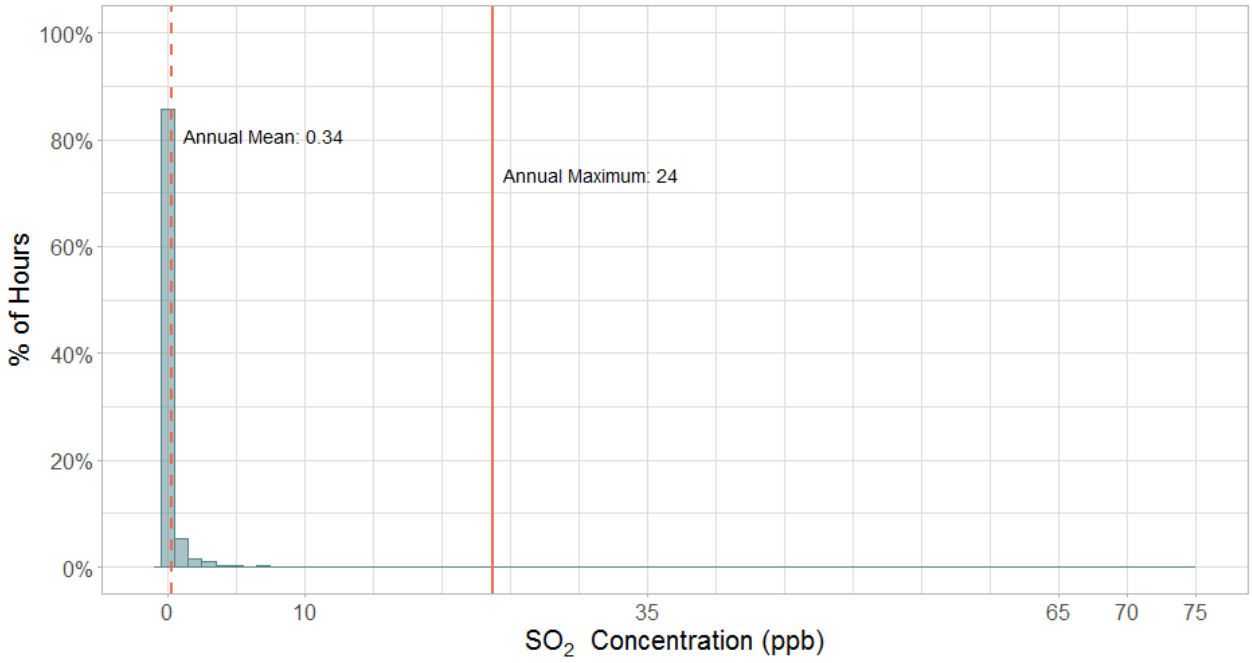


Figure 4-4. Histogram of hourly averaged SO_2 concentrations (Whitesail, 2018).

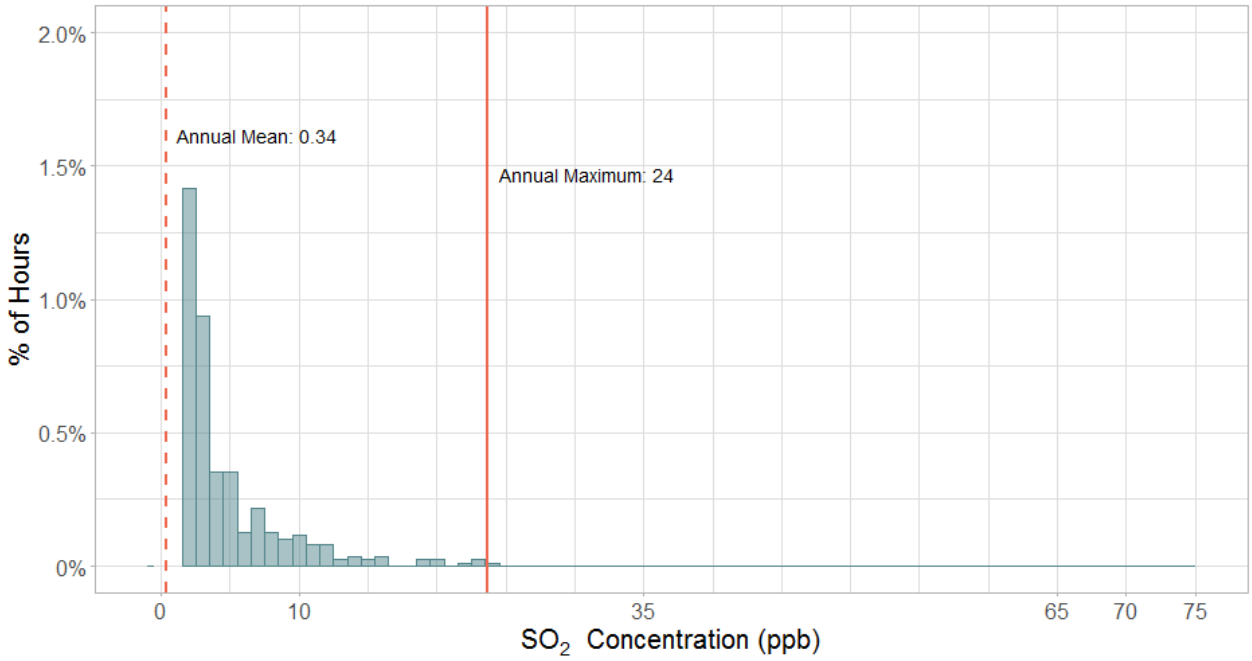


Figure 4-5. Histogram of hourly SO_2 concentrations with y-axis cut off at 2% (Whitesail, 2018). Note: The first two histogram bars are not shown because they exceed the limit of the y-axis.

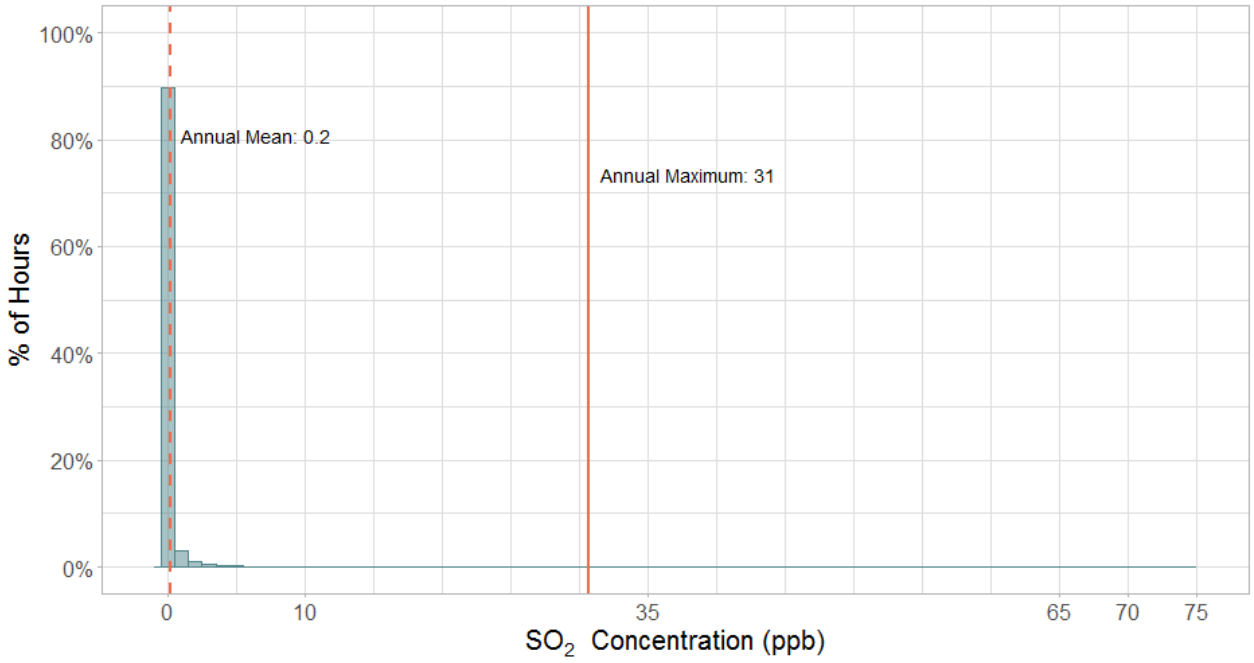


Figure 4-6. Histogram of hourly averaged SO_2 concentrations (Kitamaat Village, 2018).

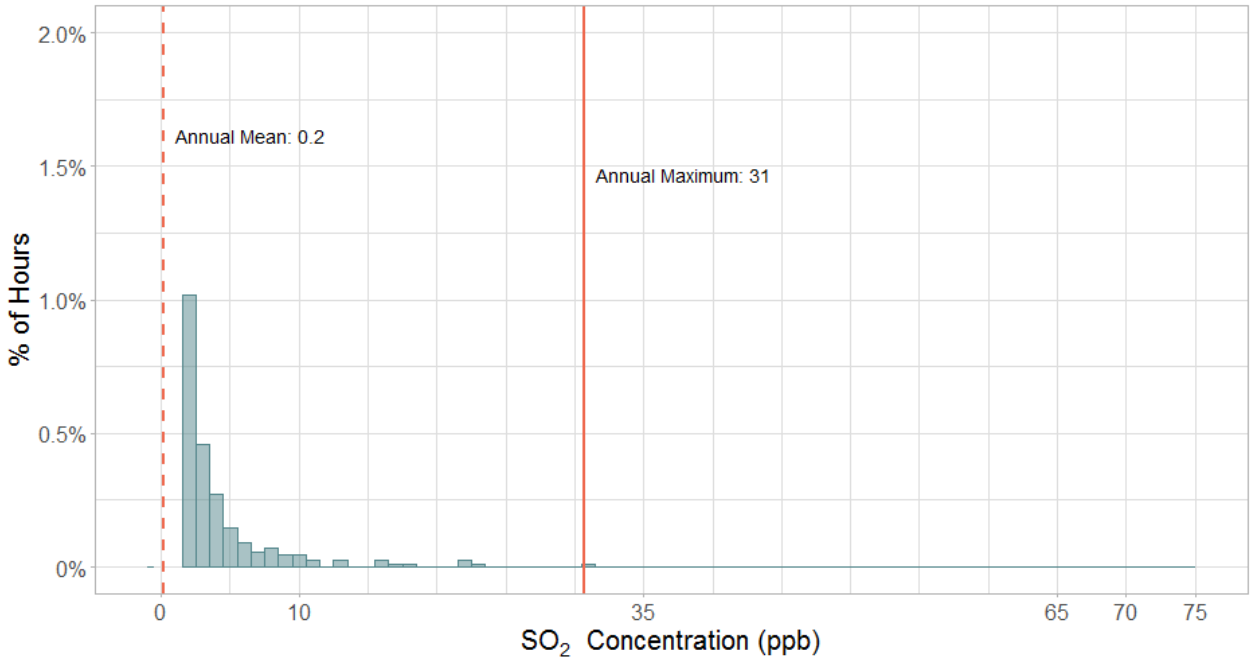


Figure 4-7. Histogram of hourly SO_2 concentrations with y-axis cut off at 2% (Kitamaat Village, 2018). Note: The first two histogram bars are not shown because they exceed the limit of the y-axis.

For the purposes of the B.C. IAQOs, and the CAAQS, the relevant measurement of air concentration is the daily maximum of the 1-hour averages of each day (i.e., the worst hour of each day, as measured by its average concentration). For brevity, this is also known by the abbreviation D1HM (daily 1-hour maximum). The figures below (Figure 4-8 to Figure 4-13) show the histograms of the daily maxima values (the D1HMs) for each monitoring station for the year 2018. The 97.5th percentile value of the D1HMs is also shown for each station, but only for 2018. For the purposes of the KPI calculations, a three-year average is used. The same types of histograms for the years 2016 and 2017 are provided in Human Health Appendix 4.

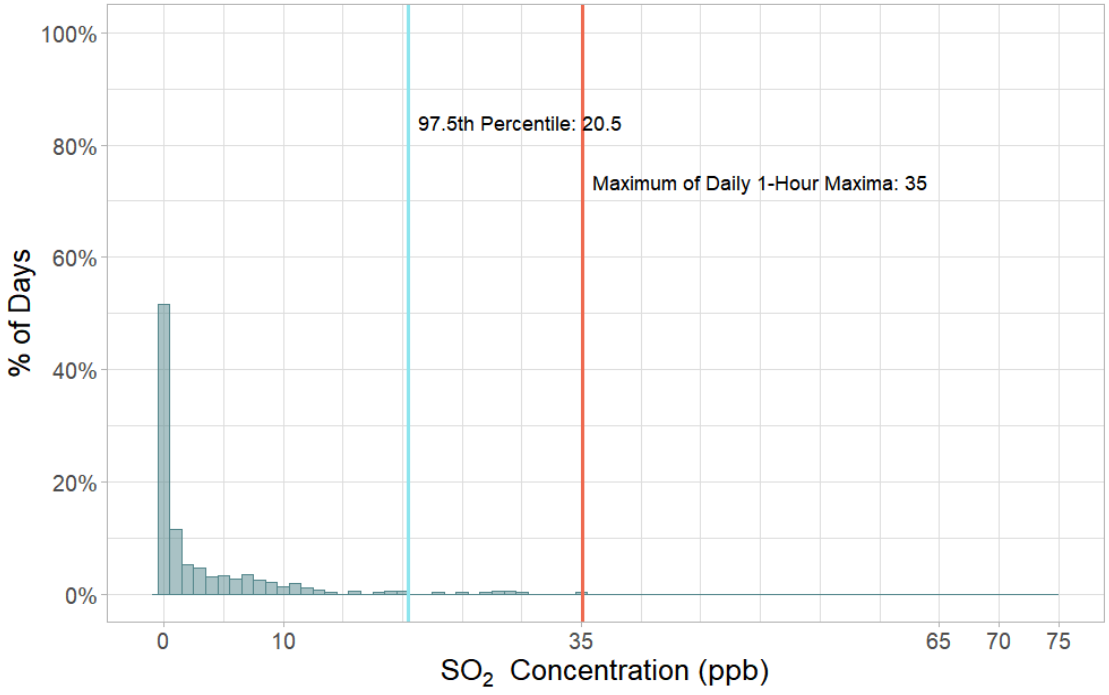


Figure 4-8. Histogram of D1HM SO_2 concentrations (Riverlodge, 2018).

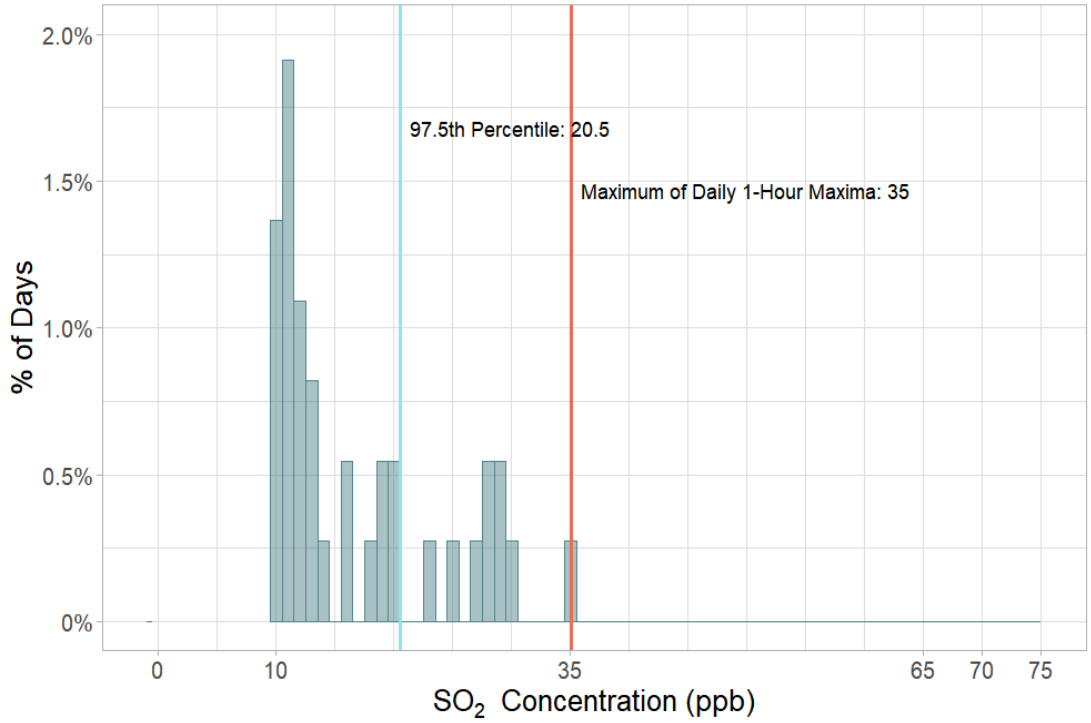


Figure 4-9. Histogram of D1HM SO_2 concentrations with y-axis cut off at 2% (Riverlodge, 2018). Note: The first ten histogram bars are not shown because they exceed the limit of the y-axis.

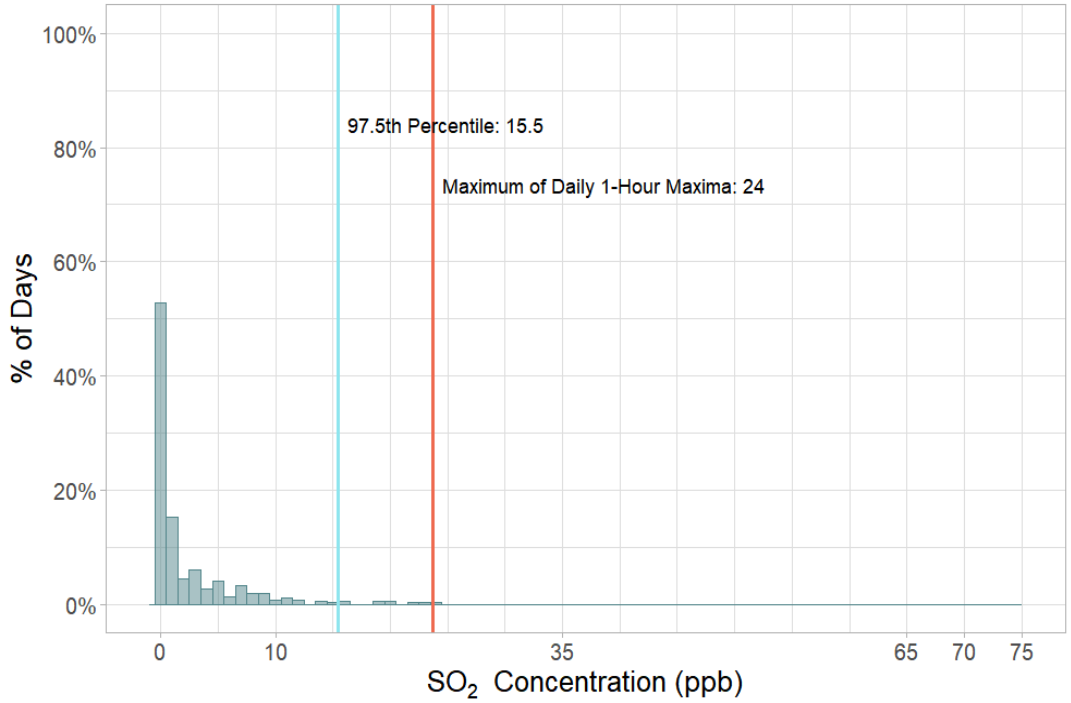


Figure 4-10. Histogram of D1HM SO_2 concentrations (Whitesail, 2018).

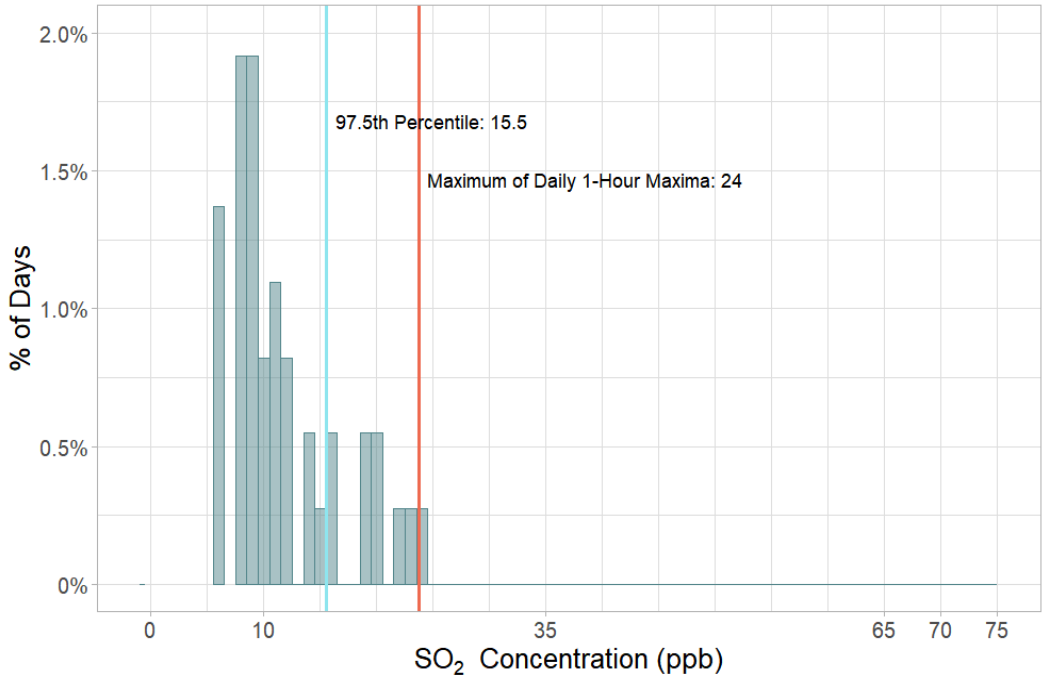


Figure 4-11. Histogram of D1HM SO_2 concentrations with y-axis cut off at 2% (Whitesail, 2018). Note: The first six and the eighth histogram bars are not shown because they exceed the limit of the y-axis.

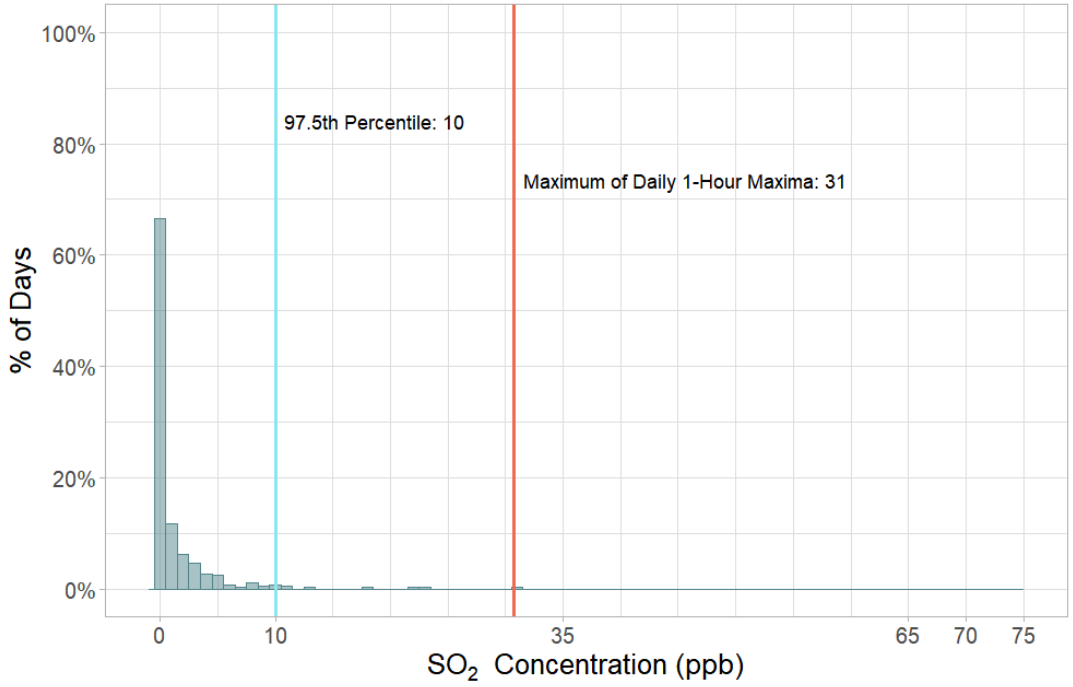


Figure 4-12. Histogram of D1HM SO_2 concentrations (Kitamaat Village, 2018).

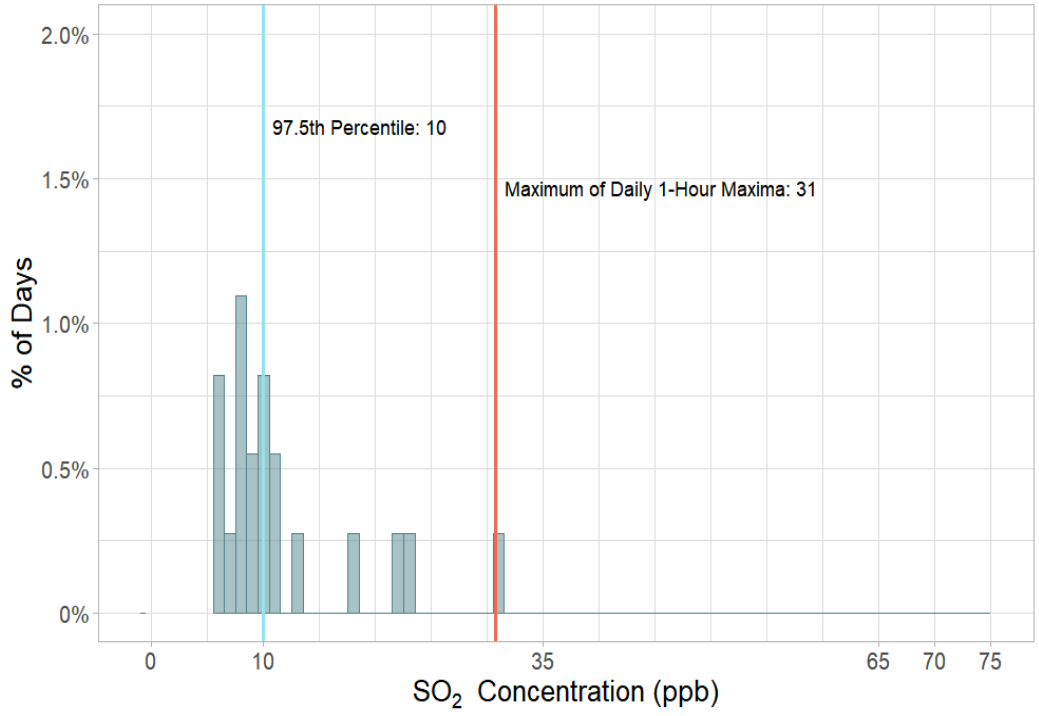


Figure 4-13. Histogram of D1HM SO_2 concentrations with y-axis cut off at 2% (Kitamaat Village, 2018). Note: The first six histogram bars are not shown because they exceed the limit of the y-axis.

Table 4-2, Table 4-3 and Table 4-4 demonstrate the upper percentiles of SO_2 concentrations (as reflected by the D1HM) for the years of 2015-2018, at all three sites.

Table 4-2. Riverlodge Monitoring Station: distribution (percentiles) of daily 1-hour maximum SO_2 concentrations.

Percentile	Xth Worst Day	SO_2 Concentrations (ppb)			
		2015	2016	2017	2018
95%	19th	4.3	9.9	11.0	13.0
97%	11th	6.3	12.9	15.5	19.7
97.5%	10th	6.4	13.8	16.8	20.5
98%	8th	7.1	14.4	17.0	24.7
99%	4th	11.4	22.1	28.0	29.2
100%	1st	20.7	31.8	44.7	35.1

Table 4-3. Whitesail Monitoring Station: distribution (percentiles) of daily 1-hour maximum SO_2 concentrations.

Percentile	Xth Worst Day	SO_2 Concentrations (ppb)		
		2016	2017	2018
95%	19th	7.7	8.7	10.6
97%	11th	11.0	12.1	14.2
97.5%	10th	12.2	12.7	15.5
98%	8th	13.2	14.9	16.0
99%	4th	14.9	21.4	20.0
100%	1st	37.0	40.7	23.7

Note: there were extensive missing data for 2015 at Whitesail monitoring station. As a result, the year 2015 is not included.

Table 4-4. Kitamaat Village Monitoring Station: distribution (percentiles) of daily 1-hour maximum SO_2 concentrations.

Percentile	Xth Worst Day	SO_2 Concentrations (ppb)			
		2015	2016	2017	2018
95%	19th	2.1	6.2	5.3	5.6
97%	11th	3.0	8.4	6.1	8.9
97.5%	10th	3.0	8.6	6.4	10.0
98%	8th	3.3	10.8	7.1	10.4
99%	4th	4.3	19.5	11.7	18.3
100%	1st	38.5	36.6	14.1	30.7

4.2.2 How do these observations compare to the Human Health Key Performance Indicator?

The human health KPI is based on maintaining concentrations of SO_2 below a threshold value for a significant proportion (i.e., 97% or 97.5%) of the year. This threshold value is applied to the worst

hour of the day (i.e., the hour with the highest average concentration of SO_2). The specific implementation is described as part of the B.C. IAQO specifications (B.C. Ministry of Environment and Climate Change Strategy 2018).

In 2017, the KPI requirement is that the worst hour of the day be below the threshold value 97% of the time, when averaged over the period 2015-2017. When converted to days, this means that the average of the worst hours on the 11th worst days of each year must be below 75 ppb.

In 2018, the KPI requirement is that the worst hour of the day be below the threshold value 97.5% of the time, when averaged over the period 2016-2018. When converted to days, this means that the average of the worst hours on the 10th worst days of each year must be below 75 ppb.

The tables below provide the relevant statistic for each site and for each year. The table also provides the three-year average of this statistic which is the value to be compared to the human health KPI threshold value. The three-year average is compared to the threshold for each monitoring location. The KPI applies to the three sites collectively, such that the KPI threshold must be met ***at all three sites***, for the human health KPI to be attained.

As seen in Table 4-5, the 97th percentile D1HM SO_2 concentration was below the KPI threshold in each of the included years (2015-2017) at each of the three sites. The year 2015 is not applied for the Whitesail monitoring station (Upper Kitimat) due to technical problems with the monitor leading to loss of valid data. For that station, the two-year average of 2016 and 2017 is compared to the KPI. As the averages are below the KPI threshold for all three sites, the KPI is attained for 2017.

Table 4-5. Comparison of monitoring results to the KPI for Human Health for 2017.

Station	Percentile (Xth Worst Day)	SO_2 Concentrations (ppb)					Three-Year Average Below Threshold?
		2015	2016	2017	Three-Year Average	KPI Threshold (2017)	
Riverlodge	97.0% (11th)	6.3	12.9	15.5	11.6	75.0	Yes
Whitesail	97.0% (11th)	n/a	11.0	12.1	11.6[a]	75.0	Yes
Kitamaat Village	97.0% (11th)	3.0	8.4	6.1	5.8	75.0	Yes
Overall Attainment of Human Health KPI for 2017 (all three residential sites met KPI)							Attained

[a] There were missing data in 2015 for Whitesail monitoring station. The extent of the missing data was such that the data were "invalid" for the purposes of applying the B.C. IAQO. As such, the KPI calculation for Whitesail in 2017 was based on the average of the values for 2016 and 2017. All three years were used for Riverlodge and Kitamaat Village.

As seen in Table 4-6, the 97.5th percentile D1HM SO_2 concentration was below the KPI threshold in each of the three years (2016-2018), and at each of the three sites. As a result, the average is below the KPI threshold and the KPI is attained for 2018.

Table 4-6. Comparison of monitoring results to the KPI for Human Health for 2018.

Station	Percentile (X^{th} Worst Day)	SO_2 Concentrations (ppb)					Three-Year Average Below Threshold?
		2016	2017	2018	Three-Year Average	KPI Threshold (2018)	
Riverlodge	97.5% (10^{th})	13.8	16.8	20.5	17.0	75.0	Yes
Whitesail	97.5% (10^{th})	12.2	12.7	15.5	13.5	75.0	Yes
Kitamaat Village	97.5% (10^{th})	8.6	6.4	10.0	8.3	75.0	Yes
Overall Attainment of Human Health KPI for 2018 (all three residential sites met KPI)							Attained

4.2.3 Spatial Representativeness of the Monitoring Network

As described in Sections 3.1.2.2 and 3.1.3.7, the Riverlodge monitor was sited to represent the highest SO_2 concentrations within the town of Kitimat. The Phase 1 monitoring network optimization concluded the Riverlodge monitor is in the most suitable location to continue to represent the highest SO2 concentrations in Kitimat under the post-KMP. The Phase 2 network optimization, based on 2016-2018 CALPUFF results and the latest SO_2 monitoring data, will reevaluate the conclusions of the monitoring network optimization. While further data analysis is needed to complete the phase 2 network evaluation, the new CALPUFF results indicate that the Riverlodge monitor site is near the highest ranked locations within the town of Kitimat (Figure 3-22).

The Phase 1 network evaluation concluded the Kitamaat Village monitor is in the most suitable location to represent the highest SO_2 concentrations in Kitamaat Village. The 2016-2018 CALPUFF model prediction of the most suitable location for measuring the highest concentrations within Kitamaat Village is along the western shoreline of Kitamaat Village, and the Kitamaat Village monitor is located along this western boundary.

4.2.4 Meteorological events giving rise to elevated levels of SO_2 in Kitimat and Kitamaat Village

Elevated SO_2 levels in Kitimat and Kitamaat Village are rare because typical meteorological conditions result in the SO_2 plume traveling north from the smelter (positioned west of the western boundary of Kitimat) or south from the smelter (positioned west of the western boundary of Kitamaat Village along the western shoreline of the Douglas channel). Certain meteorological conditions are required for elevated SO_2 concentrations to reach Kitimat or Kitamaat Village and their associated SO_2 monitors (Riverlodge and Kitamaat Village) such as stagnant wind conditions during temperature inversions, steady wind direction directly from the smelter to the monitor, and shifting wind direction. This last case of shifting wind direction beginning out of the south and shifting out of the north can result in the smelter SO_2 plume traveling north / northwest of Kitimat, then circling eastward (just north of Kitimat) and south into Kitimat. Wind directions beginning out of the north and then shifting to blow from the west or southwest can cause elevated concentrations at Kitamaat Village.

4.3 What Did We Learn, and Did We Make Any Adjustments to the EEM Program?

4.3.1 Uncertainty in the STAR: ability of CALPUFF to predict residential SO_2 concentrations

Due to the insertion of a new KPI (which is based on measurements at monitoring stations) and the determination to not further apply the informative indicator, the key uncertainty (HH-1 from Table 10.3-1) in the STAR related to the ability of CALPUFF to adequately represent residential SO_2 concentrations *is no longer applicable* for the human health component of the SO_2 EEM.

4.3.2 Uncertainty in the STAR: comparing the assumed peak-to-mean ratios to observations in 2016-2018

In the STAR, the approach to predicting the number of restricted airway events required the assumption of values for the peak-to-mean ratio. This ratio is used to extrapolate from hourly predictions (the output of the air dispersion modelling) to shorter-term peaks within each hour. The shorter-term peaks are expected to be more predictive of human health outcomes. The peak-to-mean ratio was defined as the ratio between the highest 5-minute average concentration within an hour, and the average concentration for the entire hour. During the period of development of the STAR, minute-by-minute data were only available for one monitoring location, Haul Road, which is within the industrial site and therefore is not considered to be a residential monitoring station. These data were used to provide predictions for the 5-minute peaks in the residential areas within the STAR. This assumption was identified in the STAR as a key uncertainty (HH-2 in Table 10.3-1 of the STAR) to be resolved. Resolution of this uncertainty would determine whether the use of data from Haul Road could systematically lead to under-prediction or over-prediction of the level of the peaks of SO_2 concentration at residential locations.

Although the modelling approach employed in the STAR is no longer being applied in the EEM or in this comprehensive review, the data to estimate the peak-to-mean ratio are now available. Table 4-7 provides various statistics of the peak-to-mean ratios at each of the three residential monitoring stations as well as the monitoring stations at Haul Road, for the years 2016-2018. The final rows of the table contain the three-year averages of each of the statistics at each site.

Table 4-7. Peak-to-mean ratios at residential stations and the Haul Road station.

Site	Year	Mean	95th Percentile	99th Percentile	Max
Riverlodge	2016	1.5	2.2	3.5	6.4
	2017	1.4	2.0	3.4	7.5
	2018	1.4	2.0	3.3	7.6
Whitesail	2016	1.4	1.8	2.8	7.7
	2017	1.5	2.2	3.0	5.5
	2018	1.4	1.7	2.9	7.2
Kitamaat Village	2016	1.4	1.7	2.5	6.2
	2017	1.4	1.7	2.3	4.7
	2018	1.4	1.8	2.4	5.4
Haul Road	2016	1.8	3.7	5.2	8.6
	2017	1.9	3.9	5.5	9.1
	2018	1.9	3.9	5.6	8.6
Riverlodge	3-Year Average	1.4	2.1	3.4	7.2

Site	Year	Mean	95th Percentile	99th Percentile	Max
Whitesail	3-Year Average	1.4	1.9	2.9	6.8
Kitamaat Village	3-Year Average	1.4	1.7	2.4	5.4
Haul Road	3-Year Average	1.9	3.8	5.4	8.7
Haul Road largest peak-to-mean ratio for all years and on average?		YES	YES	YES	YES

Based on Table 4-7, the distribution of peak-to-mean ratios for Haul Road yields consistently higher values for key statistics (mean, 95th percentile, 99th percentile, maximum) of the peak-to-mean ratio on a year-by-year comparison and when considering a three-year average of each of these statistics.

With this information for 2016-2018, it is reasonable to assume that the use of peak-to-mean ratios from the Haul Road monitoring station in the STAR led to some over-estimation of the distribution of peak concentrations in the residential areas when compared with using observed peak-to-mean ratios from the residential monitors. In over-estimating the peak concentrations, this assumption contributes to the potential to over-estimate the number of restricted airway events, whose likelihood was assumed to increase with increasing peak concentrations, based on the dose-response analysis applied in the STAR.

4.3.3 Adjustments to the SO_2 EEM Program

In 2016, the Province of British Columbia adopted an IAQO. This objective was established as 75 ppb for hourly averaged concentration of SO_2. This IAQO, adopted in December 2016, is applied in the EEM for the years 2017-2019. From the year 2020 forward, the IAQO value is replaced by the CAAQS values of 70 ppb and 65 ppb (starting in 2025).

Given the changes already implemented within the SO_2 EEM Program, and with the structure in place, there is no need to consider modifications to the SO_2 EEM Program or the health KPI as it will become aligned with the CAAQS starting in 2020 and become more stringent (65 ppb) in 2025.

4.3.4 Shift away from the informative indicator

Through the course of the SO_2 EEM Program, a shift occurred from relying upon an informative indicator to a KPI. The informative indicator used predictions based on air dispersion modelling, exposure assessment, and dose-response analysis.

The availability of a 2016 Human Health Risk Assessment of Sulphur Dioxide, conducted by Health Canada, for ambient SO_2, and the corresponding development of the CAAQS, allowed for the transition to a KPI that is aligned with the interim B.C. IAQO and the similar values that were adopted as part of the CAAQS process.

The use of the current KPI has the advantages of: a) being based on actual observations from monitoring data within the residential communities; and b) clear thresholds and protocols for determining attainment with the KPI. The informative indicator did not have these qualities.

4.4 What Do We Recommend for the EEM Program Going Forward?

Going forward, the KPI for the EEM Program will shift toward alignment with the CAAQS for SO_2. As such, there is no basis for a recommendation for changes to the quantitative basis for the existing KPI since it is in the process of changing according to the adoption and further adjustment of the CAAQS.

5 Review Results for Vegetation

5.1 What Did We Set Out to Learn?

The SO_2 EEM Vegetation Program was designed to monitor the potential effects of the modernized smelter on plants in the Kitimat Valley. The vegetation program centered around two measures—a visual inspection of plants at an array of sites throughout the valley and the sulphur content of current year western hemlock needles collected at those same sites. Visual inspections have been conducted every year or two since about 1970 and are designed to detect visible injury due to hydrogen fluoride (HF) and SO_2 emissions, as well as to document the general health of vegetation, the incidence and severity of diseases and insect pests, and the effects of other environmental stressors, such as drought, physical disturbance, and growing season conditions. Sampling of needles for fluoride (F) started at about the same time with S analysis added at a later date. The S content of needles was used in conjunction with F content to integrate the exposure to pollutants at the site, as mediated by uptake by vegetation. Concentrations of F and S in needles were also used as a method to map the dispersion of pollutants from the VSS smelter.

Based on air dispersion modelling in the STAR (ESSA et al. 2013), we developed a KPI related to visible injury of sensitive vegetation due to SO_2. Although the modelling results indicated that visible injury was unlikely to occur, modelled concentrations were high enough to warrant such a KPI, particularly given that the sensitivity of most vegetation in the valley has not been documented through controlled exposure studies. Sulphur content of current year needles of western hemlock was established as an informative indicator.

This comprehensive review will present data and analyses to inform the questions posed in the STAR and to make recommendations for changes in the next phase of the SO_2 EEM Program.

5.1.1 Hypotheses posed in the STAR

Upon implementation of the SO_2 EEM Program, data were collected through the visual inspections and sampling in order to address four hypotheses posed in the STAR.

5.1.1.1 *Question V1: Validation of the dispersion model—are we looking in the right place?*

Two hypotheses were posed under question V1:

- H_1 Post-KMP passive and continuous monitoring measurements show a similar SO_2 concentration distribution to that predicted by the model.
- H_2 Post-KMP passive and continuous monitoring measurements show a different SO_2 concentration distribution to that predicted by the model.

5.1.1.2 *Question V2: How healthy is vegetation in sites with predicted exceedances of critical loads of soil and/or lakes and streams south of Lakelse Lake?*

No hypotheses were proposed under question V2. Vegetation in the vicinity of predicted critical load exceedances was to be inspected.

5.1.1.3 *Question V3: Are plants of public importance showing symptoms in areas with the highest exceedances of soil critical loads?*

Three hypotheses were posed under question V3:

H_1 Negligible or no effects.
H_2 Indirect effects on plants via changes in soil base cations and Al are moderate.
H_3 Indirect effects on plants via changes in soil base cations and Al are significant.

5.1.1.4 *Question V4: Do plants at Kitimat with unknown sensitivity to SO_2 and associated pollutants (acidic deposition) fall within the range of variation in the literature*

Two hypotheses were posed under question V4:

H_1 Yes, the scientific literature accounts for the responses of the most sensitive plants.
H_2 No, symptoms indicate that plants at Kitimat may be more sensitive than those reported in the literature.

5.1.2 EEM Key Performance Indicator

We developed an SO_2 EEM KPI for Visible Injury to Vegetation because, although the modelled SO_2 concentrations in the STAR were below reported thresholds for direct effects on vegetation, they were high enough, given uncertainty in modelling, that the most sensitive of plants might have been injured. Also, if dispersion modelling was in error there could have been immediate acute effects on plants. Since most of the species present in the valley are of unknown sensitivity (through controlled exposure studies), it was possible that some would be more sensitive than what was reported in the scientific literature. The KPI threshold for increased monitoring was "More than occasional symptoms of SO_2 injury outside of Rio Tinto Alcan Kitimat properties, causally related to KMP" with associated actions of assess air monitoring and emissions data to identify potential causes and increase the frequency of visual inspection to annually. This threshold was not equalled or exceeded.

5.1.2.1 *Learning from the Key Performance Indicator*

This comprehensive review integrates the results of visual inspections to assess the effectiveness of the KPI vis-à-vis our understanding of the effects of smelter emissions on vegetation in the Kitimat Valley.

5.1.2.2 *Evaluation of the Key Performance Indicator*

Based on the analyses in this comprehensive review, we have assessed the KPI and made recommendations for change.

5.1.3 EEM informative indicator

The EEM informative indicator continued the historical collection and analysis of S concentrations in needles to try to detect spatial patterns associated with dispersion of the plume from the smelter. Because of the length of the analytical record, changes associated with increased emissions and new dispersion patterns could be compared to the patterns under the VSS smelter operational characteristics. The threshold for increased monitoring was "An increase of more than 1 standard

deviation (from pre-KMP baseline data) in 20% of the sites for 3 consecutive years, causally related to KMP. This threshold was not equalled or exceeded.

5.1.3.1 *Learning from the informative indicator*

The comprehensive review integrates the results from the informative indicator with other measures, such as dispersion model output, active and passive air sampling, and visual observations to assess potential effects of the smelter on vegetation.

5.1.3.2 *Evaluation of the informative indicator*

The informative indicator is evaluated with regard to its relationship with active and passive air monitoring and the spatial distribution of S concentration in needles in the Kitimat Valley.

5.1.4 Other questions that have emerged since the development of the EEM Program

5.1.4.1 *Evidence from the literature for more sensitive indicators of potential effects on vegetation*

Before considering the evidence for more sensitive indicators, it is important to consider the potential impact of climate change on vegetation in the area of interest as overall ecosystem health will be affected by changes in climate during the lifetime of the modernized smelter. By 2055, average temperatures in the Skeena region are expected to increase by up to 3.5C over the present during the growing season (Foord 2016), with increases in precipitation, primarily in the winter, but increases in evapotranspiration in the summer due to warmer temperatures. Extreme precipitation events, both in terms of excess (winter rain instead of snow) and deficit (summer drought) are expected to increase in frequency. Such changes will affect the vegetation of the Kitimat Valley, increasing stress on forested vegetation and changing habitat suitability. Geiser et al. (2019) point out that hot, dry temperatures will become an important driver of cyanolichen success.

Thresholds for impacts to understory and overstory vegetation

Although there is little active research on the sensitivity of plants to SO_2, and most of it addresses plants that are tropical or subtropical and/or agricultural plants, reviews of thresholds used by regulatory and advisory agencies have been conducted. No relevant new experimental or observational results have been reported since the STAR that have changed the threshold values or standards in use in the United States and Europe. Both the U.S. Environmental Protection Agency (2018) and the European Union (2008) have recently reviewed their standards set to protect natural ecosystems from the effects of SO_2. Both organizations have left their standards in place. The U.S. secondary National Ambient Air Quality Standard (NAAQS) to protect vegetation continues to be an exposure of 500 ppb averaged over three hours, not to be exceeded more than once per year. The European Union Air Quality Standard to protect vegetation of 20µg/m^3 (7.6 ppb) for both annual average and winter (October 1-March 31) average remains in effect. The EU continues to accept the recommendation of WHO (2000) of a critical level to protect lichens of 10 µg/m^3 annual average (3.8 ppb). The CAAQS have established a standard of an annual average of 5 ppb (changing to 4 ppb in 2025) to protect natural ecosystems (CCME, 2016 https://www.ccme.ca/en/resources/air/air/sulphur-dioxide.html). This standard replaced the B.C. Pollution Control Objectives cited in the STAR.

Controlled experimental studies of SO_2 effects on crop plants such as tomato (Padhi and Swain 2013), pomegranate (Swain and Padhi 2013), *Arabidopsis* (Choi et al. 2014), and grape (Considine and Fyer 2015) continue to expand knowledge of the direct effects of SO_2, however the concentrations used in the exposure studies far exceed those monitored at Kitimat.

Hu et al. (2016) used sap flow measurements to estimate whole tree stomatal conductance and estimated flux of four pollutants, including SO_2, to three species of urban trees, *Schima superba* (no English common name), *Eucalyptus citriodora* (lemon-scented gum) *and Acacia auriculaeformis* (earleaf acacia). The exposures were from ambient air; thus all four gases were present at the same time. They determined that under the climate conditions of southern China, uptake of SO_2 was greatest in the spring and least in the summer and autumn. The concentration of SO_2 was an annual average of about 12 μg/m^3 (4.6 ppb). Exposure to SO_2 did not injure the trees.

Baciak et al. (2015), offer a brief review of the effects of several air pollutants on woody plants, but do not report new, original research. Their conclusions are in concert with past findings.

Progress has been made in determining critical loads and associated effects on forests (e. g. Ouimet et al. 2006; Aherne and Posch 2013; Blett et al. 2014; Duarte et al. 2013; Fenn et al. 2011; Kosiba et al. 2018; Ouimet et al. 2001; Pardo et al. 2018; Williston et al. 2016).

Most recently, Horn et al. (2018) used forest inventory data for over 1.4 million trees and measurements of deposition of nitrogen (N) and S from the NADP to model the growth and survival relationship of 71 tree species in the US. The primary focus of the study was on the effects of N deposition; however, they did find that 31 of the 71 species showed decreasing growth with increasing S deposition; the other 40 showed no response. The survival of 40 species decreased with increasing S deposition, while 31 did not show a relationship between survival and S deposition. Their models were constrained to prevent an increase in growth or survival which the authors believe is consistent with the role S plays in acidification. Ten species that occur in the Kitimat Valley were included in the study (although trees from the Kitimat Valley were not part of the sample). Pacific silver fir, Douglas-fir, and paper birch showed a decline in growth with increasing S deposition (ranging from 0-5, 0-15, and 0-25 kg S/ha/yr respectively[26]). Lodgepole pine, paper birch, and quaking aspen showed decreased survival with increasing S deposition (ranging from 0-4, 0-15, and 0-30 kg S/ha/yr respectively). Subalpine fir, western larch, western redcedar, western hemlock, and mountain hemlock did not show any relationship between S deposition and growth or survival. Overall, they found growth decreased with S deposition at rates of -1.6% per kg change in deposition of S/ha/year. In the Pacific Northwest, growth effects were less than the overall rate. In the western US, tree survival did not change with S deposition. Analysis at the regional or national scale does remove factors such as climate, habitat suitability, and forest management that can be important locally, thus the results apply to regional trends but not necessarily to every locality.

Clark et al. (2019) used plant community data from over 14,000 plots across the U.S. along with deposition data and estimates from NADP and the U.S. EPA's Community Multi-scale Air Quality Modeling System[27] (CMAQ) (Schwede and Lear 2014) to calculate critical loads of N and S for 198 of the 348 herbaceous species examined (the remaining 150 species did not have sufficiently robust relationships to be included). Of the 198, 123 were found to have a decreased probability of

[26] Total S deposition expressed as SO_4^{2-} is three times the S deposition rate.
[27] For a description of CMAQ see https://www.epa.gov/cmaq

occurrence with increasing S deposition (ranging from 0 to about 42 kg S/ha/yr), 32 showed no response, and 43 species had an increased probability of occurrence with increasing S deposition. About 50% of the species that increased were from historically polluted areas leading the authors to postulate that where deposition is high, plant communities may have shifted to acid-tolerant species. They also conclude that the wide range of responses indicates that local environmental and edaphic factors are likely important in shaping the vulnerability of plant communities.

Thresholds for effects on lichens and mosses

Lichens and mosses have been recognized as sensitive indicators of air pollution for over 100 years (Nash 1971, 1976) and have been used as bioindicators of gaseous pollutants or bioaccumulators of metals in many locations around the world (e.g. Cowden and Aherne 2019; Geiser 2004; Leavitt and St. Clair 2019; Stolte et al. 1993). Pescott et al. (2015) provide an excellent review of the direct and indirect effects of air pollutants on lichens and bryophytes.

Lichens and mosses are sensitive to both wet and dry deposition associated with SO_2 exposure. Direct effects may center on the dry deposition of SO_2 gas or wet deposition (acidic deposition). However, indirect effects, such as acidification of substrates that support lichens and mosses, are also important, particularly to groups such as cyanolichens growing on naturally acidic substrates such as conifer boles and branches (Goward and Arsenault 2000). Cyanolichens growing on conifers are an important component of forests, particularly old growth forests, in places such as the Kitimat Valley, thus SO_2 exposure is of concern, as is habitat loss from logging and industrial development, or from possible changes in habitat suitability due to SO_2 exposure, SO_4^{2-} deposition, and climate change.

The Kitimat Valley has a long history of industrial and logging activity and it is likely that lichen populations have been affected for 60 years or more. Reid Collins and Associates (1978; 1986) conducted a lichen study in the Kitimat Valley in the 1970s and 1980s. They surveyed for the presence of lichens in three zones of pollution (control, light, and heavy, based on the F content of western hemlock needles at the sampling location). They demonstrated a significant relationship between F in western hemlock foliage and the average lichen occurrence per tree. Over 5 years of the detailed study (Reid Collins and Associates 1986) they noted little change in control plots, a continued decline in the main path of the plume, and an increase in lichen occurrence in the lightly polluted area, likely due to a concomitant decrease in F emissions from the VSS smelter that took place during the study. The map included in the 1978 report shows an area of impact on lichen richness and abundance that corresponds to the current plume path modelled by CALPUFF.

A critical level of SO_2 exposure in the form of an annual average concentration of about 4 ppb (10 $\mu g/m^3$) to protect sensitive lichens and bryophytes has been established (e.g. WHO 2000; European Union 2008; CCME 2016 [https://www.ccme.ca/en/resources/air/air/sulphur-dioxide.html]).

There have been significant advances in understanding thresholds of S exposure for lichens, particularly with regard to establishing relationships between SO_4^{2-} deposition and lichen presence, absence, and condition (Cleavitt et al. 2015; Geiser et al. 2019; Glavich and Geiser 2008; Pardo 2010; Will-Wolf et al. 2006, 2015).

The most recent and comprehensive study of SO_4^{2-} deposition, lichens, critical loads, and risk assessment is the work of Geiser et al. (2019). They used species detection data from 8,855 sites in the U.S. coupled with deposition estimates from the CMAQ (Schwede and Lear 2014), to calculate

critical loads for individual lichen species (Geiser et al. *in preparation*). Since they were seeking estimates for regional to national scale critical loads, they averaged deposition estimates over 3 years and used 90% Quantile Regression (Cade and Noon 2003) to limit the influence of environmental factors and factors such as habitat suitability over the thousands of sites they examined.

They found that cyanolichen diversity and abundance dropped rapidly with a decline of 80% at a deposition of 11 kg S/ha/yr (33 kg SO_4^{2-}/ha/yr). They estimate the critical load for the most sensitive cyanolichens to be 2.3 kg S/ha/yr (6.9 kg SO_4^{2-}/ha/yr), the lowest of all the lichen functional groups. They propose national critical loads of 6.0, 2.5, 2.6, and 2.3 kg S/ha/yr (18, 7.5, 7.8, and 6.9 kg SO_4^{2-}/ha/yr) for total species richness, sensitive species richness and diversity, and abundance of forage lichens, and cyanolichen functional groups respectively. They point out that using their method of risk estimation for functional groups is more robust than for individual species. Based on their analysis, they estimate that a low risk (<20%) of extirpation of rare species due to SO_4^{2-} deposition ranges from 4.8 to 48 kg SO_4^{2-} kg/ha/yr and a moderate risk (20-50%) ranges from 12 to 56 kg SO_4^{2-} kg/ha/yr, depending on the species under consideration.

They point out that there are uncertainties associated with the CMAQ model and that other models may well give different deposition estimates. Modelling accuracy and precision may also vary depending on methodology and local influences. Current CALPUFF modelling is subject to uncertainty as the comparison to active and passive air monitoring shows (see Sections 3.1.3.1 and 3.1.3.2 of this report). Also, as scale moves from continental to regional to local, the importance of factors removed by the 90% Quantile Regression, such as the availability of suitable habitat, topography, aspect, weather, and land use, become more important.

Geiser et al. (2019) state that recovery of lichen communities with decreasing deposition does occur and ranges in time from a few years to decades. They note that cyanolichens are not only sensitive to deposition, but also to habitat and they require forest continuity for decades to centuries. Given the decrease in F emissions from the modernized smelter and the previous reports relating F and lichen abundance and richness (Reid Collins and Associates 1978; 1986) some recovery of suitable habitat and lichen populations may occur depending on the relative importance of F versus S emissions.

Recently ENV established plots to document the presence or absence of cyanolichens in the Kitimat Valley (Patrick Williston, personal communication) and to try to relate those observations to modelled SO_2 deposition conducted as part of the STAR.

5.1.4.2 *Evidence to support or alter the present sampling array*

The present sampling array has a number of redundancies and plots that do not contribute to understanding the path of the plume or the flux of SO_2 to vegetation, as reported in Section 5.2.1.2. Concentration of S in hemlock is generally poorly correlated with measures of either smelter emissions or atmospheric concentrations of SO_2 modelled by CALPUFF. The highest correlation between %S in hemlock and measures of SO_2 concentration is 0.535 in 2018 between the 35 tpd emissions scenario 1-hour growing season daylight maximum and %S. A full evaluation of results from the vegetation sampling array can be found in Section 5.2.2.1.

5.1.4.3 *Evidence to support or alter the present sampling array with respect to ecosystems and plant species at risk*

We used the B.C. Conservation Data Centre (CDC) database to identify the spatial distribution of ecosystems and plant species deemed at risk in the study area. An analysis of the sampling array with respect to known occurrences of listed ecosystems and species can be found in Section 5.2.2.2.

5.1.4.4 *Methods from the scientific literature to evaluate vegetation health in the areas of predicted critical load (CL) exceedance*

Evaluating vegetation health in areas of predicted critical load exceedance depends on classical methods used in plant pathology, entomology, and ecology. While plants may express specific symptoms and signs related to pathogens and pests that will be useful, evaluating the health of plant communities subjected to long-term stress from atmospheric deposition and exceedance of critical loads is likely to be best expressed by changes in biodiversity. Recent studies (Aherne and Posch 2013; Baker and King 2010; Clark et al. 2019; Dirnböck et al. 2014; Mitchell et al. 2018; Simkin et al. 2016; Wilkins et al. 2016) have used changes in plant biodiversity to detect or measure the impacts of atmospheric deposition.

Many of the studies that assess changes in plant biodiversity due to deposition focus on measuring change across gradients in N deposition. Simkin et al. (2016) demonstrated a negative relationship between N deposition and species richness using over 15,000 sites across the US. They found the relationship to be common, but not universal due to fine-scale processes that can affect vegetation on a local scale. Wilkins et al. (2016) found significant changes in community composition along an N gradient, even where soil critical load for N was not exceeded, thus changes in biodiversity could contribute to understanding if effects on vegetation communities are occurring at or below the soil critical load. Clark et al. (2019) found a negative association between deposition of S and the occurrence of 51% of the 348 herbaceous species they examined. They do point out that species may respond differently based on local environmental and edaphic conditions. Mitchell et al. (2018) are using changes in plant biodiversity to study possible recovery of grasslands in Scotland where S deposition has decreased; they find some evidence for recovery. Based on these recent studies, plant biodiversity might be an appropriate indicator of soil acidification, perhaps at levels below the soil critical load.

Tree ring chronologies may be a useful tool to detect subtle, long-term effects of pollutant deposition. The chronology provides a look at tree growth over long periods of time and may be correlated with climate as well as other factors that affect tree growth (Cook et al. 1987; Dobbertin 2005; McLaughlin et al. 2002). Recording dendrometers may be used to measure changes in tree diameter, and over time, tree growth, however they would not provide a pre-KMP baseline that could be determined from tree ring studies.

Bunce (1979, 1984, 1985, 1989) measured the growth of western hemlock at many locations in and out of the plume path of the VSS smelter in the Kitimat Valley. He used tree ring measurements to estimate the growth loss (and associated economic loss) due to F emissions from the smelter. Similar techniques were used to assess the potential effects of acidic precipitation and O_3 on tree growth and decline in eastern North America (Cook et al. 1987; McLaughlin et al. 2002).

Recently, tree ring measurements and wood chemistry have been used to document the effects of climate change, pollutant deposition, and forest management on the growth of beech in Europe (Hafner et al. 2015).

In order to use tree ring chronologies to detect changes in growth due to factors such as deposition of pollutants, the effects of climate must be removed, so it will take some time—perhaps a decade or two—post-KMP to establish a growth pattern to assess any potential change in growth associated with increased SO_2 emissions from the modernized smelter.

5.2 What Methods Did We Use?

5.2.1 Data we collected

5.2.1.1 *Ambient Air Monitoring*

Ambient air was monitored at four sites and sampled with passive samplers at many more locations. Results are given in Section 3 of this report. Monitored concentrations did not exceed thresholds established in the scientific literature (Section 5.1.4.1).

5.2.1.2 *CALPUFF simulations (see Section 3.1 and Section 3.2)*

CALPUFF modelling methods are found in Section 3 of this report. In this section, we present methods for vegetation-related output from the modelling. CALPUFF modelling does carry uncertainties with it that may be estimated by comparison with active and passive monitoring of air concentrations and deposition as discussed in Sections 3.1 and 3.2.

CALPUFF modelling results didn't include background concentrations of SO_2 or deposition of SO_4^{2-}. In this section, background concentrations and deposition are detailed in table and figure captions. There are two exceptions: SO_2 concentration isopleths include background and are given in $\mu g/m^3$ as we made direct comparisons to critical levels used in Europe. To convert $\mu g/m^3$ to ppb, divide by 2.614; and in the discussion of the area of the valley that exceeds certain SO_4^{2-} deposition rates of interest, rates are given both with and without background of 3.6 kg SO_4^{2-}/ha/yr.

Figure 5-2 shows the location and identification of vegetation sampling and inspection sites used in the STAR and the SO_2 EEM. Site locations are shown on other maps in this section, but the site identifiers are not included in order to increase the legibility of the maps.

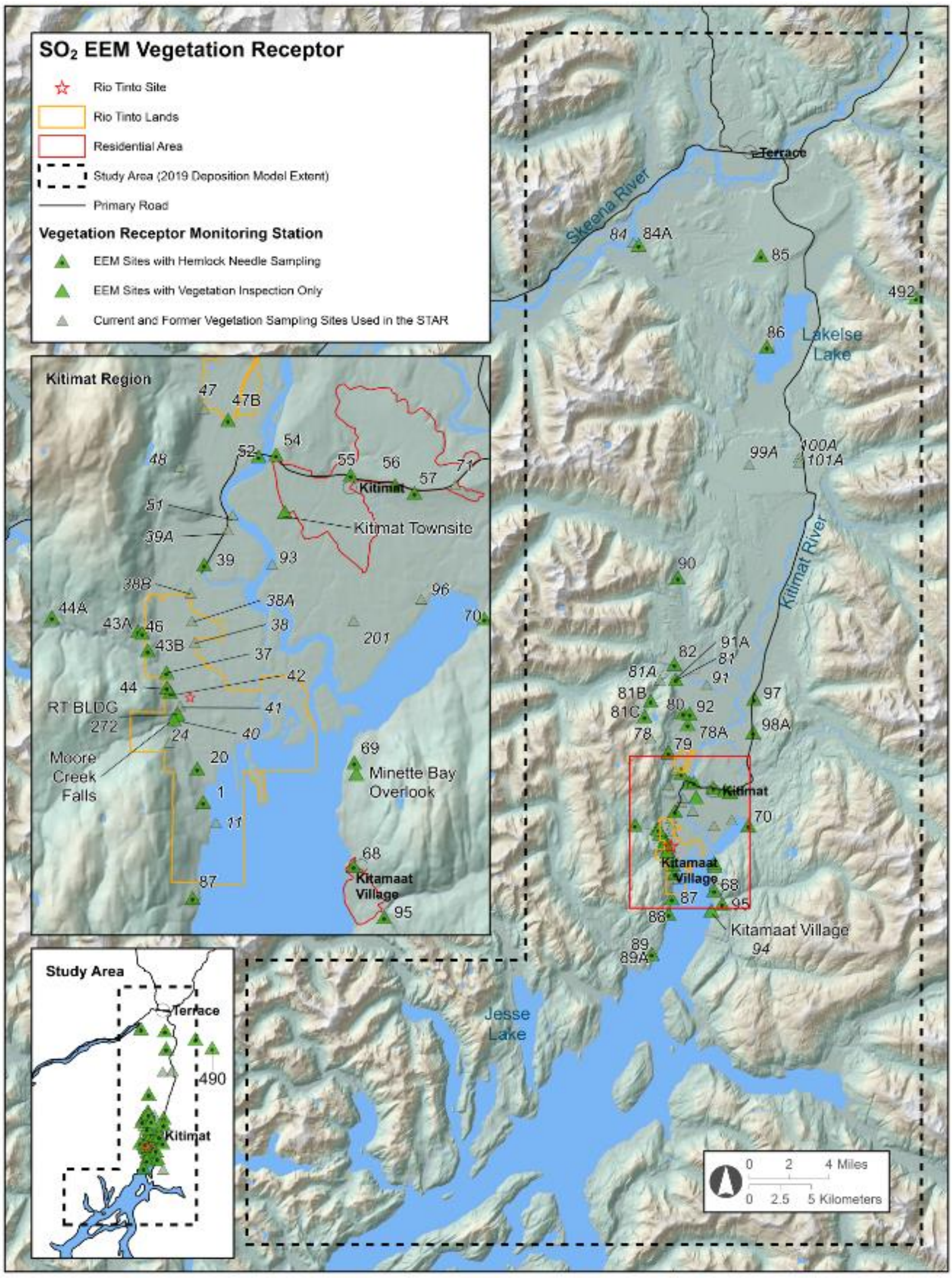


Figure 5-1. The location and identification of vegetation sampling and inspection sites used in the STAR and the SO_2 EEM Program.

Air Concentrations

Vegetation sampling locations were designated receptors in CALPUFF model runs so that SO_2 concentrations of interest, such as 1-hour, 3-hour, and 24-hour maxima; annual and growing season (April 15-October 1) means; and SO_4^{2-} deposition could be output for specific locations where observations and determinations of S in western hemlock needles were made. All three modelling cases—actual emissions, 35 tpd, and 42 tpd—were used. While we did not expect strong relationships with the 35 tpd and 42 tpd scenarios, we examined them as a method to compensate for uncertainty in modelling, particularly to detect under-prediction by CALPUFF. Separate calculations for daylight hours (7 AM to 9 PM) were made as well. Daylight hours were selected based on estimated times of significant photosynthetic activity and gas exchange and are only appropriate for use with growing season time frames.

CALPUFF results for selected measures under the actual emission scenario are shown in Table 5-1. The complete array of concentration measures for each scenario can be found in Vegetation Appendix 5.1. Background SO_2 concentrations of 5.53, 2.80, 1.74, and 0.47 ppb for 1-hour, 3-hour, 24-hour, and annual average (and growing season), respectively, are not included in the SO_2 concentrations listed in the table. However, these background values are considered when evaluating the risk of impacts to vegetation.

Table 5-1. CALPUFF-modelled air concentrations of SO_2 in ppb at vegetation sampling and inspection sites under the Actual Emissions scenario. Background SO_2 concentrations of 5.53, 2.80, 1.74, and 0.47 ppb for 1-hour, 3-hour, 24-hour, and annual (and growing season) average, respectively, are not included in the SO_2 concentrations listed in the table.

	2016					2017					2018			
Plot	1-hour Maximum	3-hour Maximum	Annual Average	Growing Season Average		1-hour Maximum	3-hour Maximum	Annual Average	Growing Season Average		1-hour Maximum	3-hour Maximum	Annual Average	Growing Season Average
	(ppb)													
1	168.0	95.1	7.1	2.9		200.9	160.5	5.9	3.6		148.7	98.5	7.4	3.9
20	151.8	134.4	8.6	5.5		329.5	199.0	8.1	6.9		398.9	262.2	9.6	10.0
37	298.9	104.3	2.1	2.7		452.1	181.1	2.6	4.1		275.6	140.2	2.7	4.4
39	115.1	68.0	4.4	7.1		81.2	54.0	4.4	7.0		60.5	40.2	4.2	6.8
42	216.1	85.3	5.4	4.2		290.4	191.7	4.8	5.1		256.9	132.9	5.3	6.9
43A	68.6	52.5	1.4	1.8		90.8	46.1	1.7	2.5		127.8	75.3	1.9	3.1
43B	111.6	85.9	1.7	2.1		148.6	65.7	1.9	2.9		168.3	80.5	2.3	3.6
44	178.9	158.6	3.4	3.9		269.7	174.0	3.0	4.4		254.4	127.0	3.7	5.8
44A	123.0	41.7	0.7	0.8		100.0	55.0	0.7	1.0		106.7	76.4	0.8	1.2
46	86.9	55.1	1.6	2.1		113.3	49.4	1.9	3.0		124.1	75.3	2.2	3.5
47B	49.8	34.2	2.8	4.3		42.4	34.4	2.9	4.3		45.8	35.6	2.8	4.3
52(A)	52.3	32.7	1.8	2.6		57.3	32.6	1.9	2.7		42.7	28.4	2.0	2.7
54	47.8	26.0	1.5	1.9		60.5	32.7	1.5	2.1		41.0	26.0	1.7	2.1
55	85.9	55.8	0.6	0.7		74.0	50.4	0.6	0.6		35.2	25.4	0.7	0.7
56(A)	70.1	40.6	0.5	0.5		63.2	54.5	0.6	0.5		38.3	26.9	0.6	0.5
57	90.5	70.8	0.5	0.4		65.0	51.5	0.5	0.4		64.3	39.8	0.5	0.5
68	33.3	18.6	0.3	0.3		43.3	25.0	0.3	0.3		20.3	12.0	0.3	0.3
69	78.3	45.4	0.4	0.3		74.0	30.6	0.3	0.3		28.0	18.3	0.3	0.4
70	21.5	14.5	0.2	0.2		15.1	8.9	0.2	0.2		19.2	11.5	0.2	0.3
78 (A)	39.4	28.1	2.3	3.2		45.8	25.3	2.5	3.5		51.5	28.8	2.4	3.5
79	72.9	39.6	3.0	4.7		105.5	41.9	3.3	5.1		71.4	45.9	3.3	5.5
80	50.1	38.5	2.5	3.8		42.5	27.3	2.7	3.8		67.6	30.7	2.6	4.0
81B	103.9	62.4	1.3	1.8		76.7	46.8	1.4	2.1		150.0	108.5	1.6	2.6
81C	40.9	31.0	1.0	1.3		59.4	37.1	1.1	1.7		151.4	98.4	1.4	2.1
82	65.9	50.6	2.3	3.7		84.6	56.6	2.4	3.6		172.1	90.2	2.4	4.0
84 (A) (B)	6.5	5.0	0.1	0.1		5.6	3.8	0.1	0.2		6.8	5.3	0.1	0.1

	2016					2017					2018			
Plot	1-hour Maximum	3-hour Maximum	Annual Average	Growing Season Average		1-hour Maximum	3-hour Maximum	Annual Average	Growing Season Average		1-hour Maximum	3-hour Maximum	Annual Average	Growing Season Average
	(ppb)													
85	11.9	8.3	0.5	0.8		10.4	6.7	0.5	0.8		11.3	8.9	0.5	0.7
86	10.4	7.4	0.7	1.1		8.9	7.8	0.8	1.1		15.2	12.8	0.8	1.1
87	163.8	59.2	4.3	1.7		78.1	56.7	3.3	1.9		83.6	59.5	3.4	2.1
88	52.4	39.7	3.2	1.3		59.2	47.4	2.7	1.5		61.2	50.5	2.6	1.7
89	52.1	40.3	2.8	1.2		40.0	29.7	2.5	1.3		51.1	29.7	2.7	1.5
89A	52.5	40.6	2.9	1.2		39.9	29.5	2.5	1.3		51.4	29.9	2.7	1.5
90	56.4	43.0	1.2	2.0		45.7	34.2	1.2	1.8		55.9	27.0	1.2	2.1
91(A)	68.3	55.2	2.3	3.7		49.3	33.8	2.4	3.5		106.2	58.6	2.3	3.8
92	48.6	28.6	2.2	3.2		60.4	31.9	2.4	3.4		53.8	30.8	2.4	3.5
95	59.2	32.6	0.3	0.2		25.1	15.8	0.3	0.2		14.6	10.0	0.2	0.2
97	25.0	19.8	0.4	0.4		17.0	13.5	0.4	0.5		32.5	28.3	0.5	0.6
98A	25.5	21.0	0.3	0.3		14.5	11.1	0.3	0.4		32.7	23.2	0.4	0.4
490	6.1	3.9	0.1	0.2		5.3	2.5	0.1	0.2		7.3	4.7	0.2	0.2
492	9.2	7.7	0.3	0.4		6.9	5.3	0.3	0.4		10.8	6.6	0.4	0.5

Table 5-2 shows sites that are projected to have an annual average exceeding 4 ppb (including background) based on CALPUFF modelling. An annual average SO_2 concentration of 4 ppb corresponds to the critical annual average concentration to protect sensitive lichens (WHO 2000) and to the CAAQS set to go into effect in 2025. Sites 1, 20, 39, 42, and 44 are close to the smelter and on Rio Tinto property. Sites 47B, 79, and 87 are located off Rio Tinto property. Sites 47B, 79, and 87 are not projected to exceed an annual average of 5 ppb, the current CAAQS, under any scenario.

Table 5-2. Sites where CALPUFF modelling indicates an annual air concentration >4 ppb SO_2.

Emissions Scenario	2016	2017	2018
Actual	1, 20, 39, 42, 87	1, 20, 39, 42	1, 20, 39, 42, 44
35 tpd	1, 20, 39, 42, 87	1, 20, 39, 42	1, 20, 39, 42, 44
42 tpd	1, 20, 39, 42, 44, 46, 87	1, 20, 39, 42, 44, 47B, 79, 87	1, 20, 39, 42, 44,47B, 79, 87

Figure 5-2 shows the location of the sampling and inspection sites in relation to CALPUFF-modelled annual average air concentration isopleths of 10 and 20 µg/m^3 (3.8 and 7.6 ppb), the threshold values used in Europe to protect sensitive lichens and natural ecosystems. The 10 µg/m^3 isopleth corresponds approximately to the 2025 CAAQS. Background SO_2 is included in the isopleth values.

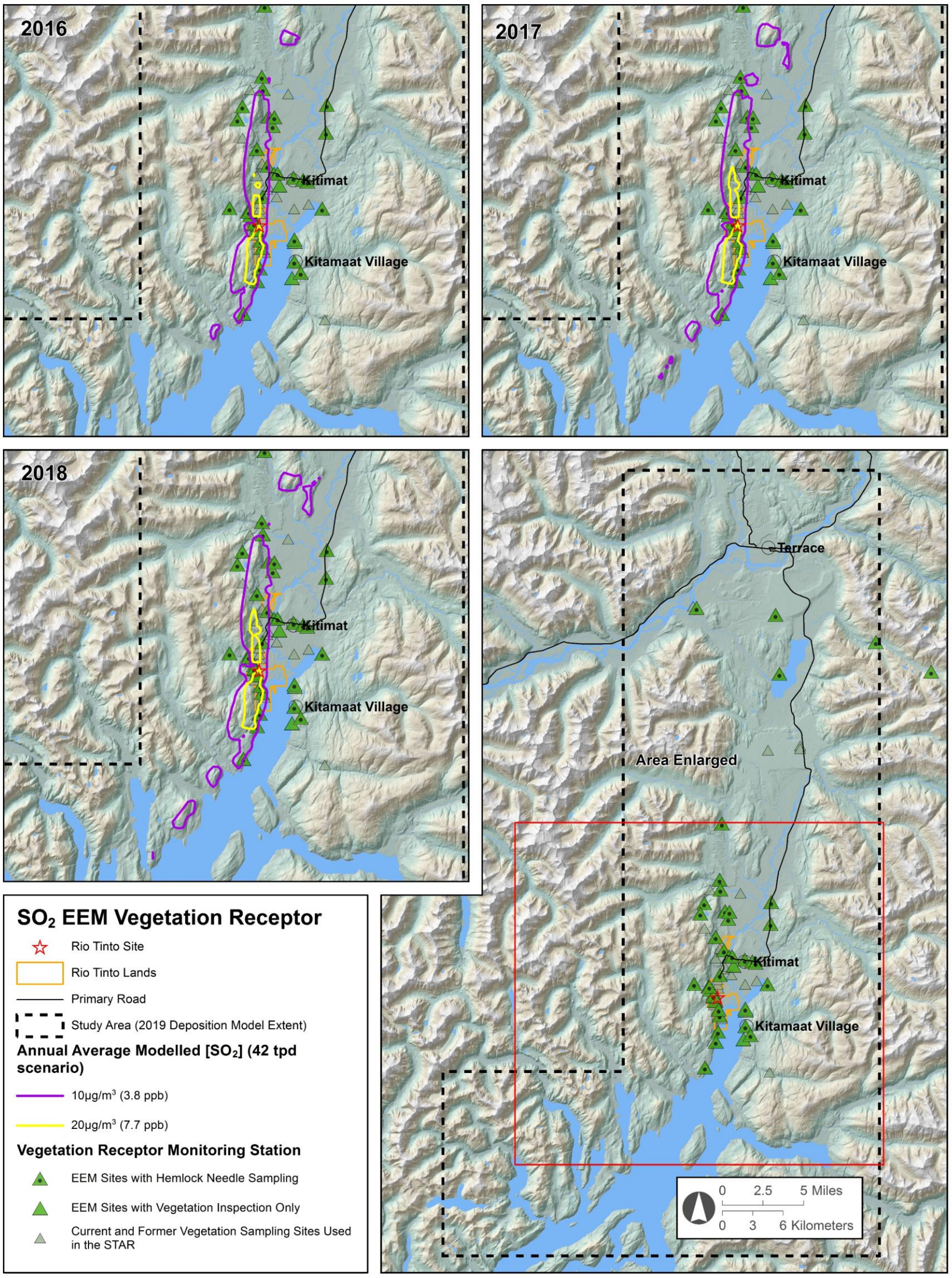


Figure 5-2. Location of sampling and inspection sites with respect to the CALPUFF-modelled annual average air concentration isopleths of 10 and 20 µg/m³ (3.8 and 7.6 ppb), the threshold values used in Europe to protect sensitive lichens and natural ecosystems. The 10 µg/m³ isopleth corresponds approximately to the 2025 CAAQS. The modelling scenario is 42 tpd (the maximum permitted level). The isopleths include background SO_2 concentrations of 0.47 ppb.

Table 5-3 presents correlation coefficients between measures of CALPUFF-modelled SO_2 concentration at sampling sites and %S in western hemlock needles collected at those sites. Correlations were calculated for all three scenarios, providing an estimate of the effect of an under-prediction of actual concentrations under the actual emission scenario. An analysis of the relationship between modelled air concentrations and %S in western hemlock needles can be found in Section 5.2.2.1.

Table 5-3. Correlation between measures of CALPUFF-modelled SO_2 concentration in ppb and %S in western hemlock needles using all vegetation sampling sites.

Air Concentration Statistic	Actual			35 tpd			42 tpd		
	2016	2017	2018	2016	2017	2018	2016	2017	2018
	Correlation Coefficient								
1-hour Maximum	0.448	0.223	0.421	0.407	0.174	0.306	0.399	0.174	0.296
1-hour Maximum Day[1]	0.339	0.272	0.386	0.507	0.215	0.321	0.514	0.170	0.311
1-hour Maximum Growing Season[1]	0.453	0.288	0.455	0.507	0.285	0.439	0.501	0.281	0.428
1-hour Maximum Growing Season Day	0.434	0.249	0.470	0.535	0.372	0.440	0.528	0.372	0.428
3-hour Maximum	0.385	0.195	0.386	0.345	0.136	0.248	0.334	0.136	0.239
3-hour Daylight	0.378	0.314	0.388	0.430	0.205	0.287	0.431	0.175	0.279
3-hour Growing Season	0.483	0.350	0.418	0.453	0.366	0.352	0.443	0.359	0.341
3-hour Growing Season Daylight	0.505	0.301	0.353	0.499	0.373	0.295	0.494	0.369	0.286
24-hour Maximum	0.263	0.362	0.283	0.174	0.153	0.204	0.161	0.149	0.195
24-hour Daylight	0.301	0.253	0.356	0.278	0.125	0.357	0.214	0.141	0.348
24-hour Growing Season	0.437	0.331	0.460	0.355	0.332	0.390	0.342	0.322	0.379
24-hour Growing Season Daylight	0.415	0.262	0.352	0.353	0.312	0.408	0.339	0.303	0.398
Annual Average	0.311	0.401	0.291	0.264	0.334	0.250	0.257	0.327	0.243
Annual Average Daylight	0.286	0.321	0.274	0.252	0.249	0.241	0.250	0.312	0.235
Growing Season Average	0.442	0.467	0.424	0.355	0.436	0.384	0.389	0.432	0.379
Growing Season Daylight	0.415	0.432	0.371	0.364	0.410	0.345	0.358	0.406	0.340

[1]Growing Season is April 15-October 1. Daylight hours are 7AM to 9PM.

In order to select a measure of SO_2 concentration for analysis with %S in western hemlock needles, we examined the relationship among the measures. A comparison of the growing season average to the annual average is shown in Figure 5-3. The effect of the seasonal dispersion pattern is clearly shown: sampling sites 42, 20, 1, 87, 88, 89, and 89A are arrayed aside or south of the smelter and the northerly flow of winds in the spring and summer results in a lower growing season average when compared to the annual average.

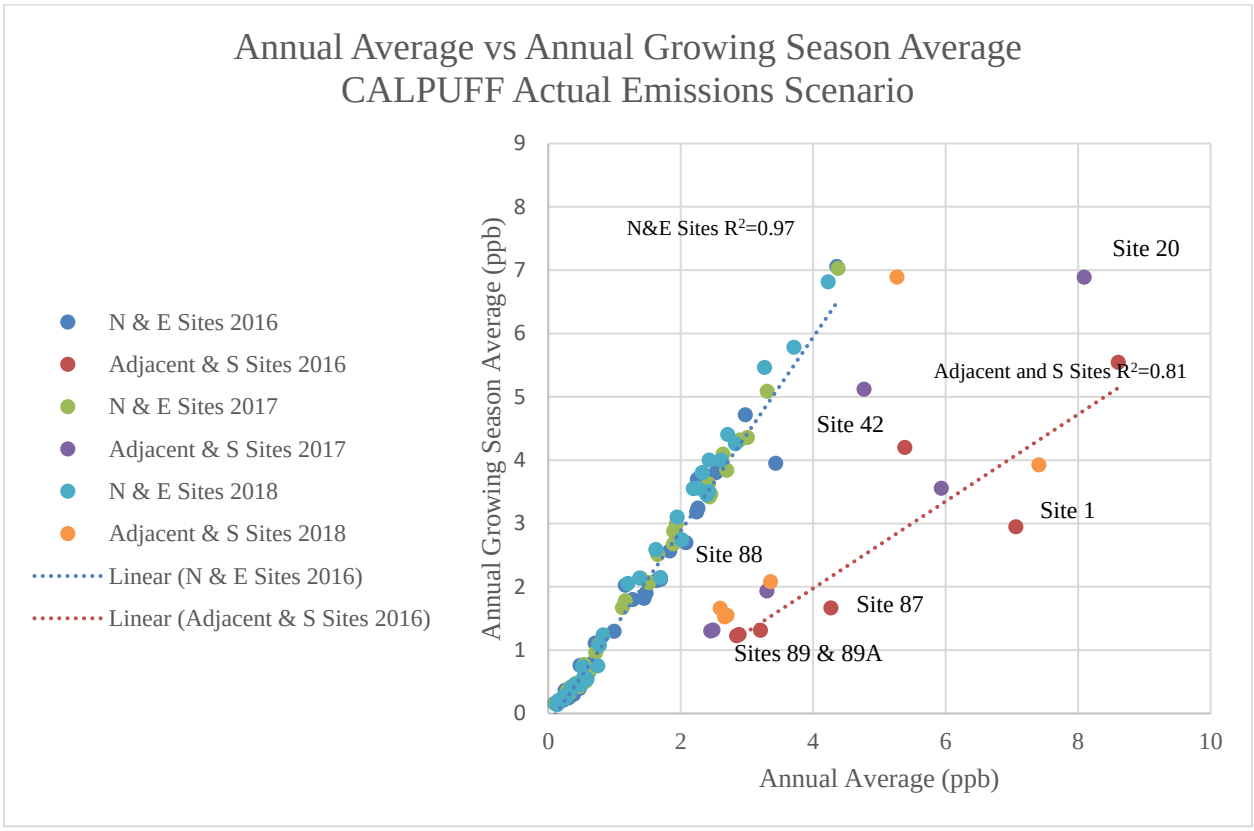


Figure 5-3. The relationship of CALPUFF-modelled annual average and growing season average SO_2 concentrations at vegetation sampling and inspection sites under the actual emissions scenario. Trend lines are fit for 2016 to illustrate the strength of the relationship. The annual and growing season averages do not include background SO_2 concentration of 0.47 ppb.

The growing season average provided a consistent, and on average, the highest correlation for the 3 years in the actual scenario, so we selected it for use in subsequent analyses of the relationship between CALPUFF-modelled SO_2 concentration and %S in needles. No measure explained more than 35% of the variation in the needle S dataset.

Average daily emissions, as reported by Rio Tinto, show a closer relationship with %S in western hemlock needles, with correlation coefficients ranging from about 0.2 to 0.9 (analysis can be found in Vegetation Appendix 5.2). Average daily emissions are also used to compare pre- and post-KMP needle S, as modelled SO_2 concentrations are not available for all pre-KMP years.

No modelled SO_2 concentration at vegetation sites exceeded the thresholds reported in the scientific literature and used in the STAR of 334, 500, and 126 ppb for 1, 3, and 24-hour maxima respectively. In two cases, 2017 and 2018 under the 42 tpd scenario, modelled concentrations at site 20 exceeded the 188 ppb 1-hour concentration that was previously used in B.C. Pollution Control Objectives as the maximum desirable level. All other sites under all scenarios and all years were well below the thresholds of concern.

The number of hours that certain key thresholds (as identified in the STAR) were exceeded at all receptors (including on-site and fence line receptors) are shown for the post-KMP period in Table

5-4. Given the number of receptor hours modelled—over 50,000,000— and the fact that on-site receptors are included, the number of exceedances of the thresholds are extremely low. In addition, given the finding that, in general, CALPUFF over-predicts SO_2 concentrations, it is highly unlikely that there will be any direct impact of SO_2 on even the most sensitive vegetation.

Table 5-4. Receptor-hours under the actual emissions scenario exceeding thresholds used in the STAR to evaluate the likelihood of visible injury to vegetation. All receptors, including on-site and fence line receptors, are included. Background SO_2 concentrations of 5.53, 2.80, and 1.74 for 1-hour, 3-hour, and 24-hour, respectively, are not included in the SO_2 concentrations listed in the table.

Averaging Period	1-Hour		3-Hour		24-Hour	
Concentration	188 ppb 491 µg/m³	334 ppb 873 µg/m³	250 ppb 653 µg/m³	500 ppb 1307 µg/m³	62 ppb 162 µg/m³	126 ppb 329 µg/m³
Model Year						
2016	317	49	19	0	3	0
2017	556	88	22	0	6	0
2018	823	108	20	0	19	0

Receptor hours = total number of hours exceeding each threshold at any receptor, including repeated occurrences at the same receptor. 12,570 receptors are modelled over 4,079 hours in the growing period, resulting in over 50,000,000 receptor-hours. Values in µg/m³ are provided for comparison to the STAR.

Locations with the highest CALPUFF-modelled SO_2 concentrations were determined for comparison with the current sampling array and are shown in Figure 5-4. Many of the highest growing season concentrations are along the ridge to the west and south of the smelter, an area of overlap with predicted soil critical load exceedance (Figure 6-5) of approximately 190 ha, of which about 87 ha are outside the Rio Tinto property line. Concentrations and coordinates for the 42 tpd growing season daylight scenario (maximum permitted level case) are found in Table 5-5. Coordinates and concentrations for other scenarios are in Vegetation Appendix 5.3. In addition, we mapped areas exceeding 10 (3.8 ppb) and 20 (7.6 ppb) µg/m³ annual average SO_2 concentrations, to determine the extent of the concentrations that exceed established thresholds for sensitive lichens and natural ecosystems used in Europe (Figure 5-5).

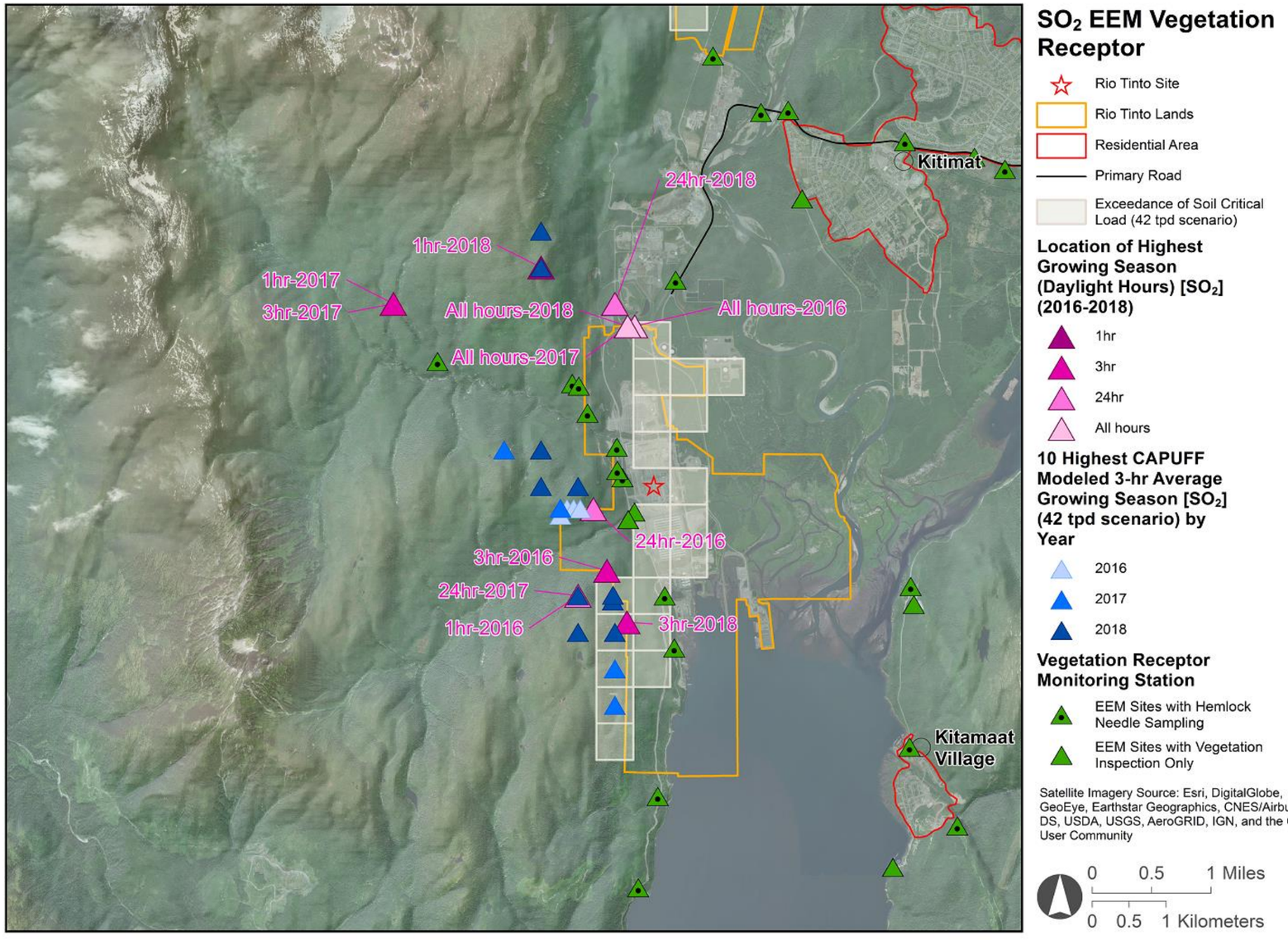


Figure 5-4. Location of the 10 highest CAPUFF modelled 3-hour average Growing Season SO_2 concentrations under the 42 tpd scenario (maximum permitted level case) for 2016-2018 (blue symbols) and the highest locations for growing season daylight hours 1-hour, 3-hour, 24-hour, and annual averages for each year (pink symbols). Background SO_2 concentrations of 5.53, 2.80, 1.74, and 0.47 ppb for 1-hour, 3-hour, 24-hour, and annual (and growing season) average, respectively, are not included but do not affect the locations.

Table 5-5. Coordinates and SO_2 concentrations (42 tpd scenario [maximum permitted level case]) at the 10 highest locations during the growing season outside the Rio Tinto fence line. Some locations appear more than once. Background SO_2 concentrations of 5.53, 2.80, 1.74, and 0.47 ppb for 1-hour, 3-hour, 24-hour, and annual (and growing season) average, respectively, are not included in the SO_2 concentrations listed in the table. The addition of background does not affect the location.

		SO_2 Concentration	UTM X	UTM Y
Avg. Period	Year	(ppb)	(km)	(km)
	2016	495	518.500	5983.500
1hr	2017	611	516.000	5987.500
	2018	351	518.000	5988.000
	2016	234	518.891	5983.842
3hr	2017	284	516.000	5987.500
	2018	228	519.163	5983.139
	2016	67	518.709	5984.689
24hr	2017	63	518.500	5983.500
	2018	62	519.000	5987.500
	2016	20	519.267	5987.193
All hours	2017	21	519.173	5987.193
	2018	21	519.173	5987.193

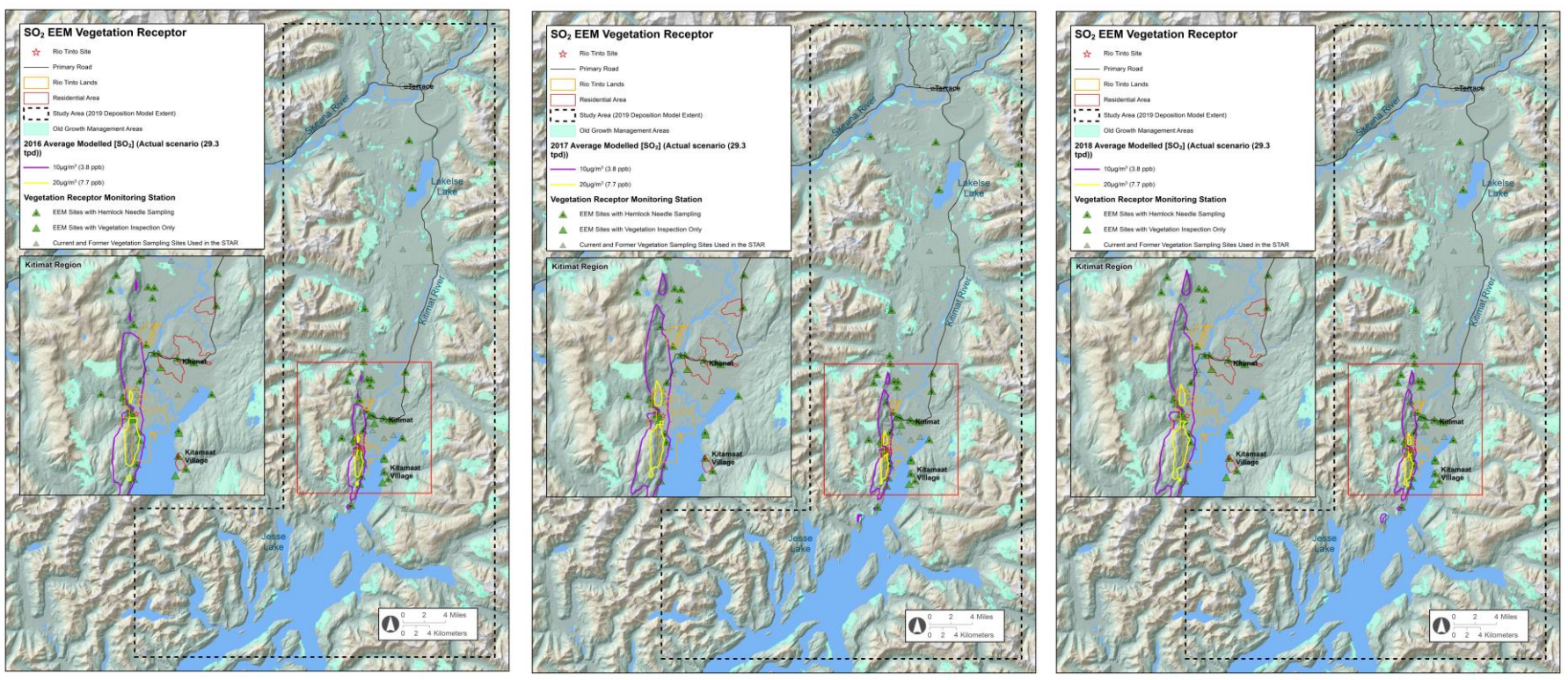


Figure 5-5. CALPUFF-modelled annual average SO_2 concentration isopleths (yellow=20 µg/m³ (7.6 ppb) and purple=10µg/m³ (3.8 ppb) for 2016-2018 under the actual emission scenario (top) and the 42 tpd scenario (bottom). Teal-coloured areas are Old Growth Management Areas. Background SO_2 concentrations are included to allow comparison to European thresholds of 10 and 20 µg/m³.

Deposition

CALPUFF was also used to model SO_4^{2-} deposition at vegetation sampling and inspection sites. The results are shown in Table 5-6. Deposition decreased rapidly with distance from the smelter. The relationship between deposition and distance from the smelter with respect to vegetation sampling sites is shown in Figure 5-6. CALPUFF-modelled deposition of SO_4^{2-} was moderately correlated with modelled SO_2 concentration, with linear regressions explaining between 56 and 73% of the variation. The spatial distribution of SO_4^{2-} deposition for the actual emissions and 42 tpd scenarios are shown in Figure 5-7. An analysis of the implications of modelled SO_4^{2-} deposition is found in Section 5.2.2.1.

Table 5-6. CALPUFF-modelled SO_4^{2-} deposition for vegetation sampling and inspection sites. Values do not include background of 3.6 kg SO_4^{2-}/ha/yr.

	CALPUFF-Modelled S Deposition kg SO_4^{2-}/ha/yr												
	Actual Emissions					35 tpd				42 tpd			
Site	2016	2017	2018	Mean		2016	2017	2018	Mean	2016	2017	2018	Mean
1	127.4	95.2	103.0	108.5		147.2	141.9	117.5	135.6	181.1	174.9	145.0	167.0
20	164.7	142.9	114.8	140.8		205.4	191.6	136.5	177.8	251.3	234.8	166.8	217.6
37	52.0	39.7	35.4	42.4		64.9	46.9	39.8	50.5	77.7	56.4	47.8	60.6
39	66.5	81.5	53.9	67.3		80.8	92.1	61.0	78.0	96.7	110.2	72.9	93.3
42	100.7	79.8	55.8	78.8		105.5	88.9	60.4	84.9	126.2	106.5	72.5	101.7
43A	19.5	16.7	15.6	17.3		23.6	18.3	17.0	19.7	28.4	22.1	20.5	23.6
43B	25.9	20.5	19.4	21.9		32.0	22.6	21.1	25.2	38.4	27.2	25.4	30.3
44	69.4	53.6	39.1	54.0		76.1	61.3	42.9	60.1	91.0	73.5	51.5	72.0
44A	6.7	6.5	6.0	6.4		8.0	7.4	6.5	7.3	9.6	8.9	7.8	8.7
46	21.8	18.8	17.4	19.3		26.6	20.6	18.7	22.0	32.0	24.9	22.5	26.5
47B	38.2	45.9	29.9	38.0		46.1	52.4	32.9	43.8	55.2	62.8	39.5	52.5
52(A)	32.8	49.6	35.4	39.3		40.6	58.3	41.9	46.9	48.7	69.8	50.1	56.2
54	31.9	50.3	33.5	38.6		39.6	60.4	38.2	46.1	47.6	72.3	45.7	55.2
55	15.4	26.8	17.1	19.8		18.9	30.6	19.7	23.1	22.8	36.9	23.8	27.8
56(A)	10.5	14.5	10.5	11.8		12.4	17.0	12.0	13.8	15.0	20.6	14.6	16.7
57	9.2	11.5	8.6	9.8		10.3	13.2	9.8	11.1	12.4	16.0	11.8	13.4
68	3.7	3.5	3.8	3.7		4.2	4.3	4.4	4.3	5.1	5.2	5.3	5.2
69	5.3	5.4	5.3	5.3		6.2	6.8	5.9	6.3	7.4	8.2	7.1	7.6
70	3.2	3.8	3.6	3.5		3.9	4.9	4.1	4.3	4.7	5.9	5.0	5.2
78 (A)	26.9	32.1	22.9	27.3		31.7	36.8	25.2	31.2	38.1	44.3	30.3	37.5
79	26.9	28.8	23.4	26.4		32.2	31.5	25.7	29.8	38.6	37.9	30.9	35.8
80	26.1	30.1	21.2	25.8		30.8	33.5	23.2	29.2	37.0	40.3	27.9	35.1
81B	9.8	10.1	9.2	9.7		11.8	10.9	10.0	10.9	14.1	13.2	12.0	13.1

	CALPUFF-Modelled S Deposition kg SO_4^{2-}/ha/yr												
	Actual Emissions					35 tpd					42 tpd		
Site	2016	2017	2018	Mean		2016	2017	2018	Mean		2016	2017	2018	Mean
81C	8.2	8.3	7.8	8.1		9.9	9.0	8.5	9.2		11.9	10.9	10.3	11.0
82	15.6	17.4	14.4	15.8		18.8	19.4	15.9	18.1		22.6	23.4	19.1	21.7
84 (A) (B)	1.7	1.3	1.1	1.4		2.2	1.5	1.2	1.6		2.6	1.8	1.5	2.0
85	3.4	3.5	3.0	3.3		4.1	4.0	3.4	3.8		4.9	4.8	4.1	4.6
86	5.1	5.4	4.7	5.1		6.2	6.2	5.2	5.9		7.4	7.4	6.3	7.1
87	48.4	40.4	38.9	42.6		54.6	49.4	42.9	49.0		66.3	59.9	52.2	59.5
88	33.3	28.6	27.5	29.8		37.2	34.4	30.4	34.0		45.1	41.7	36.9	41.3
89	22.4	19.4	20.0	20.6		25.4	23.0	21.8	23.4		30.9	27.9	26.5	28.4
89A	22.5	19.6	20.1	20.7		25.6	23.2	22.0	23.6		31.1	28.1	26.7	28.6
90	7.4	7.6	6.7	7.2		9.1	8.4	7.4	8.3		10.9	10.2	8.8	10.0
91(A)	18.4	20.1	15.9	18.1		22.0	22.5	17.5	20.7		26.5	27.1	21.1	24.9
92	25.5	30.2	21.8	25.8		30.0	34.8	23.9	29.6		36.0	41.8	28.8	35.6
95	3.0	2.9	2.9	2.9		3.4	3.4	3.4	3.4		4.2	4.1	4.1	4.1
97	7.1	10.7	8.4	8.7		8.7	12.9	9.6	10.4		10.5	15.5	11.6	12.5
98A	5.1	6.0	5.0	5.4		6.0	7.1	5.7	6.3		7.2	8.6	6.9	7.6
490	0.6	0.6	0.8	0.7		0.8	0.7	0.9	0.8		0.9	0.9	1.1	1.0
492	1.4	1.8	2.1	1.8		1.8	2.2	2.5	2.2		2.2	2.7	2.9	2.6

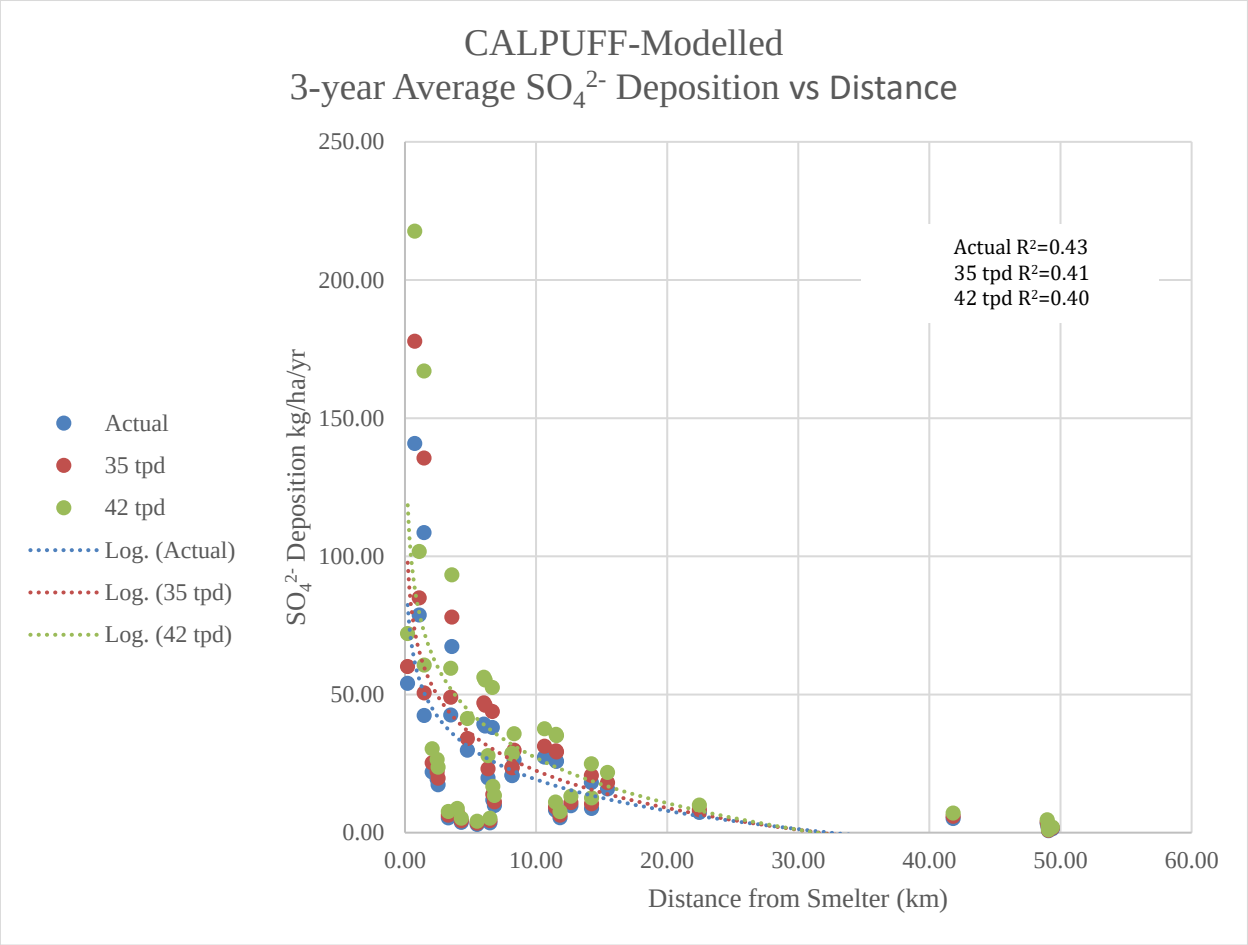


Figure 5-6. The relationship between CALPUFF-modelled 3-year average SO_4^{2-} deposition and distance of vegetation sites from the smelter. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included.

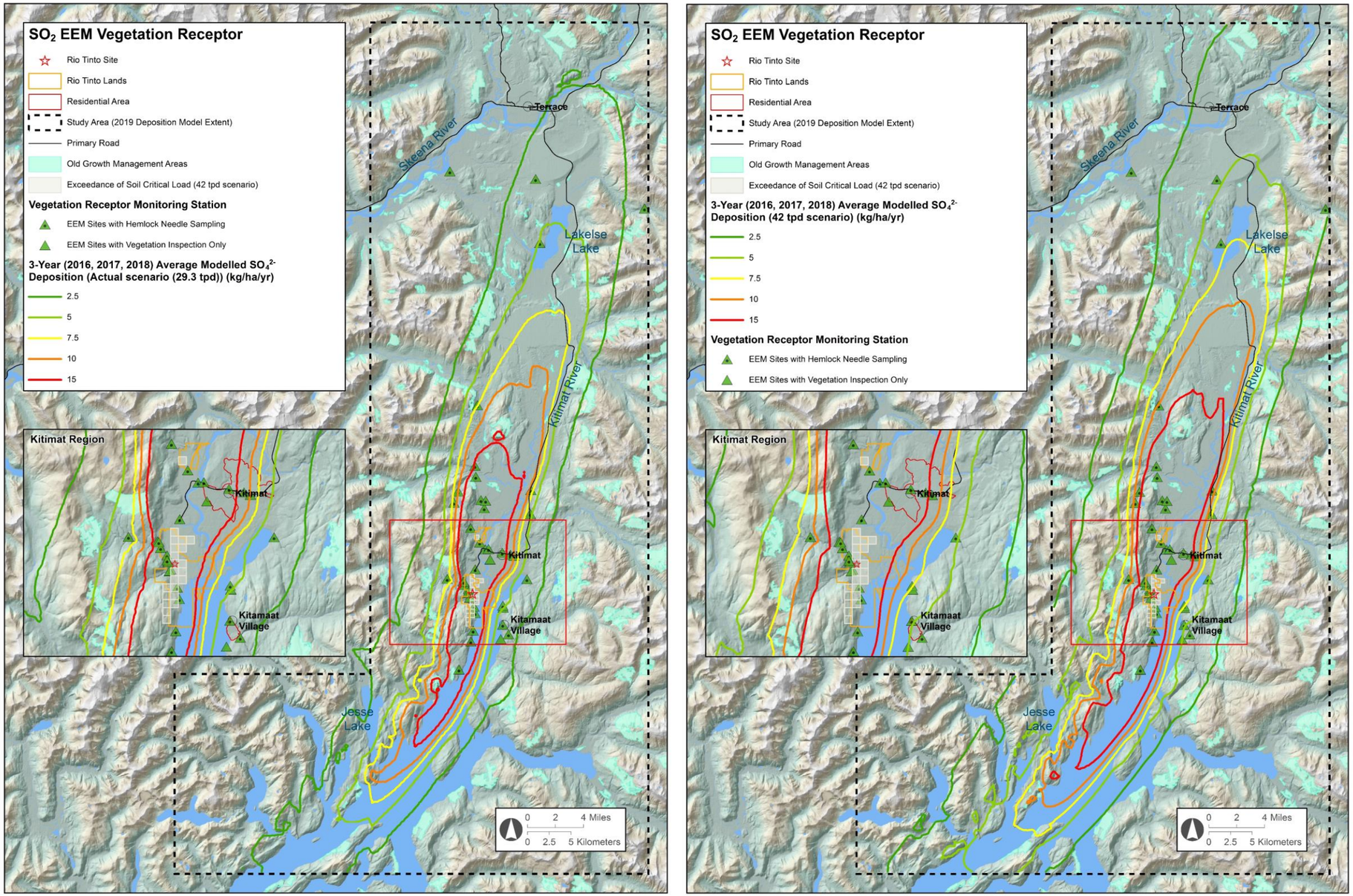


Figure 5-7. Three-year average deposition of SO_4^{2-} as modelled by CALPUFF under the actual deposition scenario (left) and 42 tpd (right). Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleths.

5.2.1.3 *Updated scientific literature on the response of vegetation and ecotypes to SO_2*

See Section 5.1.4.1.

5.2.1.4 *Field methods to document vegetation condition, health, and visible injury*

Biennially, or more frequently, a QP plant scientist (currently a plant pathologist) inspects vegetation in the Kitimat Valley. The inspection takes place at each sampling site, as well as at a few additional sites (e.g., the Rio Tinto Administration Building, Moore Creek Falls, Minette Bay overlook, Kitamaat Village, and Kitimat neighborhoods). The QP notes the general condition of vegetation and takes photos to illustrate the condition of vegetation at the time of the inspection. Symptoms and signs of plant diseases, insect infestation, and environmental stress (including drought, physical damage, and injury due to air pollution) are documented. The QP's report is prepared and submitted with the annual report of the vegetation program (see Stantec Consulting Ltd. and Laurence 2019). Full details of the methods are provided in Vegetation Appendix 5.4.

5.2.1.5 *Concentrations of S in western hemlock foliage*

Sampling and Collection Methods

Sampling and collection methods were the same as used in the annual vegetation program (Stantec Consulting and Laurence 2019) and were subject to Stantec's quality assurance program. Complete details of the sampling, collection, and sample processing methods can be found in Vegetation Appendix 5.4. Sample collection and inspection sites are shown in Figure 5-8.

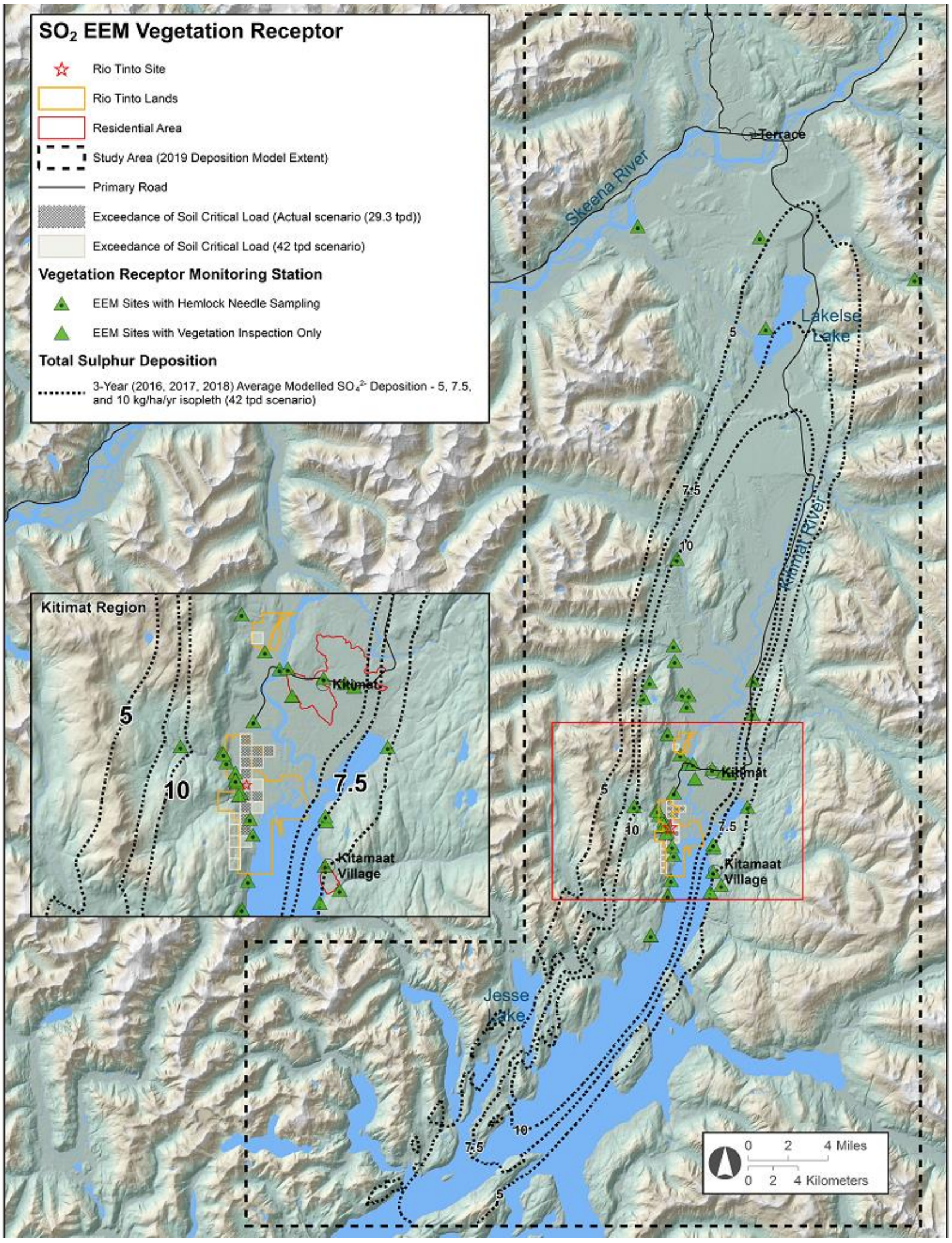


Figure 5-8. Location of vegetation sampling and inspection sites, as well as isopleths of SO_4^{2-} deposition. Background deposition of 3.6 kg SO_4^{2-}/yr is not included in the isopleths.

Chemical analysis methods

Chemical analysis of western hemlock needles to determine the S and F content is conducted by the Rio Tinto laboratory in Jonquière, Québec. Sulphur is determined using combustion, collection of gases in sodium hydroxide (NaOH), and analysis using ion chromatography column. F is determined using combustion, collection of gases in $H_2SO_4^{2-}$ or NaOH, and analysis with an ion-specific electrode. Complete details are reported in Stantec Consulting and Laurence (2019) and Laurence (2018).

5.2.2 Analyses we conducted with these data

5.2.2.1 *Spatial Evaluation of post-KMP CALPUFF simulation results versus post-KMP sulphur in western hemlock*

Air Concentration

CALPUFF-modelled measures of air concentrations were not highly correlated with %S in western hemlock needles. An example of the relationship, %S in needles and modelled growing season average SO_2 concentration is shown in Figure 5-9. No SO_2 concentration statistic explained more than 35% of the variation in S content of needles. Table 5-3 shows the correlation coefficients between all modelled air concentration statistics and %S in western hemlock.

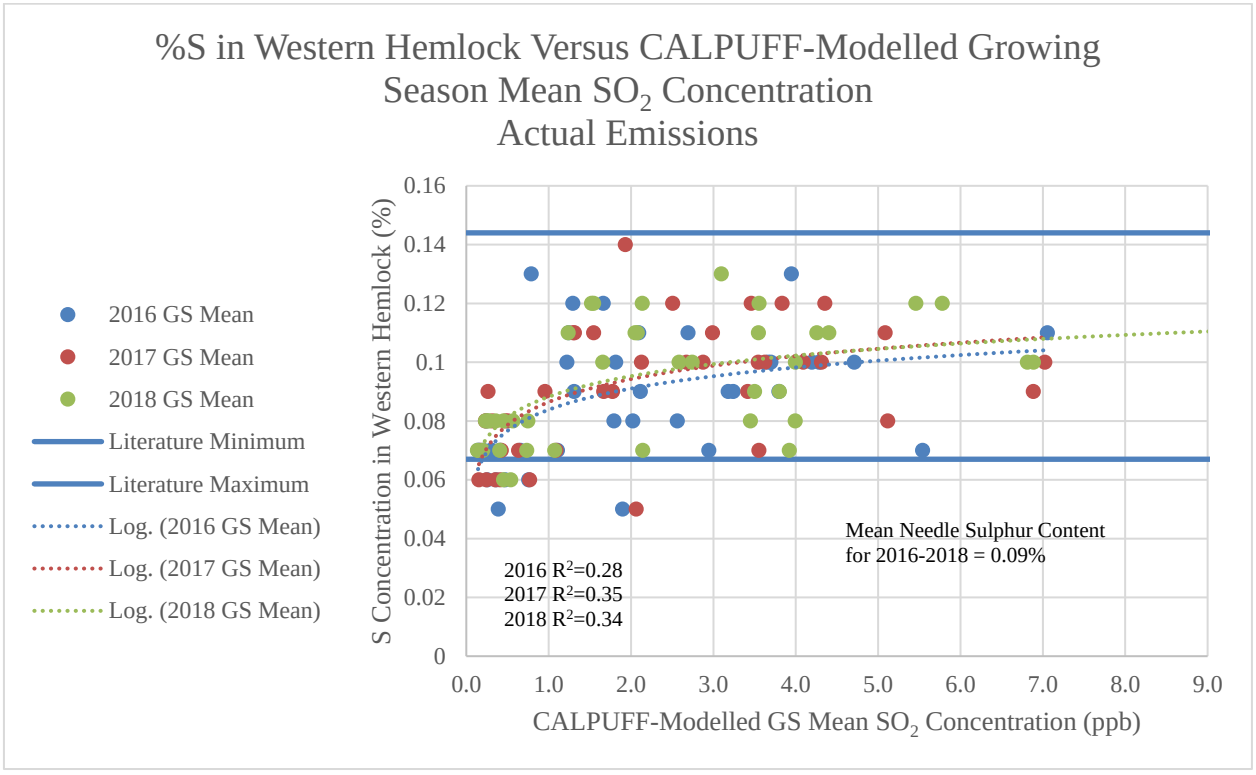


Figure 5-9. Relationship between annual growing season mean CALPUFF-modelled SO_2 concentrations and %S in western hemlock needles. Correlations for individual years are provided in Table 5-3. Background SO_2 concentration of 0.47 ppb is not included.

Figure 5-10 shows the spatial distribution of vegetation sampling sites with post-KMP average needle S concentrations and isopleths of modelled (actual scenario) annual growing season average SO_2 concentrations of 10 and 20 µg/m^3 (3.8 and 7.6 ppb), thresholds established in Europe to protect sensitive lichens and natural forest ecosystems, respectively (WHO 2000; European Union 2008). Thirty of 40 vegetation sampling sites are located outside of the 10 µg/m^3 SO_2 isopleth and represent the full range of %S found in western hemlock needles. Similarly, sites with the full range of %S occur inside the 10 µg/m^3 SO_2 isopleth as well. No vegetation sites were located inside the 20 µg/m^3 SO_2 isopleth.

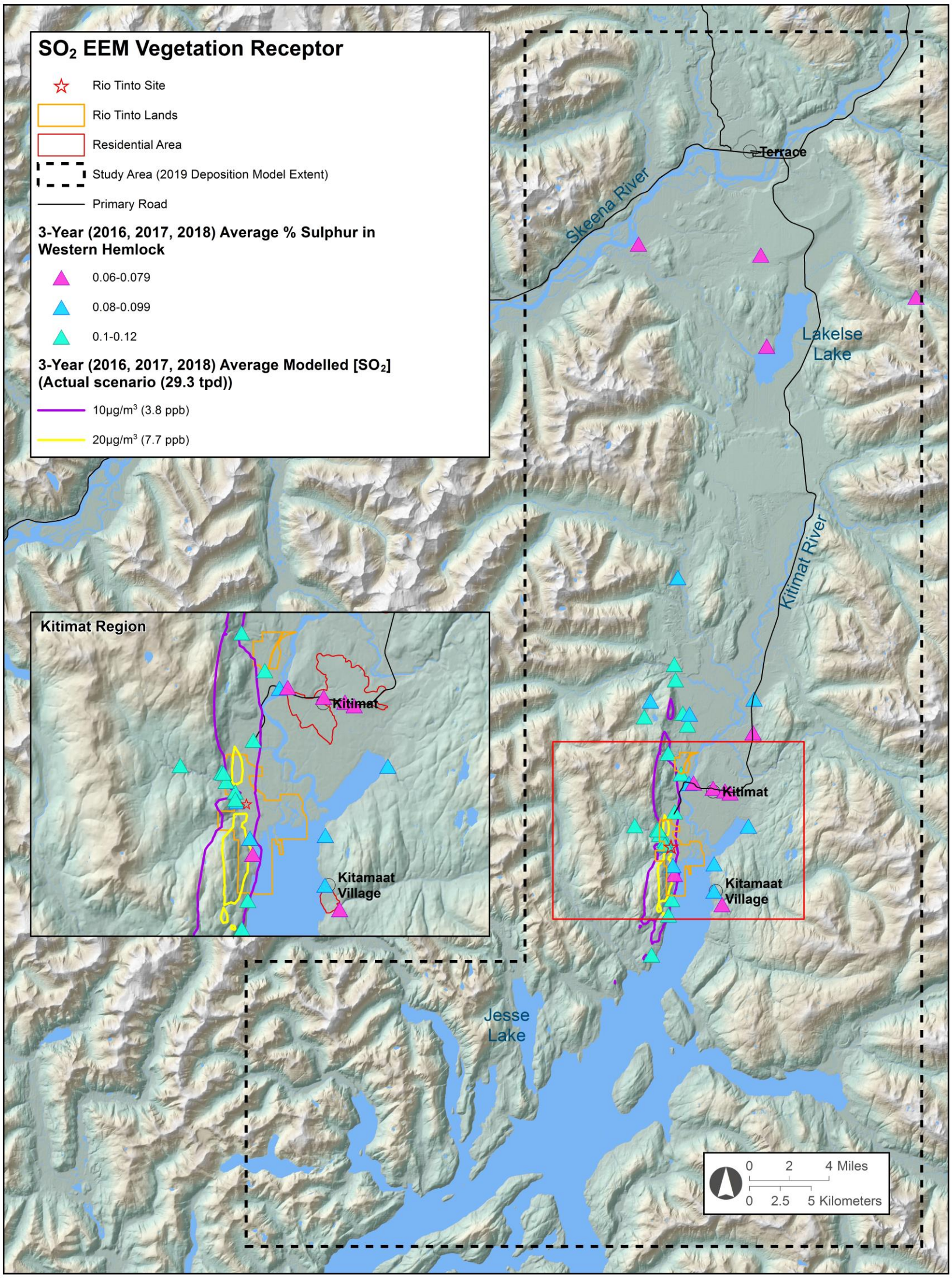


Figure 5-10. The spatial distribution of %S in western hemlock needles in relation to SO_2 concentrations as modelled by CALPUFF. Purple symbols are at sites that have a post-KMP average %S between 0.06 and 0.08; blue symbols %S between 0.08 and 0.10; cyan symbols %S between 0.10 and 0.12. Isopleths represent growing season means of 10 and 20 µg/m^3, threshold concentrations established in Europe for the protection of sensitive lichens and natural forest ecosystems respectively. Background air concentrations of SO_2 have been added.

All needle S data are provided in Vegetation Appendix 5.5. Modelled air concentrations for all post-KMP years and all scenarios at individual vegetation sampling sites are provided in Vegetation Appendix 5.1.

Deposition

Modelled SO_4^{2-} deposition was not a good predictor of %S in western hemlock. As with modelled SO_2 concentrations, we examined the relationship between SO_4^{2-} deposition and %S in western hemlock needles under all emission scenarios to guard against CALPUFF under-prediction. For example, the relationship with the post-KMP average annual deposition is shown in Figure 5-11. In no case—individual year or post-KMP average—did modelled deposition in any scenario explain more than 25% of the variation in the needle S dataset.

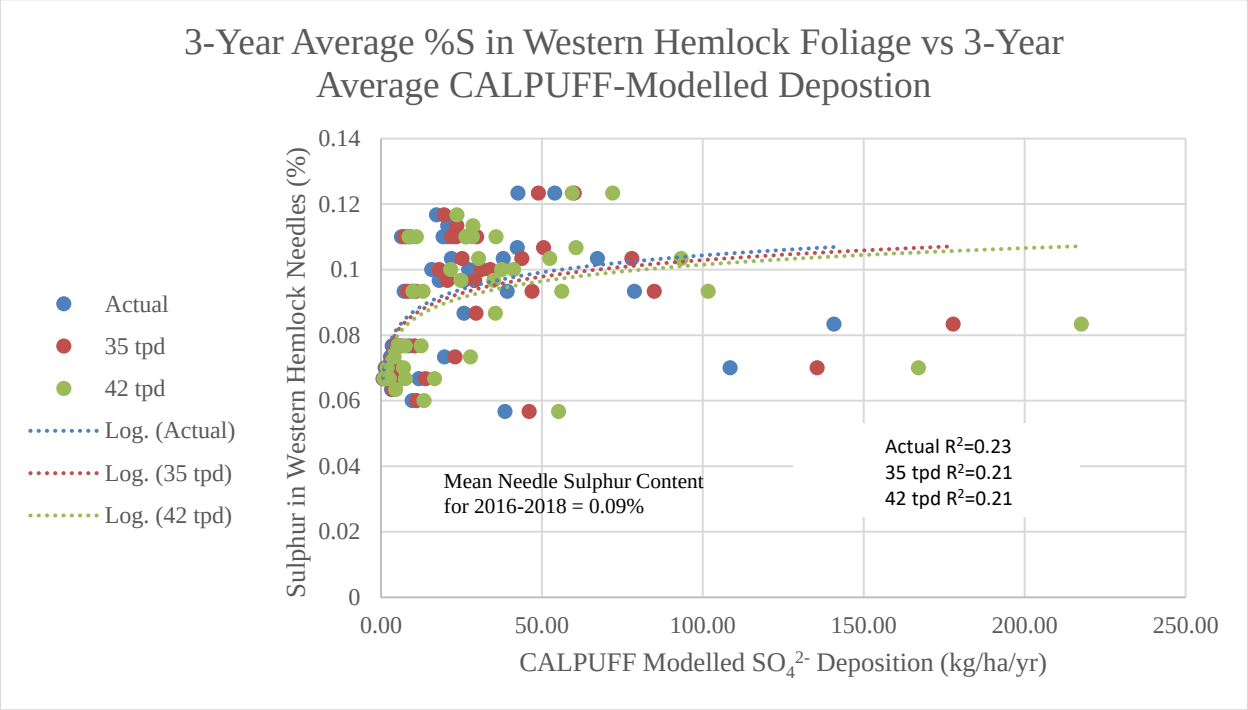


Figure 5-11. Average sulphur content (2016-2018) in western hemlock needles as related to 3-year average CALPUFF-modelled SO_4^{2-} deposition at vegetation sampling sites. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included.

The spatial association of needle sulphur and SO_4^{2-} deposition is shown in Figure 5-12. No clear pattern is apparent other than sites with concentrations above the overall mean (0.09% S in needles – represented by cyan-coloured symbols) occur mostly within the 10 kg SO_4^{2-}/ha/yr/ha/year isopleth. However, three of the sites in the lowest class (0-06-0.07 %S) also occur inside the 10 kg SO_4^{2-}/ha/yr isopleth.

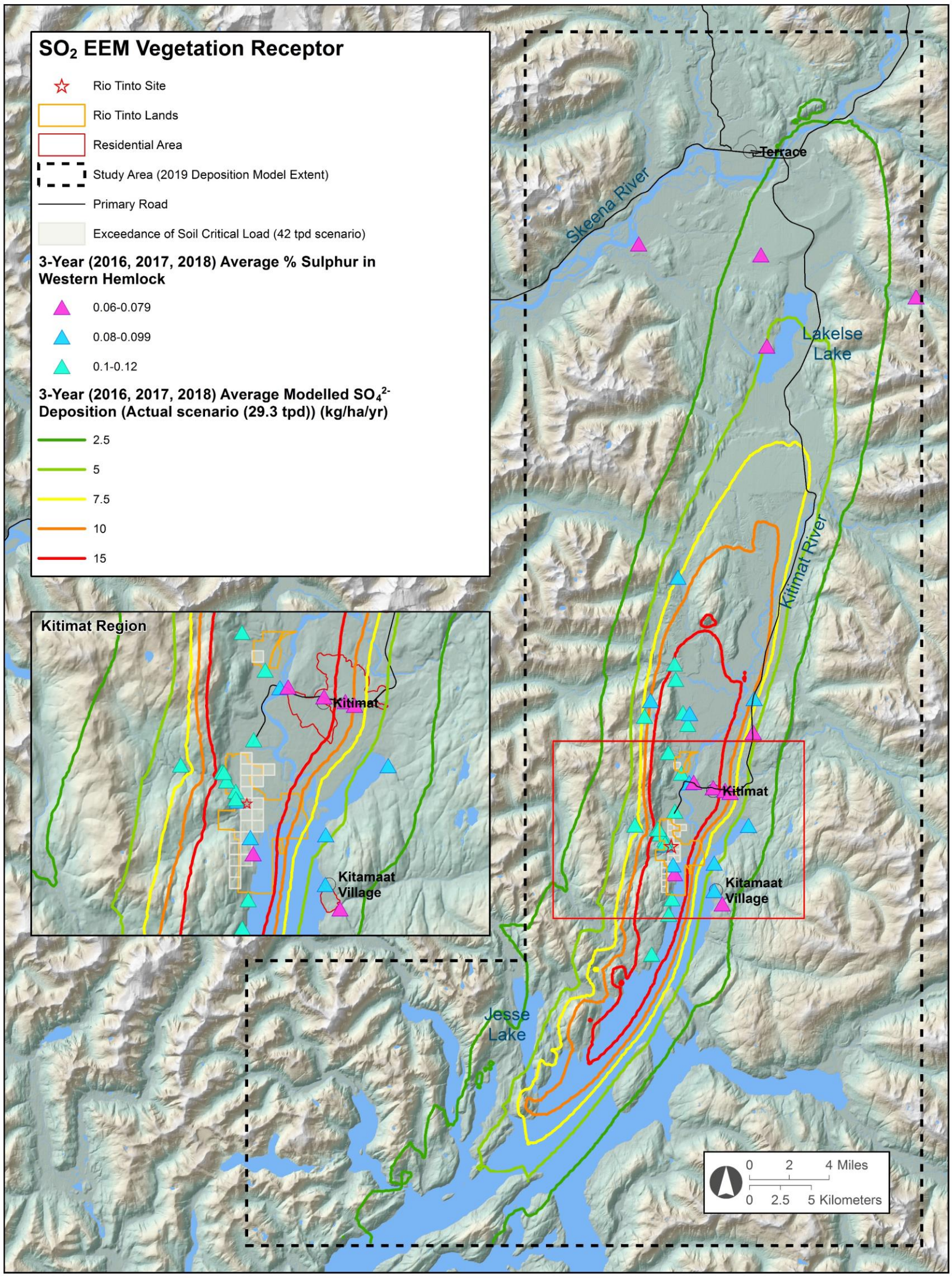


Figure 5-12. The spatial distribution of %S in western hemlock needles in relation to SO_4^{2-} deposition as modelled by CALPUFF. Purple symbols are at sites that have a post-KMP average % S between 0.06 and 0.08; blue symbols % S between 0.08 and 0.10; cyan symbols % S between 0.10 and 0.12. Isopleths represent 2.5, 5, 7.5, and 10 kg SO_4^{2-}/ha/yr. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included.

Pre-KMP, SO_2 emissions from the smelter were a better predictor of %S in western hemlock needles than any of the current model estimates of SO_2 concentration or SO_4^{2-} deposition. However, the relationship between emissions and %S in needles was not strong with the exception of a few sites (Vegetation Appendix 5.2). The relationship between F emissions and F in needles was generally much stronger (Vegetation Appendix 5.2). Post-KMP, it appears that the relationship between SO_2 emissions and needle sulphur has changed, with needle S generally not responding to increased emissions (see Section 5.2.2.2).

Comparison of %S in needles with passive samplers

Nine western hemlock sampling sites are within 2 km of passive samplers (Table 5-7). The relationship between %S in western hemlock and growing season means from the passive samplers explained between 0 and 17% of the variation in the needle %S data (Figure 5-12). Inspecting the two closest pairs where vegetation samples were taken less than 200 m from a passive sampler, the passive sampler growing season mean varied by about 2.1 to 2.25-fold in 3 years of collection while the %S in needles was within the margin of error for the analytical method (0.01%) and apparently did not respond to changes in air concentration or deposition.

The passive samplers have been shown to have a very close relationship with distance from the smelter, illustrating a decrease in air concentration and deposition with distance (see Figure 3-9). Figure 5-14 shows results from regressing %S on distance along a transect to the north of the smelter and indicates a relatively strong relationship—stronger than when regressed on estimates of SO_2 concentration, SO_4^{2-} deposition, or actual estimates of measurements of emissions. However, the relationship is not nearly as strong as that between passive samplers and distance (see Section 3.1.3.2). The same relationship did not hold for sites south of the smelter where %S in needles increased with distance from the smelter, or on the east side of Minette Bay where there was no relationship with distance. Passive sampler results from south of the smelter show a decrease in air concentration with distance.

Given the comparisons to modelled air concentration and deposition, and the measurements with passive samplers, %S in western hemlock needles is not a consistent and effective method to monitor the path of the plume.

Table 5-7. Comparison of passive sampler results and %S in western hemlock needles at vegetation sites within 2 km of passive monitors. Passive sampler sites V01-V04 are more than 2 km from the nearest vegetation sampling site.

Passive Sampler	Vegetation Site	Distance & Direction (P to V)	%S in Western Hemlock Needles			Growing Season Mean SO_2 Concentration					
						CALPUFF			PASSIVE		
			2016	2017	2018	2016	2017	2018	2016	2017	2018
V05	91A	920m @219.1°	0.1	0.1	0.09	3.7	3.5	3.8	0.4	1.5	1.8
V06	80	608m @220°	0.09	0.12	0.08	3.8	3.8	4.0	1.2	0.8	1.6
V07	78A	997m @332.3°	0.09	0.12	0.09	3.2	3.5	3.5	0.9	2.4	0.3
V08	79	676m @290.0°	0.1	0.11	0.12	4.7	5.1	5.5	0.5	3.0	2.6
V09	39	1,625m @148.7°	0.11	0.1	0.1	7.1	7.0	6.8	1.5	4.0	3.6
V10	37	96m @1.5°	0.1	0.11	0.1	2.7	4.1	4.4	1.8	3.0	4.1
V11	88	183.5m @218.5°	0.09	0.11	0.1	1.3	1.5	1.7	2.7	2.0	4.5
V12	89	1034.5m @201.5°	0.1	0.11	0.12	1.2	1.3	1.5	2.9	2.1	3.0
V13	89	1622.7m @224.8°	0.1	0.11	0.12	1.2	1.3	1.5	1.9	1.3	2.8

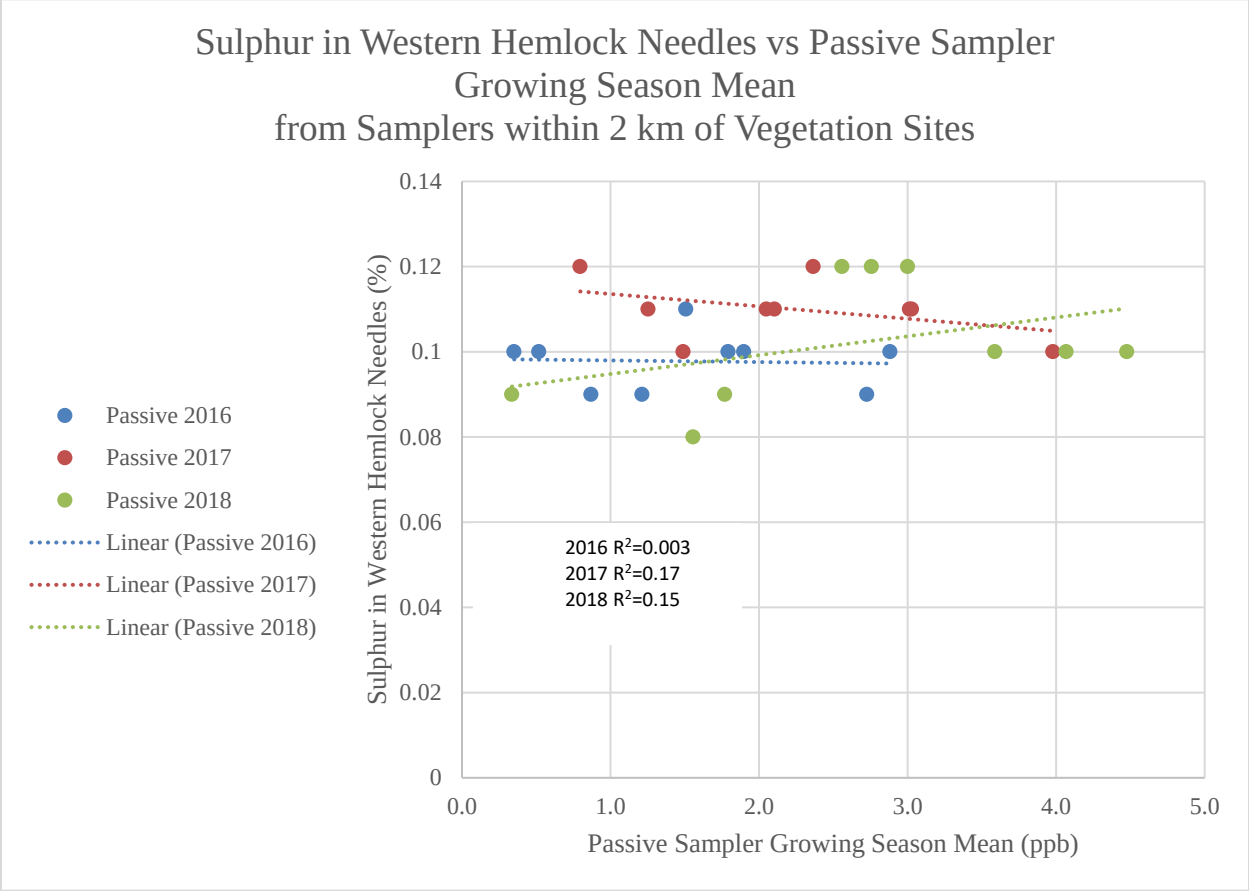


Figure 5-13. Relationship between needle S and growing season mean as measured with passive samplers at 9 sites within 2 km of vegetation sampling sites.

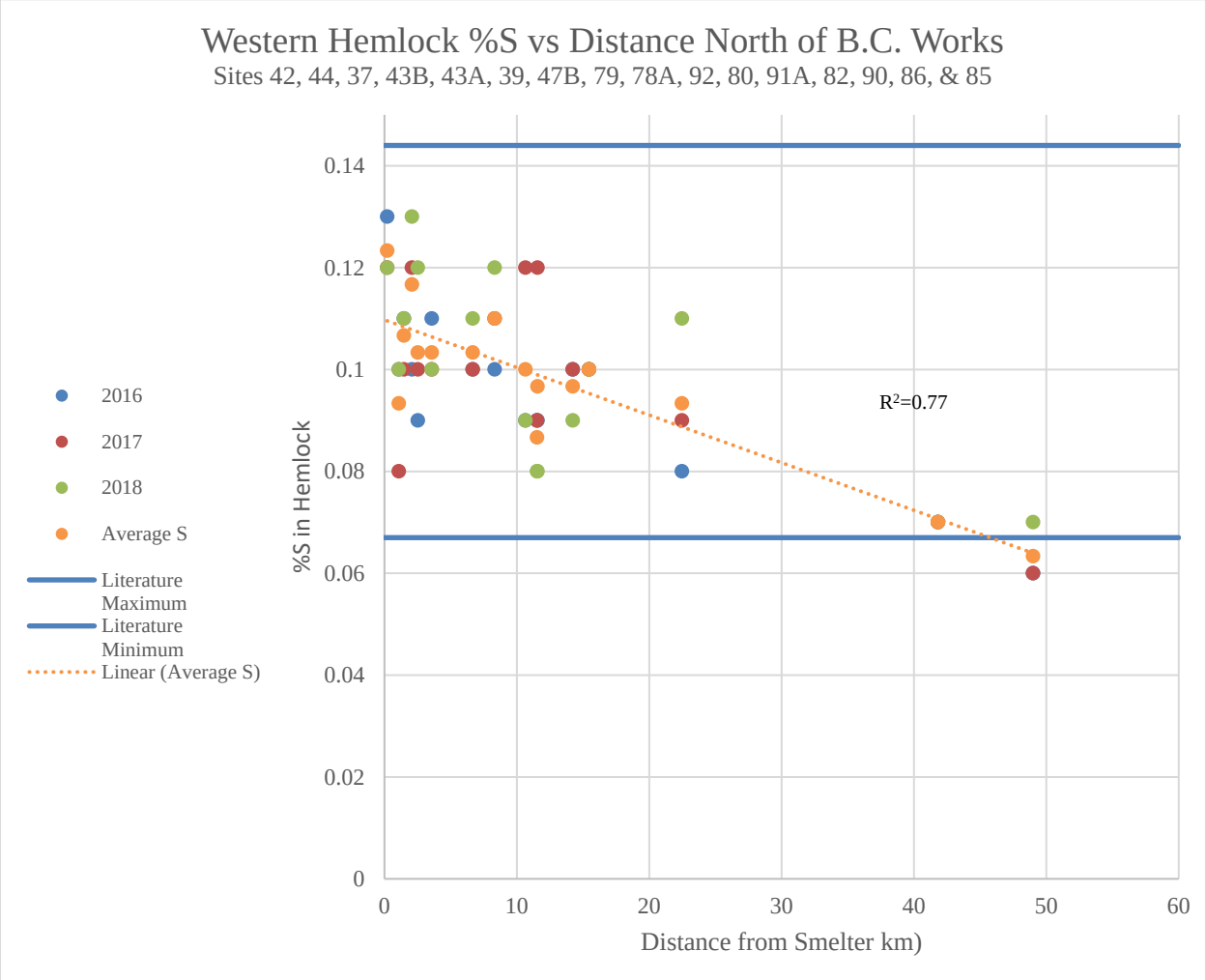


Figure 5-14. The relationship between %S in western hemlock and distance north of the smelter.

5.2.2.2 *Identification of areas of deposition of concern to vegetation, including lichens and ecosystems and species at risk*

We used the B.C. CDC search function to map the approximate locations of listed ecological communities, plants, and lichens at risk in the study domain (Figure 5-15). Exact locations of reported occurrences are not available to non-governmental users. The database does not contain an exhaustive survey but rather a catalogue of reported occurrences and the date of the report. Occurrences of listed species are not necessarily updated, so it is possible that the species or community no longer occurs at the location or that species and communities may occur at additional locations. Species and ecological communities that potentially occur in the study area and have a Provincial designation of Red or Blue may be found in Vegetation Appendix Tables 5.6.1 and 5.6.2.

The study domain has reported or historical occurrences of three listed lichens (*Nephroma occultum* [at two locations], *Pseudocyphellaria rainierensis*, and *Lobaria retigera*) and one listed plant (*Arctopoa eminens*). One listed ecological community, black cottonwood-red alder-salmonberry, occurs on the Skeena River near the northern extent of the study area. The array of sampling sites includes locations near the listed community and species, with the exception of *Arctopoa eminens*, which occurs near the southeast extent of the study domain and out of the modelled path of the plume. Reported locations for listed species and ecological communities are not in the area of predicted soil critical load exceedance. The estimated depositions at the modelling receptors closest to the sites are shown in Table 5-8. The reports from the B.C. CDC search may be found in Vegetation Appendix 5.6.

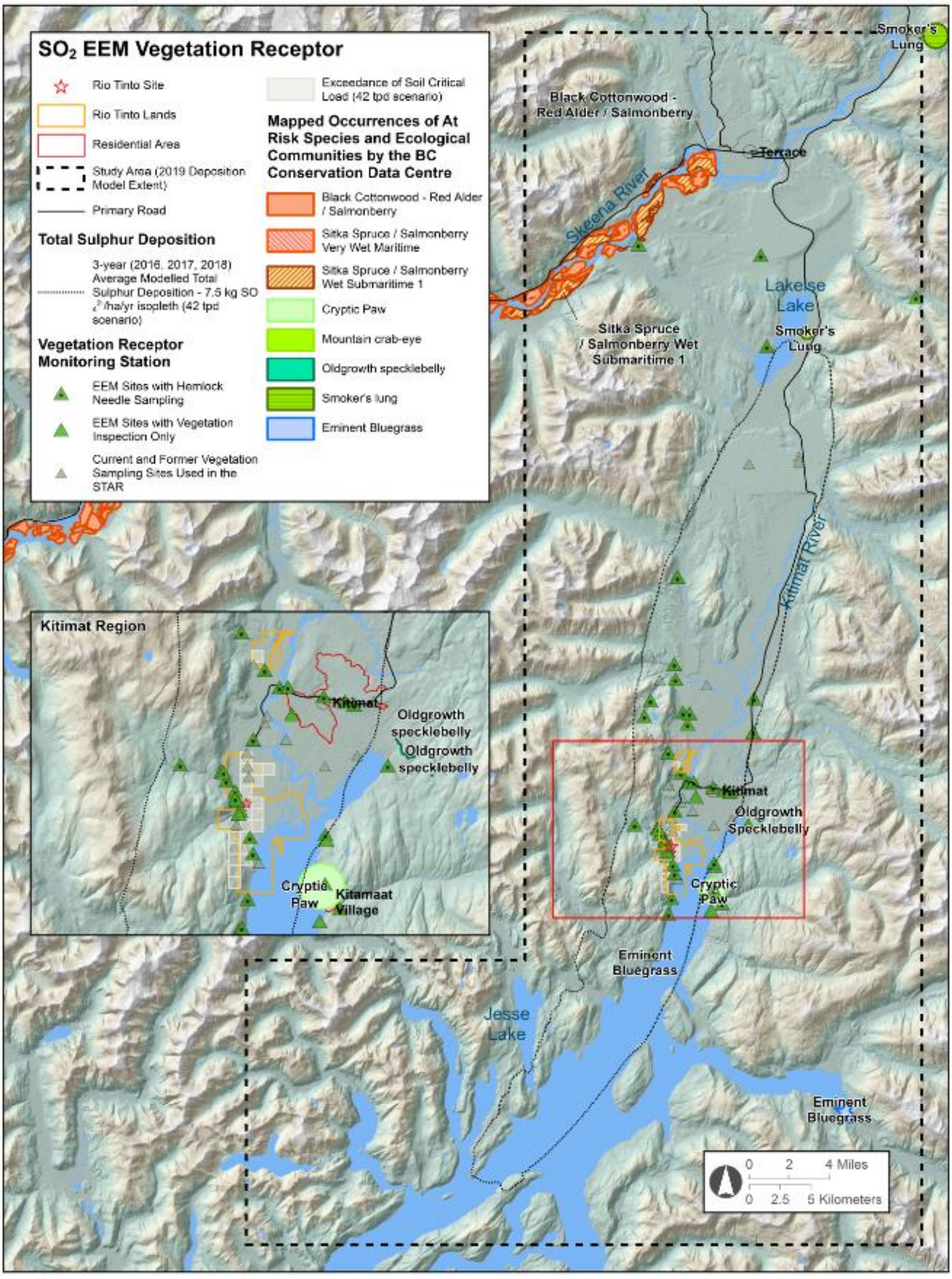


Figure 5-15. Approximate locations of listed ecological communities, plants, and lichens at risk in the study domain. The data are from the British Columbia Conservation Data Centre, accessed on February 14th, 2020.

Table 5-8. Estimated 3-year average SO_4^{2-} deposition from CALPUFF near reported sites with listed species or ecological communities. Deposition rates do not include a background of 3.6 kg SO_4^{2-}/ha/yr.

Species	Common Name	Conservation Status[1]	Actual Emissions	42 tpd
			SO_4^{2-} (kg/ha/yr)	
Nephroma occultum (Kitamaat vicinity)	Cryptic paw	Blue List Threatened/Special Concern	5.83	7.65
Nephroma occultum (Bish Cove vicinity)	Cryptic paw	Blue List Threatened/Special Concern	20.5	27.0
Pseudocyphellaria rainierensis	Old growth specklebelly	Blue List Special Concern	3.84	5.53
Lobaria retigera	Smoker's lung	Blue List Threatened	4.37	6.68
Arctopoa eminens	Eminent bluegrass	Red List Not listed	0.26	0.38
Populus trichocarpa-Alnus rubra-Rubus spectabilis	Black cottonwood-red alder-salmonberry	Blue List None	1.16	1.72

[1]Provincial designations of Blue or Red List followed by national designation.

All four sites with listed lichen species have a modelled SO_4^{2-} deposition under the actual emissions scenario that exceeds the suggested critical load for cyanolichens of 6.9 kg SO_4^{2-}/ha/yr (Geiser et al. 2019) when background deposition is added in. The caveats discussed previously such as modelling uncertainty and the importance of local factors that may influence suitable habitat apply here as well.

Table 5-9 shows the estimated area within the study domain that exceeds certain deposition thresholds. We estimate that under the actual emissions scenario (including background deposition), approximately 79,850 ha (22% of the comprehensive review study domain) exceed deposition of 7.5 kg SO_4^{2-} /ha/yr, the critical level proposed by Geiser et al. (*in preparation*) for the United States. A substantial part of that area (based on land cover mapping) does not support habitat needed for the most sensitive lichens, cyanolichens growing on conifers. That includes land use such as industrial lands or town sites, water bodies such as Minette Bay and lakes, and industrial forest land or land that has been logged and consists presently of second growth stands of western hemlock and Sitka spruce that are in the stem exclusion stage of development. Most current old growth habitat is off the valley floor at elevations above 500 m (J. Laurence, personal observation) and may be in areas of lower deposition. About 50% of the land area in the study domain is classified as conifer, with 8% of the study domain classified as dense conifer, greater than 60% crown closure, and 75% of the basal area made up of conifers (see Figure 6-3 for land cover in the Kitimat Valley). With forestry activities such as commercial thinning and variable density management, the large blocks of land harvested 30-50 years ago will move towards more suitable lichen habitat if they are not subject to future regeneration harvest or other intensive forestry practices. The rate at which lichens will re-establish depends on dispersion from old

growth refugia and could take decades, even with suitable habitat (Geiser et al. 2019; Richardson and Cameron 2004).

Table 5-9. Estimates of the area in the study domain subject to SO_4^{2-} deposition with and without 3.6 kg SO_4^{2-}/ha/yr background. Approximately 1% of the area with deposition greater than 5 kg SO_4^{2-}/ha/yr and less than 15 kg SO_4^{2-}/ha/yr is in Minette Bay.

SO_4^{2-} Deposition (kg/ha/yr)	Actual Emissions Case	% of Total Area	Actual Emissions Case + Background 3.6 kg SO_4^{2-} /ha/yr	% of Total Area	42 tpd Case	% of Total Area	42 tpd Case+ Background 3.6 kg SO_4^{2-} /ha/yr	% of Total Area
	ha	%	ha	%	ha	%	ha	%
0-2.5	234,925	64.3	0	0.0	180,800	49.5	0	0
2.5-3.7	45,250	12.4	875	0.2	57,075	15.6	0	0
3.7-5	24,050	6.6	156,150	42.7	35,000	9.6	108,775	29.8
5-7.5	21,650	5.9	128,475	35.2	34,650	9.5	135,350	37.0
7.5-10	12,375	3.4	33,550	9.2	16,025	4.4	51,625	14.1
>10	27,100	7.4	46,300	12.7	57,825	11.4	69,600	19.1

Old growth forest is an important component of a diverse ecosystem. Species, such as cyanolichens, that are sensitive to SO_2 often depend on old growth forest habitat. In addition, old growth forest serves as a refuge for many species that are otherwise affected by management activities such as right-of-way clearing, construction, and logging. The locations of non-legal Old Growth Management Areas in the study area were obtained from the B.C. Data Catalogue (https://catalogue.data.gov.bc.ca/dataset/old-growth-management-areas-non-legal-current accessed August 30, 2019). Only the non-legal (forest licensees may choose to manage for diversity in a variety of ways versus prescribed methods in legal old growth management areas) layer is available to non-government users.

Table 5-10 shows the land areas by vegetation type that fall within the 10 and 20 µg/m^3 annual average SO_2 isopleths. Under the actual emissions scenario, 9 to 20 ha (depending on year) of old growth management areas fall inside the 10 µg/m^3 (3.8 ppb) annual average SO_2 isopleth modelled by CALPUFF (Figure 5-5). Under the 42 tpd scenario, 177 to 304 ha of old growth management areas fall into the 10 µg/m^3 annual average SO_2 isopleth, depending on the year. No old growth management areas fall within the 20 µg/m^3 annual average SO_2 isopleth. We chose those levels for examination because the European Union has established 20 µg/m^3 annual average SO_2 (7.6 ppb) as a critical level to protect natural ecosystems and 10 µg/m^3 annual average SO_2 (3.8 ppb) as a critical level to protect sensitive lichens.

Table 5-10. Land areas by vegetation type under the actual and 42 tpd emission scenarios that fall within the 10 and 20 µg/m³ SO_2 isopleths. Land cover classifications are based on the Canadian Land Use Cover data (circa 2000) used in the SO_2 EEM Program and comprehensive review.

Scenario	SO_2 Isopleth	2016				2017				2018			
		Forest	Herb	Wetland	Shrub	Forest	Herb	Wetland	Shrub	Forest	Herb	Wetland	Shrub
		Hectares											
Actual	10	1110.7	508.7	42.5	102.9	1455.9	556.4	44.0	149.1	1593.5	549.8	47.0	151.1
	20	206.1	94.5	5.2	13.67	244.5	80.7	17.0	18.8	278.8	78.9	13.2	20.0
42 tpd	10	2642.8	757.6	92.1	332.7	3302.2	791.1	98.0	465.2	3688.4	803.7	90.8	456.4
	20	388.6	147.4	21.6	35.3	476.1	227.1	23.9	48.7	528.2	224.1	22.5	50.8

All or parts of 17 old growth management areas fall within the >5 kg SO_4^{2-}/ha/yr isopleth (>8.6 kg SO_4^{2-}/ha/yr including background) as shown in Figure 5-16. These areas are spatially defined areas of old growth forest and likely contain habitat that support the growth of cyanolichens. Accessibility of the sites could make them difficult to monitor directly

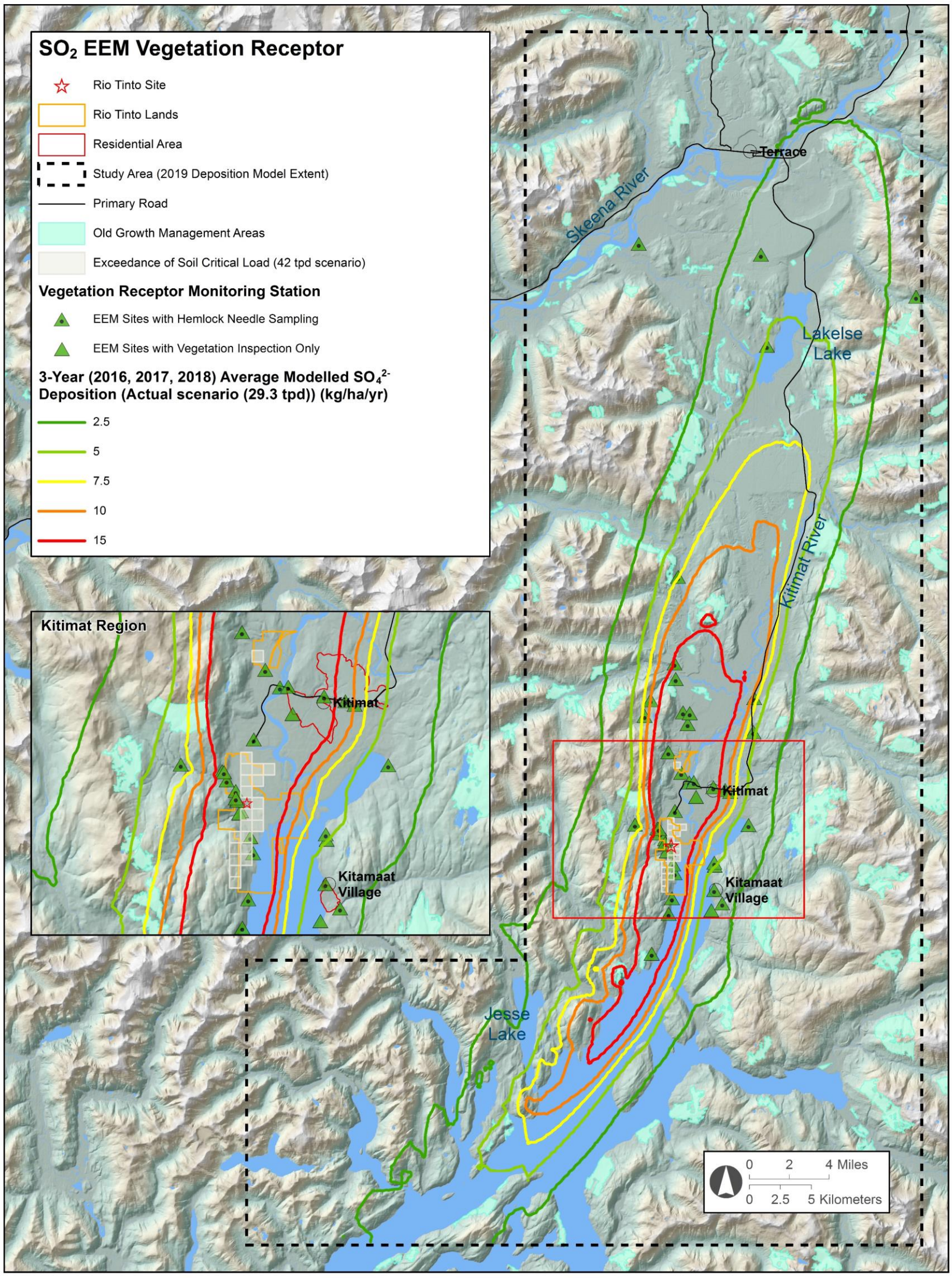


Figure 5-16. Location of old growth management areas in relation to modelled SO_4^{2-} deposition under the actual emission scenario. Isopleths shown are 2.5, 5, 7.5, 10, and 15 kg SO_4^{2-}/ha/yr. Deposition rate isopleths do not include background deposition of 3.6 kg SO_4^{2-}/ha/yr.

5.2.2.3 *Evaluation of post-KMP sulphur in western hemlock foliage to pre-KMP periods of interest*

Concentrations of F and S in current year needles of western hemlock in the Kitimat Valley have been a mainstay of the vegetation monitoring program for decades. Western hemlock was chosen as the bioaccumulator species for the program because it is not particularly sensitive to either HF or SO_2, thus the needles continue to accumulate pollutants throughout the growing season as opposed to plants that might be injured, as necrotic tissues do not continue to conduct gas exchange with the atmosphere.

During the STAR and subsequent design of the SO_2 EEM, the period of 1998-2011 was chosen and agreed upon as a baseline timeframe for pre-KMP S in western hemlock. That period represented a time of more-or-less consistent and continuous operation of the VSS smelter. In 2012 decommissioning of the VSS smelter began during construction and transition to the modernized smelter. Emissions of both HF and SO_2 declined as VSS reduction pots were removed from production.

In this review, we identified four periods of time for analysis: the pre-KMP baseline of 1998-2011, all years pre-KMP starting in 1998 (included at the request of ENV), 2015 which was during the transition to the new smelter and had very low SO_2 emissions compared to full operation, and post-KMP, 2016-2018.

All %S in western hemlock data used in the analyses reported below, graphs of the S concentrations versus smelter SO_2 emissions for each site, and box and whisker plots of %S in western hemlock needles for pre-KMP baseline (1998-2011), all years (1998-2018), and post-KMP (2016-2018) are found in Vegetation Appendix 5.5. Emissions data are used in place of deposition or air concentration, as comparable model estimates are not available pre-KMP. A total of 38 sites were sampled pre-KMP; two sites were added post-KMP as reference sites at the request of ENV. Figure 5-1 shows the location of the 40 sites that are currently sampled.

Analyses are based on data from 38 sites that existed pre-KMP. Reference sites are included post-KMP for comparison to other sites. Table 5-11 and Table 5-12 summarize those data for the purposes of this report. Figure 5-17 shows S data for all sites plotted against emissions which varied during the time period; thus, the graph is not chronological. The 2015 emission level is the lowest emission level on the graph. The line identifying the pre-KMP maximum emission level marks the transition to KMP; emissions greater than that are for the period 2016-2018. The graph shows that pre-KMP, some sites regularly exceeded 0.144%, the highest level reported for western hemlock in B.C. (Kayahara et al. 1995), however, no site has exceeded 0.14% since 2009 and so no sites have exceeded 0.144% post-KMP.

Comparison and assessment of post-KMP to pre-KMP baseline (1998-2011)

Table 5-11 and Table 5-12 identify one site out of 38 – site 89A – that had a post-KMP mean (2016-2018) that exceeded the SO_2 EEM baseline (1998-2011) but did so by less than 1 pre-KMP standard deviation. Site 89A is essentially co-located with site 89 (they are approximately 30 m apart) and had only two measurements pre-KMP. For the purposes of the vegetation inspection, sites 89 and 89A have always been considered one site. Site 89 did not exceed the EEM pre-KMP baseline mean.

Comparison and assessment of pre-KMP and post-KMP to 2015

We compared both pre-KMP and post-KMP to 2015, the year of low emissions of SO_2. When comparing pre-KMP to 2015, 33 sites decreased, but only 19 sites decreased by more than 1 standard deviation (data can be found in Vegetation Appendix 5.5). Twenty-five sites had a post-KMP mean S concentration greater than 2015 with increases ranging from 0.01% to 0.05% (the standard deviation of the analytical technique is ±0.01%). Five sites had post-KMP means that decreased (0.01 to -0.05%) and 8 sites showed no change from 2015. Only 5 of the 25 sites (69, 70, 78A, 80, and 82) that increased had an increase of more than 1 pre-KMP standard deviation (Table 5-12). Sites 69 (3.7 km ESE, 64 m elevation) and 70 (6.7 km ENE, 12 m elevation) are located on the east side of Minette Bay along the Kitamaat Village Road. They have not been disturbed recently and are representative of second-growth western hemlock forest with essentially the same vegetation as most other sites. Sites 78A (9.9 km, 32 m elevation), 80 (10.7 km, 53 m elevation), and 82 (14.8 km, 170 m elevation) north of Rio Tinto B.C. Works' aluminium smelter (referred to as "B.C. Works" in the remainder of this report) along the Wedeene Road. They, too, are undisturbed second growth western hemlock with an understory similar to almost all forested sites we sampled. Even with increased concentrations from 2015, they were well within the range of S in western hemlock needles reported in Kayahara et al. (1995) (Figure 5-18). Figure 5-18 shows foliar S concentration related to emissions which varied during the time period; thus, the graph is not chronological. The 2015 emission level is the lowest emission level on the graph. The line identifying the pre-KMP maximum emission level marks the transition to KMP; emissions greater than that are for the period 2016-2018.

Comparison and assessment of post-KMP to all pre-KMP 1998-2014

One site (89A) had a post-KMP mean (2016-2018) that exceeded the mean of all pre-KMP years (1998-2015) but by less than 1 standard deviation (Table 5-11 and Table 5-12). That result is expected as 2012 to 2014 was a period in which average monthly emissions decreased as production was reduced.

Table 5-11. Mean and standard deviation sulphur concentrations in western hemlock for the EEM baseline period (1998-2011), all years pre-KMP (1998-2014), 2015 (a historically low emission year), and post-KMP (2016-2018). The complete S in western hemlock data set is in Vegetation Appendix 5.4. Precision of the analytical technique is ±0.01%.

Site	EEM Mean (1998-2011)	EEM SD (1998-2011)	All Years Pre-KMP Mean (1998-2015)	All Years Pre-KMP SD (1998-2015)	2015	Post KMP (2016-2018)	Post-KMP SD
%S in current year needles							
1	0.10	0.02	0.09	0.03	0.07	0.07	0
20	0.12	0.02	0.12	0.03	0.07	0.08	0.01
37	0.16	0.03	0.15	0.03	0.11	0.11	0.01
39	0.13	0.02	0.12	0.03	0.09	0.10	0.01
42	0.16	0.03	0.15	0.04	0.12	0.09	0.01
43A	0.15	0.02	0.14	0.02	0.11	0.12	0.02
43B	0.16	0.04	0.15	0.04	0.07	0.10	0.02
44	0.16	0.04	0.15	0.04	0.09	0.12	0.01
44A	0.17	0.04	0.16	0.04	0.11	0.11	0.02
46	0.16	0.03	0.15	0.04	0.13	0.11	0.00
47B	0.12	0.02	0.12	0.02	0.09	0.10	0.01
52A	0.10	0.02	0.10	0.03	0.08	0.09	0.01
54	0.10	0.01	0.10	0.02	0.06	0.06	0.01
55	0.10	0.01	0.09	0.02	0.07	0.07	0.01
56	0.09	0.02	0.08	0.02	0.06	0.07	0.01
57	0.09	0.03	0.08	0.03	0.05	0.06	0.01
68	0.09	0.01	0.08	0.02	0.07	0.08	0.02
69	0.09	0.01	0.08	0.02	0.06	0.08	0.01
70	0.09	0.01	0.09	0.01	0.06	0.08	0.01
78A	0.14	0.03	0.12	0.04	0.06	0.10	0.02
79	0.12	0.03	0.12	0.03	0.1	0.11	0.01
80	0.11	0.01	0.11	0.01	0.07	0.10	0.02
81B	0.14	0.04	0.13	0.04	0.06	0.09	0.01
81C	0.11	0.03	0.11	0.03	0.09	0.11	0.02
82	0.11	0.02	0.10	0.02	0.07	0.10	0.00
84AB	0.08	0.01	0.08	0.01	0.07	0.07	0.00
85	0.08	0.02	0.08	0.02	0.05	0.06	0.01
86	0.08	0.02	0.08	0.02	0.08	0.07	0.00
87	0.14	0.04	0.13	0.04	0.12	0.12	0.02

Site	EEM Mean (1998-2011)	EEM SD (1998-2011)	All Years Pre-KMP Mean (1998-2015)	All Years Pre-KMP SD (1998-2015)	2015	Post KMP (2016-2018)	Post-KMP SD
%S in current year needles							
88	0.13	0.02	0.13	0.02	0.09	0.10	0.01
89	0.14	0.03	0.14	0.03	0.1	0.11	0.01
89A	0.11	0.02	0.10	0.01	0.1	0.11	0.01
90	0.10	0.02	0.10	0.03	0.08	0.09	0.02
91A	0.10	0.02	0.10	0.02	0.14	0.10	0.01
92	0.10	0.02	0.10	0.02	0.09	0.09	0.01
95	0.08	0.02	0.08	0.02	0.07	0.07	0.01
97	0.09	0.02	0.09	0.02	0.09	0.08	0.01
98A	0.08	0.02	0.08	0.01	0.08	0.07	0.01
490						0.07	0.01
492						0.07	0.01

Table 5-12. Difference in S concentration between post-KMP and pre-KMP for the EEM baseline (1998-2011) and for all pre-KMP years (1998-2014), and for post KMP and 2015. Precision of the analytical technique is ±0.01%.

	% S Post-KMP – Pre-KMP EEM baseline (1998-2011) (Positive=Increase)	Greater than 1 SD?	Post-KMP – Pre-KMP (All Years) Positive is Increase	Greater than 1 SD?	% S Post-KMP – 2015 (Positive=Increase)	Greater than 1 SD?
1	-0.03	NO	-0.02	NO	0.00	NO
20	-0.04	NO	-0.03	NO	0.01	NO
37	-0.05	NO	-0.04	NO	0.00	NO
39	-0.03	NO	-0.02	NO	0.01	NO
42	-0.07	NO	-0.06	NO	-0.03	NO
43A	-0.03	NO	-0.02	NO	0.01	NO
43B	-0.05	NO	-0.04	NO	0.03	NO
44	-0.03	NO	-0.03	NO	0.03	NO
44A	-0.06	NO	-0.05	NO	0.00	NO
46	-0.05	NO	-0.04	NO	-0.02	NO
47B	-0.02	NO	-0.01	NO	0.01	NO
52A	-0.01	NO	0.00	NO	0.01	NO
54	-0.05	NO	-0.04	NO	0.00	NO
55	-0.02	NO	-0.02	NO	0.00	NO
56	-0.02	NO	-0.02	NO	0.01	NO
57	-0.03	NO	-0.02	NO	0.01	NO
68	-0.01	NO	-0.01	NO	0.01	NO
69	-0.01	NO	-0.01	NO	0.02	YES
70	-0.01	NO	-0.01	NO	0.02	YES
78A	-0.04	NO	-0.02	NO	0.04	YES
79	-0.01	NO	-0.01	NO	0.01	NO
80	-0.02	NO	-0.01	NO	0.03	YES
81B	-0.05	NO	-0.03	NO	0.03	NO

	% S Post-KMP – Pre-KMP EEM baseline (1998-2011) (Positive=Increase)	Greater than 1 SD?	Post-KMP – Pre-KMP (All Years) Positive is Increase	Greater than 1 SD?	% S Post-KMP – 2015 (Positive=Increase)	Greater than 1 SD?
81C	0.00	NO	0.00	NO	0.02	NO
82	-0.01	NO	0.00	NO	0.03	YES
84AB	-0.01	NO	-0.01	NO	0.00	NO
85	-0.02	NO	-0.01	NO	0.01	NO
86	-0.01	NO	-0.01	NO	-0.01	NO
87	-0.02	NO	-0.01	NO	0.00	NO
88	-0.03	NO	-0.03	NO	0.01	NO
89	-0.03	NO	-0.03	NO	0.01	NO
89A	0.01	NO	0.01	NO	0.01	NO
90	-0.01	NO	0.00	NO	0.01	NO
91A	0.00	NO	0.00	NO	-0.04	NO
92	-0.01	NO	-0.01	NO	0.00	NO
95	-0.01	NO	-0.01	NO	0.00	NO
97	-0.01	NO	-0.01	NO	-0.01	NO
98A	-0.01	NO	-0.01	NO	-0.01	NO

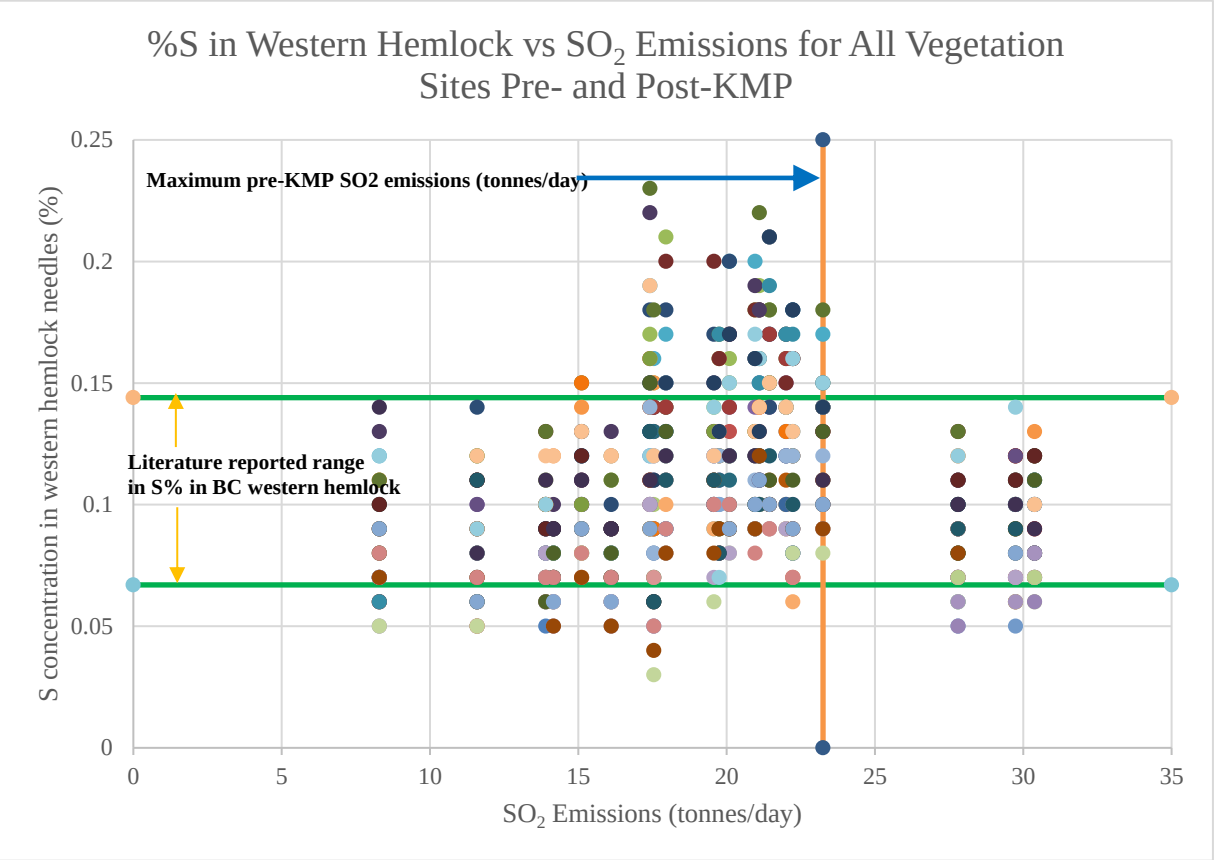


Figure 5-17. Sulphur concentration in current year needles of western hemlock at all sampling sites, for all years. Literature maximum and minimum are reported in Kayahara et al. (1995) for western hemlock in British Columbia. Individual site graphs can be found in Vegetation Appendix 5.5.

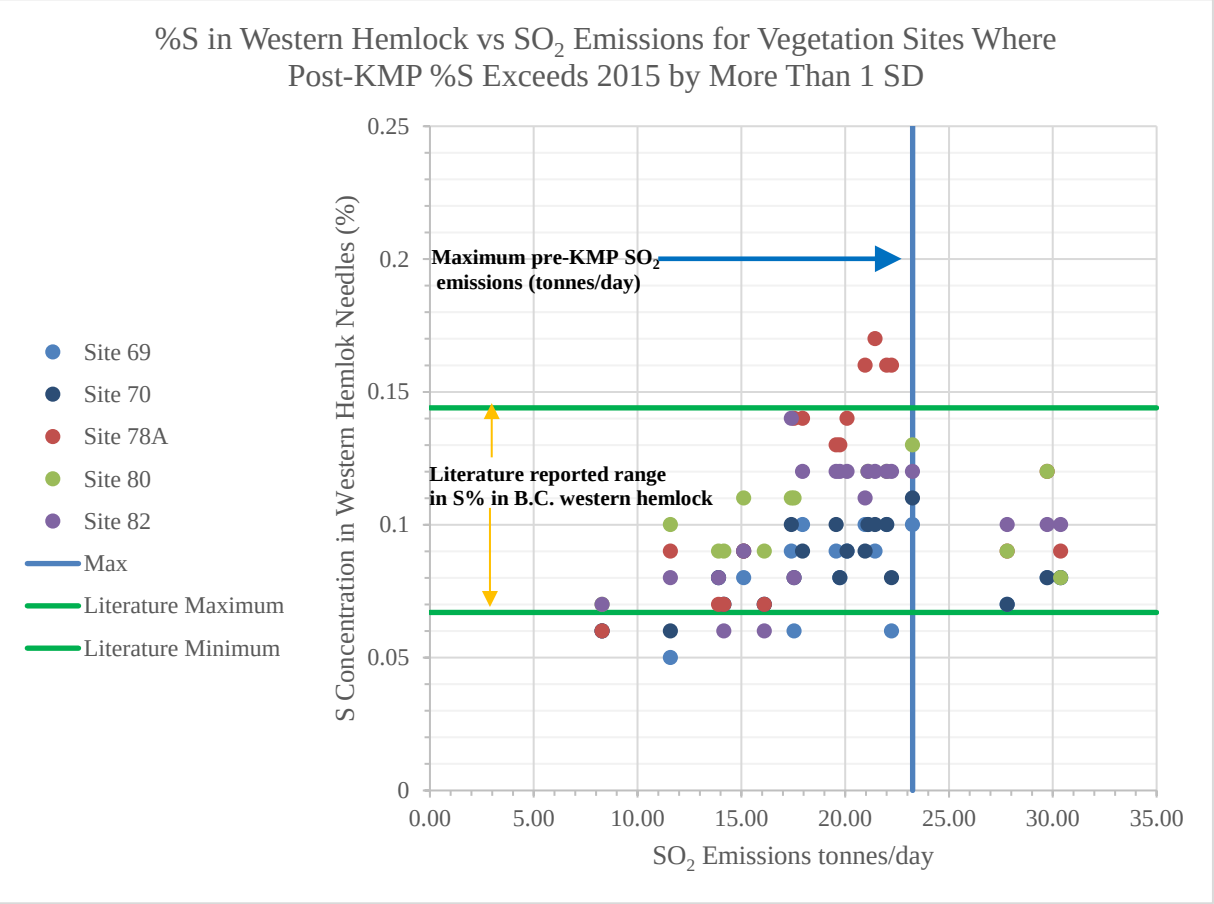


Figure 5-18. Sulphur concentration in western hemlock needles where the difference between post-KMP and 2015 exceeded one pre-KMP standard deviation (Sites 69, 70 ,78A, 80, and 82). Literature maximum and minimum are reported in Kayahara et al. (1995) for western hemlock in British Columbia. Individual site graphs can be found in Vegetation Appendix 5.5.

5.2.2.4 *Evaluation of the value and coverage of vegetation sampling sites using S and F in western hemlock foliage and soils information*

Based on 3 years of post-KMP sampling and analysis of S and F in western hemlock needles, the results do not significantly contribute to the understanding of the dispersion of the plume from the smelter that is gained from active and passive sampling of SO_2 concentrations and dry and wet deposition estimates from NADP collectors. The variability in S concentration in needles throughout the Kitimat Valley could not be extrapolated spatially; attempts using regression kriging were unsuccessful in creating isopleths of S concentration in hemlock (J. Aherne, personal communication). Only one site exceeded the pre-KMP baseline and there is generally a poor correlation with estimates of air concentration of SO_2 or deposition of SO_4^{2-}. In an evaluation of sites conducted in 2019, only 4 sites were found to have a relationship between S in needles and SO_2 emissions that accounted for more than 50% of the variation in the dataset (Vegetation Appendix 5.2). Correlations with needle S content and estimates of SO_2 air concentration or SO_4^{2-} deposition were even lower.

Post-KMP, S content of needles has increased since 2015, however, all sites remain below the maximum S content in western hemlock in B.C. reported by Kayahara et al. (1995).

The reduction in F emissions has resulted in a measured reduction of F in western hemlock needles. Post-KMP, only 12 sites have an average needle concentration greater than 15 ppm and 9 of those sites are on Rio Tinto property. Only 8 sites have an average concentration greater than 20 ppm with a maximum of 31 ppm. For all intents and purposes, post-KMP F concentrations in needles off-site are at or near background levels. Background F concentrations in most vegetation is considered to be from about 2 to 20 ppm (Weinstein and Davison 2004). Based on almost 50 years of measurement of F in western hemlock in the vicinity of B.C. Works, we estimate background concentrations to be 10 ppm or less.

Soils information does not supplement what is learned from sampling and analyzing foliage as S is not measured at soil plots because it is generally very low. It is regarded as a mobile ion and the largest pool may be associated with organic matter rather than deposition (J. Aherne, personal communication). Soils do contain substantial amounts of F but it is not generally taken up by plants nor is it an essential element as is S (Weinstein and Davison 2004).

Two vegetation sampling and inspection sites (1 and 20) are located in the area of predicted soil critical load exceedance (under the 42 tpd emissions scenario) and eight additional sites (87, 42, 44, 43B, 46, 37, 39, and 47B) are within 700 m of an area of predicted soil critical load exceedance. One additional inspection location, Moore Creek Falls, is in the area of predicted soil critical load exceedance. No signs or symptoms associated with soil acidification were observed at any site; vegetation at the sites post-KMP was typical of vegetation in the rest of the valley.

5.2.2.5 *Evaluation of the results of vegetation inspections pre- and post-KMP for visible injury and plant health*

Results of visible injury inspections

No visible injury due to SO_2 was observed at any location post-KMP. Visible injury due to SO_2 has not been reported in the results of the vegetation monitoring program since before 1999. Injury to sensitive vegetation due to HF has decreased substantially since the early 2000s. By 2014, injury was only observed in the immediate vicinity of Rio Tinto at locations such as the administration building and visitor center. No injury due to HF has been observed at any site post-KMP.

Results of plant health assessment

Plants in the Kitimat Valley show a normal range of conditions driven primarily by the growing conditions at the site and weather of the year. Growing conditions vary dramatically from site to site. For instance, some sites are relatively undisturbed by industrial activity or forest management practices. Other sites have been affected by construction of powerlines, work camps, new industrial facilities, and by forest harvest. Some sites close to the smelter have been cleared of natural vegetation in the past and continue to show signs of the legacy of more than 60 years of industrial activity. Many sites have disturbed soils that are more subject to drought due to increased drainage though gravelly and sandy soils.

In general, plants in the Kitimat area suffer from the same pathogens, pests, and environmental stressors (with the exception of industrial emissions) as may be observed at locations distant from the smelter such as Terrace or the reference vegetation sites in the Williams Creek drainage. Generally, on a year to year basis, rainfall and temperature are the most important drivers of plant health. In some years, such as 2018, low summer rainfall causes early senescence of leaves and needles, particularly on drier sites. Early or late frosts also cause growing season effects. To this point these normal stresses have not resulted in permanent effects that can be observed. If projections play out, future climate could alter ecosystem health, particularly for forests on thin soils subject to increased evapotranspiration, due to increased temperatures that will deplete soil moisture.

Vegetation in the areas of soil critical load exceedance under actual emissions and predicted under the 42 tpd maximum permitted level were inspected. No unusual signs or symptoms were observed at sites 1 and 20 or along Smeltersite Road (in the area of critical load exceedance under actual emissions). Areas of soil critical load exceedance under the actual emissions that are to the south of LNG Canada were not accessible. Visual inspection when flying over the area did not reveal any unusual observations.

We conclude that no change in the general condition of vegetation has been observed post-KMP.

Comparison of visible injury pre- and post-KMP

There was no SO_2 injury pre-KMP and none has been observed post-KMP. No visible injury due to HF has been observed post-KMP.

Extent of insect infestations and disease epidemics with regard to plant health

A slight infestation of hemlock woolly adelgid began about 2014. It was at a very low level and was found primarily at sites near the smelter and not at other sites inspected in the valley. The intensity varies from year to year but has improved since 2014. Stantec Consulting Ltd. and Laurence (2019) reported detecting adelgids at 13 of 40 sites, down from 18 sites in 2017. They report extent of the infestation as % of sample branch and sample tree affected. In only one case did the percent of a branch affected exceed 5% and no more than 2% of a single tree was affected. Their estimates indicate that the woolly adelgid is not occurring at a significant level nor is it affecting the general health of trees in the area. No adelgid infestations were observed during a survey completed in September 2019 (J. Laurence, personal communication).

There are no current plant disease epidemics occurring in the Kitimat area. Normal levels of diseases such as poplar rust, dwarf mistletoe, tar spot, and various fungal leaf spot diseases occur throughout the Kitimat Valley.

We conclude that there has been no increase in the incidence or severity of insects and plant disease post-KMP.

Presence of species selected by ENV pre- and post-KMP

In 2014, at the request of ENV, we added a checklist of plants to the vegetation inspection protocol. The list is a subset taken from Tables 3-2 and 3-3 in Legge et al. (1998). In those tables, the species are reported to be "relatively sensitive to SO_2", however, "relatively sensitive" is not defined, nor are references provided for the species in the list. The agreed-upon protocol for the program was for the QP conducting the inspection to note the presence of the species on the list. Since the inspection does not utilize a defined area at each site, the resulting checklist is not a quantitative assessment of biodiversity—it only indicates that the species was observed during the visit.

Presence or absence of many species will be determined by the growing conditions at the specific site, thus the "absence" of species close to the smelter may be driven more by physical disturbance than by any other condition, for instance the presence of higher concentrations of SO_2 or greater deposition of SO_4^{2-}.

The results do not show any clear pattern (other than some taxonomical confusion in the genera of *Alnus* and *Sorbus*), just three years post-KMP. However, we recommend a change in protocol be considered that would define an area of observation and catalog the species within that area in order to detect change.

The complete dataset is provided in Vegetation Appendix 5.7.

5.2.2.6 *Suitability of KPI and informative indicator based on 2016-2018 results*

KPI

At the time of the STAR, modelled air concentrations were such that visible injury to sensitive vegetation, although unlikely, was possible. In addition, since the sensitivity of most vegetation in the Kitimat area to SO_2 is not documented in the scientific literature, a cautious approach was taken and the KPI was established based on visible injury. Given the results of air monitoring post-KMP, it now appears extremely unlikely that the threshold concentration for visible injury will be exceeded for any species. Furthermore, the maximum off-site concentrations modelled are substantially below the thresholds to protect sensitive vegetation identified in the STAR and recently confirmed in the scientific literature (European Union 2008; U.S. EPA 2018).

Given results to date, the KPI is not suitable to be used to trigger increased monitoring or facility mitigation.

Informative indicator

The informative indicator is currently based on S concentration in current year needles of western hemlock. It is of limited value due to natural range of variability of %S in western hemlock needles plus the variability in the analytical technique (±0.01%).

Pre-KMP, the correlation between emissions and %S in foliage was greater than 0.6 in fewer than half the sites. Post-KMP, the sulphur concentration in foliage has decreased from the pre-KMP mean and has not exceeded the reported range for S in western hemlock foliage in British Columbia. The relationship between %S in western hemlock needles and CALPUFF-modelled

SO_2 concentrations and SO_4^{2-} deposition is not strong: no air concentration averaging period or deposition estimate explained more than 35% of the variation in the %S in western hemlock.

The informative indicator was poorly correlated with nearby passive samplers. Passive samplers provide a clear advantage over measuring S in needles as they can be calibrated and provide estimates of both air concentration of SO_2 and deposition of SO_4^{2-}.

Alternative KPIs and informative indicators based on the scientific literature

The question of whether emissions from the modernized smelter will directly injure sensitive vegetation in the Kitimat Valley has been answered. Monitored concentrations of SO_2 are far below the thresholds established in the scientific literature and in use by regulatory agencies in North America and Europe. The results to date and knowledge from the scientific literature point to creating a Terrestrial Ecosystems Line of Evidence that has KPI(s) focused on detecting mid- to long-term effects of S deposition. Given the SO_2 concentrations and deposition at most off-site locations, it is likely that if effects on vegetation occur, they will be long-term and mediated through soil acidification. Therefore, the Soil Critical Load KPI is an appropriate KPI for vegetation effects as well.

An informative indicator could be focused on biodiversity plots where both the overstory and understory are mapped and re-visited periodically. Changes in the biodiversity over time that are not related to natural causes or climate change could be used to imply long-term response to deposition and inform the Soil Critical Load KPI. A study to identify appropriate locations and establish necessary sample sizes and frequencies would need to be conducted to establish plant biodiversity as an informative indicator.

An informative indicator related to tree growth could be considered. A tree-ring study could be undertaken—most likely delayed until at least 10 years post-KMP to allow time for response separate from climate—to determine pre- and post-KMP growth rates of appropriate tree species. We investigated the use of the Canadian National Forest Inventory plots however the coverage in the study domain is too sparse to provide a useful tool for assessing tree growth. Only two ground plots are located in the area and both are out of the plume path. Given the importance of changing climate, it will be necessary to detect and remove that signal from the growth record. We believe plots established by the then Ministry of Forestry in the 1970s to assess regeneration potential in the Kitimat Valley are also too few, and without suitable controls, to be used in the future other than to provide anecdotal information or to be used in a tree-ring study.

Periodic inspections to document plant health and to detect potential changes related to insects, diseases, climate change, and other environmental stress should be used as an informative indicator in the Terrestrial Ecosystems Line of Evidence. Changes in plant health associated with B.C. Works and in areas of critical load exceedance would inform both the Terrestrial and Aquatic Lines of Evidence.

ENV has established lichen plots in the Kitimat Valley and those plots should be revisited 5 years after initiation to document changes in lichen communities that might indicate effects of increased deposition of SO_4^{2-} or community recovery due to reductions in F emissions.

5.3 What Did We Learn, and Did We Make Any Adjustments to the EEM Program?

5.3.1 Knowledge gained

5.3.1.1 *Summary and interpretation of updated scientific literature on the effects of SO_2 and soil/air acidification on vegetation including lichens*

Higher vegetation

Little new information on the direct effects of SO_2 has been reported since the STAR. The controlled fumigation studies that have been conducted have used plant species that are not relevant to the SO_2 EEM. Exposures (concentration x time) used in the studies also far exceed those that occur in the Kitimat Valley.

Since the STAR, Canada has adopted new ambient air quality standards and the European Union and U.S. EPA have retained their SO_2 concentration recommendations and standards. The CAAQS are in line with the European recommendation of an annual average of 10 µg/m^3 to protect sensitive lichens and natural ecosystems. The U.S. secondary NAAQS continues to be based on a short term, high concentration rather than an annual or growing season average.

New methods for detecting long-term effects of SO_4^{2-} deposition have been reported (see Section 5.1.4.1) and point to the use of measures of biodiversity (species richness and abundance) in relation to deposition in order to detect effects on trees, understory shrubs, and herbaceous plants (Clark et al. 2019; Horn et al. 2018). These new large-scale studies have, in some cases, proposed critical loads to protect plant biodiversity. Working at large scale, however, essentially removes local topographic, habitat, and climate variability so implementing a program at a local scale will require careful selection of measurement sites.

Lichens and mosses

Research since the STAR has focused on calculating critical loads to protect lichens and the use of mosses as bioaccumulators of metals. In the US, a national critical load of S of 2.5 kg/ha/yr (7.5 kg SO_4^{2-} has been proposed with a slightly lower critical load of 2.3 kg S/ha/yr (6.9 kg SO_4^{2-} /ha/yr) identified for cyanolichens. As with higher vegetation, implementation of the methodology at a local scale requires careful attention to topography, climate, and habitat disturbance.

5.3.1.2 *Summary and interpretation of post-KMP CALPUFF air concentration and deposition modelling with regard to vegetation thresholds*

Post-KMP SO_2 concentration modelling results are well below the thresholds of concern for visible injury to vegetation. Monitoring (both active and passive) and modelling results delineate an area where the growing season average SO_2 concentrations exceed the levels established in Canada and Europe to protect sensitive lichens and natural ecosystems. The area exceeding 20 µg/m^3 (7.6 ppb) is mostly restricted to the industrialized part of the valley near the smelter. Under the 42 tpd maximum permitted level scenario, the area exceeding 10 µg/m^3 (3.8 ppb) extends about 25 km to the north and 7 km to the south of the smelter. A considerable portion of the area is managed for commercial timber harvest and would not, in our opinion,

be classified as a sensitive natural system. It is likely that these areas have been exposed to elevated concentrations of both SO_2 and HF for decades.

Post-KMP CALPUFF modelling and passive monitoring delineates areas of the valley where SO_4^{2-} deposition rates exceed those thought to represent critical loads to protect sensitive lichen species. While much of the area is not currently suitable habitat for cyanolichens, there are old growth forest patches present where modelled deposition exceeds published estimates of regional to national critical loads. Caution must be used when down-scaling those estimates, however, as they don't take into account climate, topography, and other factors that may affect the suitability of habitat regardless of SO_4^{2-} deposition. In addition, some old growth habitat is in an area affected by the industrial legacy.

5.3.1.3 *Summary and interpretation of pre- and post-KMP sulphur concentrations in western hemlock foliage*

Sulphur concentrations in western hemlock needles post-KMP (with one exception, site 89A) do not exceed the pre-KMP baseline (1998-2011). Using all pre-KMP years (1998-2014), the results are the same. In neither case did site 89A exceed the mean by more than 1 standard deviation. No site since 2009 has exceeded the maximum measured S concentration of 0.144% reported for western hemlock needles province-wide in B.C., including post-KMP. Based on post-KMP measurement, all sites are within the range reported in the scientific literature. Sulphur concentration in western hemlock is weakly related to measures of air concentration or deposition modelled with CALPUFF and only slightly more related to emissions from the smelter. Estimates of air concentration and deposition did not account for more than 35% of the variation in needle S; measures of emissions appear to have a different relationship to needle S concentrations post-KMP as, although emissions have increased, S in needles has declined from the pre-KMP baseline.

5.3.1.4 *Summary and interpretation of pre-and post-KMP vegetation inspections*

No symptoms of injury due to SO_2 or F have been observed post-KMP. Injury due to SO_2 was not observed pre-KMP. No insect outbreaks or plant disease epidemics have been noted beyond what would be considered normal incidence and severity levels. Hemlock woolly adelgid did occur on some trees near the smelter, but at levels that are of no concern to the health of the trees. Environmental stresses such as drought have the greatest impact at this time.

5.3.1.5 *Summary and interpretation of the value of vegetation sampling and inspection locations*

The sampling array was well-aligned with the plume path as determined by CALPUFF modelling given the constraints of accessibility due to terrain. Sites accessed by helicopter did provide an opportunity to sample vegetation at higher elevation but did not reveal any unique responses to changes in emissions. Sulphur concentrations in hemlock needles at reference sites (490 and 492), at sites near Terrace (84A, 85, and 86), and sites on the east side of the bay (68, 69, 70 and 95) were similar, ranging from 0.07% to 0.08%.

Given the post-KMP results, neither S nor F in needle tissue provided information that is predictive or explanatory vis-à-vis emissions from the smelter. The sites do provide an adequate array for periodic visual inspection to document plant and ecosystem health. In many

cases, the inspection sites are near both ENV lichen plots and the few approximate locations – exact locations are not available – of listed plant species in the Kitimat Valley.

Ten existing vegetation sampling sites and one supplementary inspection site (Moore Creek Falls) are either in (2 sites plus Moore Creek Falls) or within 700 m of areas of predicted soil critical load exceedance (42 tpd scenario) and provide adequate coverage of the area at or near the valley floor. Vegetation inspections are currently made from the air over the inaccessible parts of the predicted soil critical load exceedance extent.

5.3.2 Modifications to the EEM Program

Going forward, the EEM Program will face added challenges due to changes in climate that are forecasted and will affect ecosystem health in the Kitimat Valley. Warmer, drier summers and wetter winters with reduced snowpack will introduce stresses that are likely to exceed the effects of SO_2 emissions on vegetation. Any modifications to the EEM need to recognize changes that will occur over the lifetime of the modernized smelter.

5.3.2.1 *Potential changes to the KPI and informative indicator*

KPI

The question of whether vegetation would be injured by short-term, high concentration exposures to SO_2 has been answered: no direct injury of vegetation has been observed and results from both the passive and active monitoring programs show concentrations far below those that would cause such injury. The KPI was not exceeded post-KMP and based on modelling and monitoring completed as part of this review, we believe it is highly unlikely that visible injury due to direct effects of SO_2 will occur in the future. For that reason, we recommend that the KPI based on visible injury to vegetation be discontinued. Results to date lead us to believe that any effects on vegetation are likely to be mediated through effects of SO_4^{2-} deposition and the resulting acidification of soils and substrates for organisms such as lichens and mosses. The soil critical load KPI supported with an informative indicator based on plant biodiversity should be sufficient to protect vegetation and sensitive ecosystems.

Informative indicator

The informative indicator has not proven effective either as an indicator of potential stress on vegetation (e.g. the concentrations of sulphur in western hemlock needles have not exceeded those reported as within the natural range for the species in B.C.) or as a surrogate for monitoring as it is poorly correlated with other monitoring and modelling methods. To a large extent, the array of vegetation sampling sites in the plume path now corresponds with the passive monitor network that provides estimates of both air concentration and deposition. The latter is particularly important with regard to potential acidification of the ecosystem. We recommend the collection of western hemlock needles for chemical analysis be discontinued.

Alternative KPIs and informative indicators

We recommend that a Terrestrial Ecosystem Line of Evidence be developed that utilizes the Soil Critical Load KPI and informative indicators of plant biodiversity, assessment of plant health, and perhaps tree growth determined by tree ring analysis at a future date. In order to

implement the Terrestrial Ecosystem Line of Evidence, we recommend that a pilot study to determine the extent and intensity of a series of plant biodiversity measurement plots be undertaken with the aim of developing a new informative indicator.

5.3.2.2 Potential adjuncts to the present vegetation sampling and inspection program

The present vegetation sampling and inspection program should be aligned to support a Terrestrial Ecosystem Line of Evidence. Periodic inspections of a subset of the current sampling and inspection sites should be continued to document plant and ecosystem health and the incidence and severity of any insect outbreaks or disease epidemics, and potential changes due to climate change (e. g. drought, early or late frost, and root/soil freezing).

5.3.3 Comprehensive synthesis ('pulling the pieces together')

5.3.3.1 *Relation of vegetation results to soil and aquatic critical load results*

We found no signs or symptoms related to plant health associated with the predicted areas of exceedance (under the 42 tpd scenario) of soil or aquatic critical loads. Eleven sampling and/or inspection sites are located in or near the area of predicted soil critical load exceedance and provide adequate coverage to detect effects of acidification, had any been apparent. No symptoms were observed from a recent aerial survey of the predicted area of soil critical load exceedance. In the case of the aquatic line of evidence, no vegetation sampling and/or inspection sites are located adjacent to EEM lakes. An aerial survey conducted as part of the vegetation program included flying over some of the EEM lakes and we did not observe anything out of the ordinary.

While the areas of predicted soil critical load exceedance have been exposed to considerable deposition in the past, it is possible that it will take some time soil critical loads to manifest with regard to vegetation in the areas of predicted exceedance. If and when it does, it will most likely be through changes in plant communities or a decline in the health of acid-sensitive species.

5.3.3.2 Potential changes to vegetation sampling array

Based on results post-KMP, we conclude that vegetation sampling and analysis should be discontinued.

5.3.4 Conclusions

5.3.4.1 *Effectiveness of the KPI and informative indicator*

The KPI was not exceeded during the first 3 years post-KMP. Given the results of air monitoring and dispersion modelling, the KPI will not be an effective tool as visible injury due to SO_2 seems highly unlikely to occur.

5.3.4.2 *Changes to the risk to vegetation associated with the modernized smelter*

Given the results of measurements and observations to date, the risk to vegetation remains unlikely to very unlikely and of minor consequence. Based on deposition modelling and recent

findings in the scientific literature, it is possible that some lichens will be affected. However, there is a strong legacy of more than 60 years of industrial and forestry activities in the area of greatest deposition. Studies in the 1970s and 1980s documented an area of impact on lichens that corresponds to the areas of greatest deposition modelled as part of this review. In those areas, the risk of further impact is small and likely of minor consequence as the area supports little suitable habitat. Based on our analysis, we conclude that outside the legacy area, the risk to cyanolichens growing on conifers is unlikely and of minor consequence in areas where deposition is less than <15 kg SO_4^{2-} /ha/yr (including background) and are of suitable habitat (e.g. undisturbed old growth for cyanolichens).

5.3.4.3 *Relation of the vegetation sampling and inspection program to other components of the SO_2 EEM Program*

The vegetation sampling and inspection program should be re-formulated to support a Terrestrial Ecosystems Line of Evidence that focuses on detecting mid to long-term effects of SO_2 and SO_4^{2-} deposition. Results of periodic inspections of vegetation could be an informative indicator to supplement the Soil Critical Load KPI and a potential plant biodiversity informative indicator.

5.3.4.4 *Conclusions regarding Questions V1-V4 from the STAR*

V1: Validation of the dispersion model – are we looking in the right place?

For the most part, the locations of vegetation sampling and inspection sites aligned well with the predicted path of the plume. Additional sites were well outside the areas of projected deposition and provided reference information. The areas off the B.C. Works site where the highest concentrations are projected to occur are not safely accessible from the ground or the air. Aerial survey of the area does not reveal any indication of change in forest condition. The vegetation informative indicator of S concentration in western hemlock needles did not help verify model predictions as there was a poor correlation between %S in needles and measures of air concentration of SO_2 or deposition of SO_4^{2-}.

V2: How healthy is vegetation in sites with predicted exceedance of critical loads of soil and/or lakes and streams south of Lakelse Lake?

Significant differences in plant heath throughout the Kitimat Valley were not observed post-KMP. There were no significant insect outbreaks or plant disease epidemics during the period under review. The greatest stress to vegetation during the period was associated with drought in 2018. No differences were observed in vegetation in the areas of soil critical load exceedance under actual emissions. On-the-ground or aerial inspection of vegetation in the area of predicted soil critical load exceedance under the maximum permitted emission level (42 tpd) did not reveal differences in the health of vegetation compared to sites located at distance, including reference sites. With respect to aquatic critical loads, only LAK044 at the northern boundary of the study area exceeded its critical load; its critical load is 0. Vegetation sampling and inspection was not conducted in the vicinity of that lake, however, inspection south of LAK044 (e.g. Lakelse Lake) did not reveal any symptoms of acidification.

V3: Are plants of public importance showing symptoms in areas with the highest exceedances of soil critical loads?

Hypothesis H_1 of no or negligible effects on plants of public importance is supported by the observations and measurements made. No symptoms associated with emissions from the modernized smelter were observed.

V4: Do plants at Kitimat that have unknown sensitivity to SO_2 and associated pollutants (acidic deposition) fall within the range of variation in the literature?

It appears that plants in the Kitimat Valley are within the range of sensitivities reported in the scientific literature. Given the low ambient concentrations of SO_2, injury would not be expected to occur, and it did not.

5.4 What Do We Recommend for the EEM Program Going Forward?

5.4.1 Recommendations for the Key Performance Indicator

We recommend that a Terrestrial Ecosystem line of evidence be established to integrate the vegetation and soils lines of evidence. The current KPI for vegetation should be discontinued and measures of plant health and plant biodiversity should be developed to replace the current KPI/informative indicators. A plant biodiversity pilot project needs to be conducted to develop appropriate thresholds and related measures of variability to assure success.

5.4.2 Recommendations for the informative indicator

Informative indicators of changes in plant biodiversity and changes in plant health due to emissions from B.C. Works based on established plant biodiversity field plots and a triennial inspection to assess and document plant and ecosystem health should be established to support the Soil Critical Load KPI. Documented changes in plant and ecosystem health would trigger increased measurement and inspection frequency.

5.4.3 Recommendations for the vegetation sampling and inspection program

The vegetation sampling and inspection program should be changed to focus on detecting mid to long-term effects on terrestrial ecosystems by:

- implementing a set of biodiversity plots to detect changes in plant communities related to Rio Tinto's B.C. Works;
- revisiting lichen plots at appropriate intervals (e.g. every 5 years) to document changes in lichen communities;
- conducting a triennial inspection to document changes in plant and ecosystem health; and
- discontinuing sampling and chemical analysis of western hemlock foliage in favor of maintaining a valley passive sampler network and measuring more informative endpoints of vegetation health.

6 Review Results for Terrestrial Ecosystems (Soils)

6.1 What Did We Set Out to Learn?

The soils component of the SO_2 EEM Program set out to address critical uncertainties and data gaps identified in the STAR (ESSA et al. 2013), i.e., gaps in the regional coverage of soils data, the use of bedrock type to regionalise soil weathering rates, and the lack of empirical observations of soil base cations.

The SO_2 EEM Program expanded the regional coverage of soils data and applied state-of-the-art mapping techniques to assess the spatial sensitivity of soils to acidic deposition. In addition, long-term soil plots were established and sampled over time to monitor changes in soil chemistry, quantify the minimum detectable change in soil base cations, and provide an estimate of time-to-depletion in base cation pools.

Ultimately the program set out to assess if the thresholds of the KPIs for soils were exceeded.

The three critical uncertainties identified under the STAR are now not relevant as soil weathering rates are now mapped using regression kriging rather than 'averaged by bedrock type' (STAR question S1), the current buffering capacity of soils in exceeded areas is only addressed if the KPI for critical loads is exceeded (STAR question S2), and long-term soil plots were established to assess changes in soil base cation pools (STAR question S3).

6.1.1 EEM Key Performance Indicators and informative indicators

There are two KPI for soils: (a) atmospheric sulphur deposition and critical load exceedance risk, and (b) long-term soil acidification (rate of change of base cation pool) attributable to sulphur deposition. The first KPI is prediction-based and uses measured soil physicochemical data from regional surveys to model and map the spatial distribution, magnitude (i.e., how large an area might be affected) and the level of exceedance of critical loads of acidity for soils (i.e., the magnitude of deposition greater than critical load). The second KPI is observation-based and uses measured soil chemistry data at long-term monitoring plots to track changes in soil base cations over time.

The soils component included three informative indicators, two of which (magnitude of exchangeable base cation pools and time to depletion of exchangeable base cation pools) will only be evaluated if the KPI thresholds are exceeded. The third is soil base cation weathering rates, which is required for the determination of critical loads.

6.2 What Methods Did We Use?

The methods were focused on two principal tasks: a regional survey of soil physicochemical properties to support the modelling and mapping of critical loads across the study domain, and the establishment of long-term soil monitoring plots to track changes in exchange base cations. For a detailed description on the methodology for the determination of critical loads of acidity, please see ESSA et al. (2013, 2014b), UNECE (2004), and de Vries et al. (2015).

6.2.1 Data we collected: regional soil survey for critical loads

Critical loads of acidity (S) for soils were revised to support the prediction-based KPI of 'critical load exceedance risk'. Digital soil maps were not available for the study region area (Figure 6-1); accordingly, a regional survey of forest soils was used to generate coverages (e.g., organic matter, sand, coarse fragment and base cation weathering) required to estimate critical loads.

Under the STAR, 51 soil pits were sampled and analysed for bulk density, organic matter content, particle size distribution and total element content. These data were used to estimate soil base cation weathering rates, which were subsequently regionalised across the study domain. Since 2013, soil sampling has been carried out in the Kitimat Valley (see Figure 6-1) under several projects (i.e., the Kitimat Airshed Emissions Effects Assessment (KAEEA) (ESSA et al. 2014b) [n = 11] and the LNG Canada Project [URL: lngcanada.ca/; n = 22]). Further, as recommended in the STAR, additional soil sampling was carried out during 2015–2017 (n = 31; see Table 6.1 in Terrestrial Ecosystems (Soils) Appendix 6.1) to address critical uncertainties and data gaps (Technical Memo S02, 2015). Soil data for the determination and mapping of soil base cation weathering rates (a key determinant of critical loads) are now available from 115 sites within the Kitimat Valley (Figure 6-1), including soil samples collected from 93 sites during 2012–2017 following a consistent sampling and analysis protocols, as described under the STAR, and data for 22 sites obtained from LNG Canada.

Soil data (at 93 locations; Figure 6-1) were obtained from field surveys conducted during June 2012 (n = 51), October 2013 (n = 11), July 2015 (n = 15) and July 2016 (n = 16); all surveys used consistent field protocols (described in ESSA et al. 2013). Under the STAR, site selection was primarily stratified by bedrock geology to ensure sample replication within the principal bedrock types (scale 1:250 000; Massey et al. 2005) and surficial geologies (scale 1:5000 000; Fulton 1996) for forest soils in the study region. In general, soil sampling locations were randomly selected from mapped geology units; however, sites were weighted towards road accessible areas (ESSA et al. 2013). Under the SO_2 EEM program, additional sites were sampled to fill gaps highlighted in the STAR, e.g., high elevation sites. At each sampling location, soil samples were collected from the four corners and centre point of a 10 m × 10 m quadrate using a soil auger and composited to obtain a representative sample for chemical analysis (ESSA et al. 2013). Mineral soils (i.e., excluding forest floor) were sampled at three fixed depths (0–10 cm; 15–25 cm and 40–50 cm) approximately representing the A and upper and lower B soil horizons. In addition to the composite soil samples, a fixed-volume bulk density core sample was taken at each mineral soil depth from the centre point.

All composite soil samples (three depths per site) were analysed for pH, loss-on-ignition (LOI: estimate of soil organic matter) and particle size (sand, silt and clay). Bulk density was determined on the fixed-volume core samples from the centre pit for each site (Terrestrial Ecosystems (Soils) Appendix 6.1). A weighted-average mineral soil sample for each site (i.e., composite of all depths weighted by bulk density and depth) was analysed for total oxide content (n = 93; Terrestrial Ecosystems (Soils) Appendix 6.1). All composite samples from several sites were analysed for qualitative mineralogy (Table 6-1 in Terrestrial Ecosystems (Soils) Appendix 6.1). All laboratory analysis is described in Terrestrial Ecosystems (Soils) Appendix 6.2.

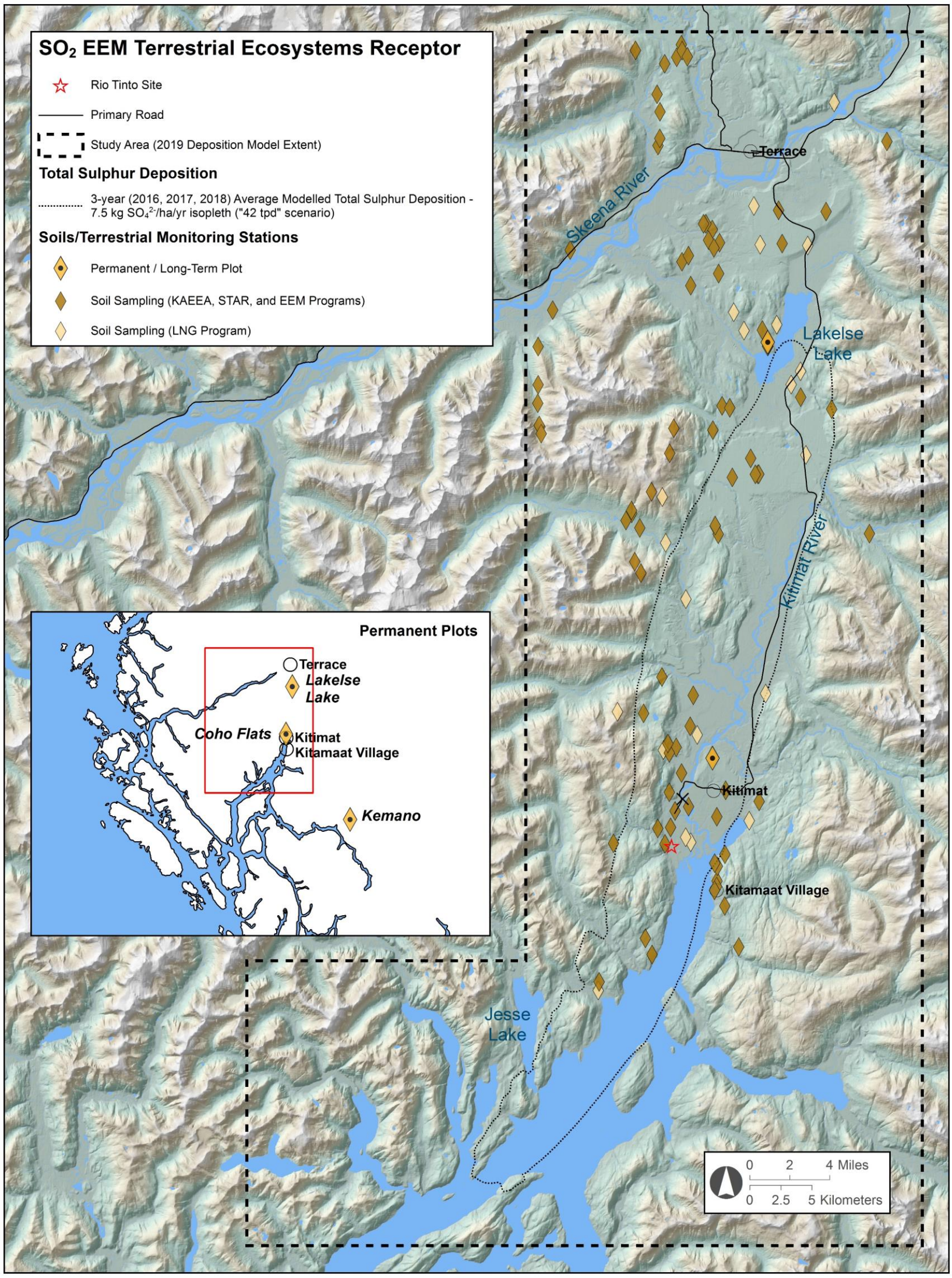


Figure 6-1. Location of the regional soil pits (n = 115) and long-term monitoring plots (n = 3). The inset depicts the location of the three long-term soil plots at Coho Flats (latitude: 54.07660, longitude: –128.65117), Lakelse Lake (latitude: 54.37827, longitude: –128.57990) and Kemano (latitude: 53.53032, longitude: –127.97384). Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleth.

6.2.2 Data we collected: long-term soil plots for exchangeable base cations

Under the SO_2 EEM Program, long-term soil monitoring plots were established to address the KPI 'observed change in base cation pool over time' (ESSA et al. 2014a). The objective of the long-term soil plots is to monitor changes in soil chemistry (base cation pools) over time through repeated sampling and analysis (every five years). The monitoring plots provide a framework for systematic replicate random sampling of soils, allowing for the statistical assessment of changes between sampling campaigns. The plot design follows the same conceptual basis as the Long-Term Soil Acidification Monitoring (LTSAM) program in Alberta (Cho et al. 2019), i.e., to provide an early warning of adverse effects of SO_2 emissions on soils, and to detect subtle changes in soil chemical parameters that would have the potential to affect plant growth, while factoring out natural variations. The soil plots were established on Rio Tinto property in near-field and far-field locations with respect to smelter emissions to ensure a gradient in potential exposure to SO_2 and to ensure long-term stability in the monitoring program. In addition, a background or reference plot was established (remote from emissions sources outside the Kitimat Valley) to assess whether a change soils (if observed) is causally related to KMP. Plot establishment and initial soil sampling (systematic random sampling) was carried out during 2015 (see Terrestrial Ecosystems (Soils) Appendix 6.11); the first soil resampling was carried out during June 2018.

During October–December 2015, near-field and far-field plots were established at Coho Flats and Lakelse Lake, respectively, and during 2016, the control plot was established at Kemano. At each location, primary and secondary (backup) plots were established within forest stands dominated by western Hemlock (see Terrestrial Ecosystems (Soils) Appendix 6.11 Table 6.5); soil was sampled from all plots (including primary and secondary) during establishment. All soil samples were analysed for basic physicochemical properties (organic matter, pH and bulk density); the soils from the secondary plots and control plot were archived without additional analysis. The secondary plots (located within 500 m of the primary plot) provide a backup or replacement to the primary plot if disturbed or destroyed within the lifetime of the monitoring program. The primary plots at Coho Flats and Lakelse Lake were resampled during June 2018 to assess changes in soil chemistry (e.g., exchangeable base cations) since the initial sampling during 2015. The control plot is only resampled and analysed if changes in soil chemistry exceeding the KPI threshold are detected at the Coho Flats and Lakelse Lake plots. All trees on the plots with a diameter at breast height (DBH) > 10 cm were recorded to assess the potential base cation uptake (Bcu) attributed to tree growth if a KPI is exceeded (see Terrestrial Ecosystems (Soils) Appendix 6.11 Table 6.10 and Figure 6.11). The secondary plots are only resampled and analysed if the primary plots are disturbed.

Each long-term soil plot is 32 m by 30 m in size and composed of twenty 8 m by 6 m sub-plots lettered A to T; the A sub-plot is oriented to the north-west corner of each plot (see Figure 6-2; and Figure 6.10 in Terrestrial Ecosystems (Soils) Appendix 6.11). Each sub-plot is further divided into twelve 2 m by 2 m sampling grids (numbered 1 to 12); one numbered grid was randomly sampled (without replacement) from each lettered sub-plot (see Table 6.6 in Terrestrial Ecosystems (Soils) Appendix 6.11 for a list of sample grids) at three depths in the mineral soil: 0–5 cm, 5–15 cm, and 15–30 cm depths (yielding a total of 60 soil samples for each plot, i.e., three soil samples by depth within each of the 20 lettered sub-plots). Soils were analysed for bulk density, coarse fragment, organic matter content, pH, exchangeable cations

and exchangeable acidity (see Terrestrial Ecosystems (Soils) Appendix 6.2 for details on the laboratory analysis).

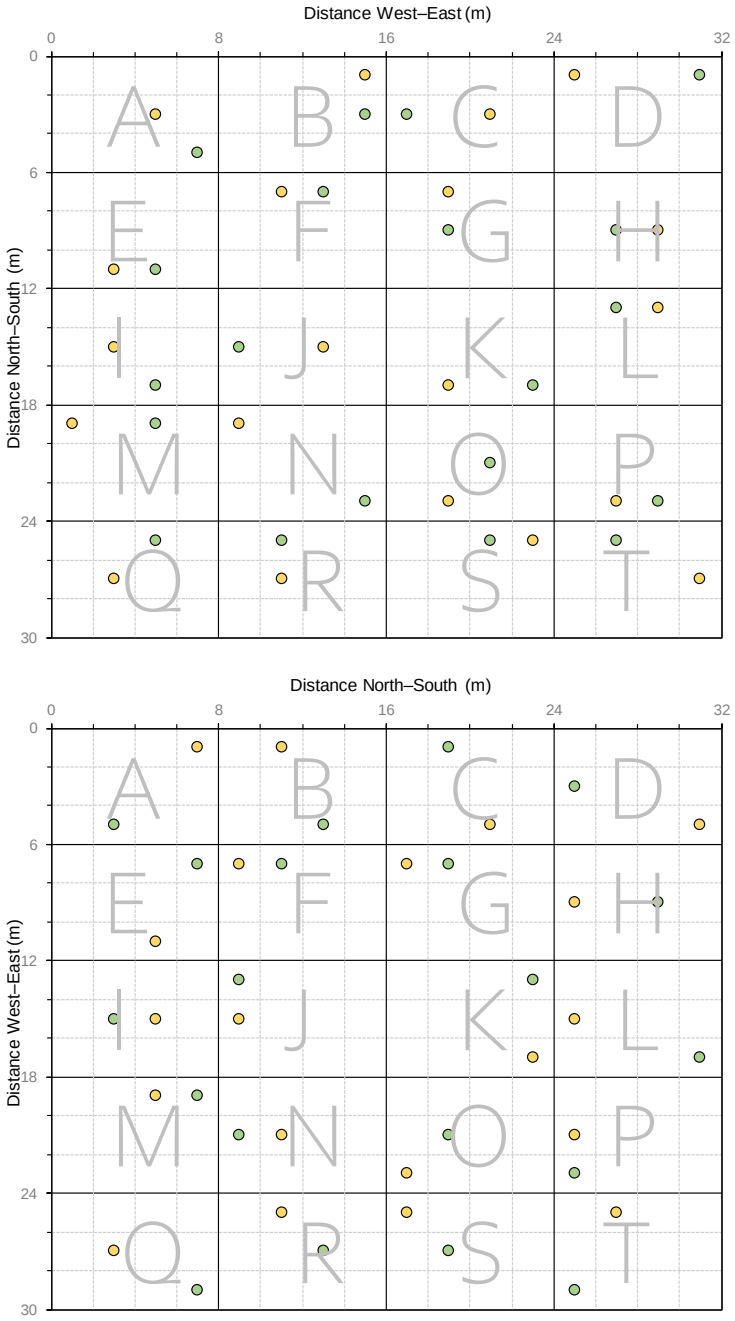


Figure 6-2. Layout of the long-term soil monitoring plots at Coho Flats (upper) and Lakelse Lake (lower) showing the lettered grids (n = 20) containing 12 sub-grids, which are randomly sampled without replacement; the green-filled circles indicate the sub-grids sampled for soil during 2015, and the orange-filled indicate the sub-grids sampled for soil during 2018. See Table 6.6 and Figure 6.10 in Terrestrial Ecosystems (Soils) Appendix 6.11 for further details.

6.2.3 Analyses we conducted: critical loads

The determination of critical loads of acidity (S) for terrestrial ecosystems (Figure 6-3) in the study region incorporated updated model parameters as recommended under the STAR and outlined under the EEM program (Technical Memo S05, 2017; Terrestrial Ecosystems (Soils) Appendix 6.5). The revised mapping incorporated new site-specific observations of soil data (see Terrestrial Ecosystems (Soils) Appendix 6.1), improved regionalisation methods (see Terrestrial Ecosystems (Soils) Appendix 6.5) and continuous digital (mapped) coverages for a range of environmental data (Table 6-1).

Critical loads of acidity (sulphur) were estimated using the Steady-State Mass Balance model (Table 6-2 and Table 6-3) following methods described in UNECE (2004) and de Vries et al. (2015). Receptor ecosystem area was delineated into 0.5 km × 0.5 km grids aligned with the modelled S deposition grid, and the areal proportion of coniferous forests (including mixed forests and shrub), deciduous forests and wetlands were recorded for each grid. The total number of receptor grids was 12,505; not all grids had 100% coverage; the average receptor cover within each 0.5 km × 0.5 km grid was 76%. Critical loads of acidity (sulphur) were estimated for each receptor ecosystem in each grid across the study area (see Figure 6-3) by combining input parameters (Table 6-3) obtained from existing environmental data sets (Table 6-1) and literature values (e.g., UNECE 2004) with derived mapped variables, e.g., soil base cation weathering rate, modelled from point observations of soil oxides that were regionalised using a geostatistical regression-kriging approach (see Appendices 6.3 and 6.4 for a detailed description of methods used to model weathering rates and map soil properties).

The level of protection for forest soils was specified via a critical ANC leaching and for wetlands via an acid neutralizing capacity limit (ANC_{limit}) similar to surface waters (see Table 6-2). The most widely used acidification threshold linking soil chemical status and plant response is a critical molar base cation (Bc) to Al ratio; sodium is excluded as it does not protect plant roots against Al toxicity. A soil solution critical molar Bc:Al ratio = 1.0 within the top 50 cm (the principal rooting zone) was chosen to be protective (95% of root growth) of the dominant tree species (*Tsuga heterophylla*, western hemlock) in the region (Sverdrup and Warfvinge 1993). In areas dominated by deciduous forests, a critical Bc:Al ratio = 8.0 within the top 50 cm (Sverdrup and Warfvinge 1993) was chosen to ensure protection of the more sensitive deciduous tree species, such as *Populus tremula* (trembling aspen)[28]. The ANC_{limit} is generally based on regional-scale assessments of the selected biological indicator; a 'default' limit of ANC_{limit} = 20 µeq/L, derived from an empirical relationship between lake water chemistry and fish status in Norway, is widely applied to protect fish, aquatic invertebrates, and benthic organisms (Lien et al. 1996; Posch et al. 2015)[29]. Non-marine base cation wet deposition (BC_{dep})[30] was derived from a constant precipitation concentration across the study area combined with mapped rainfall volume (Table 6-1; and Figure 6.7 in Terrestrial Ecosystems (Soils) Appendix 6.6). Base cation concentration in precipitation was set to 0.71 µeq/L based

[28] The critical molar Bc:Al ratios for western hemlock and trembling aspen were both directly taken from Sverdrup and Warfvinge (1993); they are set to protect 95% of tree biomass or root growth

[29] The ANC_{limit} = 20 µeq/L was selected for wetlands to protect aquatic biota rather than plant roots via the Bc:Al ratio; an ANC_{limit} = 20 µeq/L has been shown to be widely protective of fish, aquatic invertebrates, and benthic organisms (Lien et al. 1996)

[30] BC = Ca^{2+} (calcium) + Mg^{2+} (magnesium) + K^{+} (potassium) + Na^{+} (sodium)

on annual average observations during 2014–2018 at two NADP precipitation chemistry monitoring stations (Port Edward [BC24] and Lakelse Lake [BC23]). The determination of Bcu[31] and runoff (or soil percolation; Q) followed ESSA et al. (2013; 2014b). The final mapped resolution was consistent with the modelled deposition scenarios, i.e., critical load variables were estimated as the area-weighted average of all receptor ecosystems in each 0.5 km × 0.5 km grid square across the study domain.

Exceedance of critical loads of acidity was estimated under three SO_2 emissions scenarios: actual 2016–2018, 35 tpd and 42 tpd (see Section 3). Estimated exceedance also included a background total non-seasalt sulphur deposition owing to transboundary sources outside of the study domain. Background S deposition was set to a constant value of 7.5 meq/m^2/yr across the study area (for further details are given in Terrestrial Ecosystems (Soils) Appendix 6.7).

Table 6-1. Environmental data sets (site-specific observations and digital [mapped] coverages) used for the determination of critical loads of acidity (sulphur) for terrestrial ecosystems in the Kitimat Valley.

Data	Description and Source
Soil chemistry and geochemistry	Site-specific data in the study area (115 locations; see Figure 6-1), with observations of location (co-ordinates), bulk density, coarse fragment, organic matter content, particle size, major oxide content, qualitative mineralogy and site descriptions (Terrestrial Ecosystems (Soils) Appendix 6.1). Source: Terrestrial Ecosystems (Soils) Appendix 6.1
Soil maps	Soil properties (Version: v0.2, 2018) Sand content, clay content, pH, bulk density, organic carbon content and coarse fragment at 6 standard depths (1, 10, 30, 60, 100 and 200 cm) at 250 m resolution. Source: LandGIS — Open Land Data service [openlandmap.org] [github.com/Envirometrix/LandGISmaps#soil-properties-and-classes]
Geology	Bedrock Geology (Version: 2018-04-05). Source: British Columbia Geological Survey [www2.gov.bc.ca/gov/content/industry/mineral-exploration-mining/british-columbia-geological-survey/geology/bcdigitalgeology]
Elevation	Digital Elevation Model (scale: 1:20 000). Source: B.C. Ministry of Environment and Climate Change Strategy
Meteorology	Climate normals (1960–1990) for annual rainfall and annual average temperature estimated by PRISM at a 4 km by 4 km grid resolution (Daly et al. 1994). Source: ClimateWNA (Wang et al. 2006; 2012) [http://www.climatewna.com]
Precipitation chemistry	Wet-only precipitation chemistry at Haul Road, Lakelse Lake and Port Edward. Source: National Atmospheric Deposition Program [nadp.slh.wisc.edu]
Hydrology	Long-term modelled annual runoff (based on 1960 to 1990 climate normals) at a 400 m by 400 m grid resolution (Moore et al. 2012).
Land cover	Canadian Land Cover, circa 2000. GeoBase Series, 1996-2005. Grids 103H and 103I (scale: 1:250 000). Source: Natural Resources Canada. GeoPortal Canada [open.canada.ca/data/en/dataset/97126362-5a85-4fe0-9dc2-915464cfdbb7] Forest properties (Version: v0 (beta), September 2003) at 250 m resolution. Source: National Forest Inventory [https://nfi.nfis.org/en/]

[31] Bc = Ca^{2+} + Mg^{2+} + K^{+} (no Na^{+})

Data	Description and Source
Nutrient harvest	Mapped biomass removals based on allowable annual cut for TSAs, TFLs, and community forests combined with nutrient concentrations as described by ESSA et al. (2013).

Table 6-2. Critical load mass balance model for the assessment of acidification for forest soils and wetlands; see Table 6-3 for a description of model parameters and data sources.

Critical Load and Exceedance Equation	Number
Critical load: $CL(A) = BC_{dep} - Cl_{dep} + BC_w - Bc_u - ANC_{le(crit)}$	Eqn (6-1)
Where [for mineral soils] $$ANC_{le(crit)} = -Q^{\frac{2}{3}} \cdot \left(1.5 \cdot \left(\frac{Bc_w + Bc_{dep} - Bc_u}{(Bc:Al)_{crit} \cdot K_{gibb}}\right)\right)^{\frac{1}{3}} - 1.5 \cdot \left(\frac{Bc_w + Bc_{dep} - Bc_u}{(Bc:Al)_{crit}}\right)$$	Eqn (6-2a)
Or [for wetlands] $$ANC_{le(crit)} = ANC_{limit} \times Q$$	Eqn (6-2b)
Exceedance: $Exc = S_{calpuff} + S_{background} - CL(A)$	Eqn (6-3)

Critical load of acidity (CL(A)) was determined for forest (coniferous, deciduous, mixed and shrub) and wetland ecosystems (area = 2,378 km²). Exceedance was determined as the proportion (%) of the effects' domain, which is defined as the receptor ecosystem area enclosed by the 7.5 kg SO_4^{2-}/ha/yr modelled S deposition isopleth under each emission scenario.

Table 6-3. Description of input parameters and their data sources required to determine critical loads of acidity for terrestrial ecosystems in the study.

Parameter	Description	Data source
BC_{dep}	Non-marine non-anthropogenic base cations (BC = Bc (base cations) + Na^+ (sodium), Bc = Ca^{2+} (calcium) + Mg^{2+} (magnesium) + K^+ (potassium)) deposition.	Derived from observations of precipitation concentrations and long-term rainfall volume (NADP [two regional stations]). See Terrestrial Ecosystems (Soils) Appendix 6.6
Cl_{dep}	Non-marine chloride (Cl^-) deposition; it is assumed that non-marine (Cl^-) is negligible in the study area.	–
BC_w	Estimated using the A2M-PROFILE model chain (Warfvinge and Sverdrup 1992 (PROFILE); Posch and Kurz 2007 (A2M)) from site-specific soil and soil geochemical observations at 115 locations (Figure 6-1); regionalised using a regression-kriging approach (Hengl et al. 2004).	Table 6-1 (soil chemistry); Terrestrial Ecosystems (Soils) Appendix 6.3
Bc_u	Base cation removal in harvested biomass based on Annual Allowable Cut and literature values for tree species (Western Hemlock) base cation (Ca^{2+}, Mg^{2+} and K^+) concentrations.	ESSA Technologies (ESSA et al. 2013, 2014b)

Parameter	Description	Data source
$Bc:Al_{(crit)}$	For mineral soils, the critical molar base cation to Al ratio is the chemical criterion associated with ecosystem damage. Following the ESSA et al. (2014), Bc:Al = 1.0 for coniferous and mixed forests and Bc:Al = 8.0 for deciduous (updated from 6.0 to 8.0).	ESSA et al. (2014b), Sverdrup and Warfinge (1993)
ANC_{limit}	For wetland soils, the acid neutralising capacity limit was selected as the chemical criterion to protect aquatic biota. A widely used default value for broad ecosystem protection is 20 µeq/L.	UNECE (2004), de Vries et al. (2015)
Q	Long-term annual soil percolation or runoff.	Table 6-1 (hydrology)
K_{gibb}	Gibbsite equilibrium constant: Based on soil organic matter content following UNECE (2004) – pKgibb = 9.0 (LOI <5%), 8.5 (LOI >5 % and <15%) and 7.6 (LOI > 15%). Site observations of LOI (Terrestrial Ecosystems (Soils) Appendix 6) were regionalised using a regression-kriging approach.	UNECE (2004), de Vries et al. (2015)
$S_{calpuff}$	Anthropogenic sulphur deposition estimated from the CALPUFF model under three SO_2 emissions scenarios (actual 2006–2018, 35 tpd and 42 tpd). Simulated deposition is based on Rio Tinto emissions only	Section 3
$S_{background}$	Background total deposition of non-seasalt sulphur owing to transboundary sources outside of the study domain	Terrestrial Ecosystems (Soils) Appendix 6

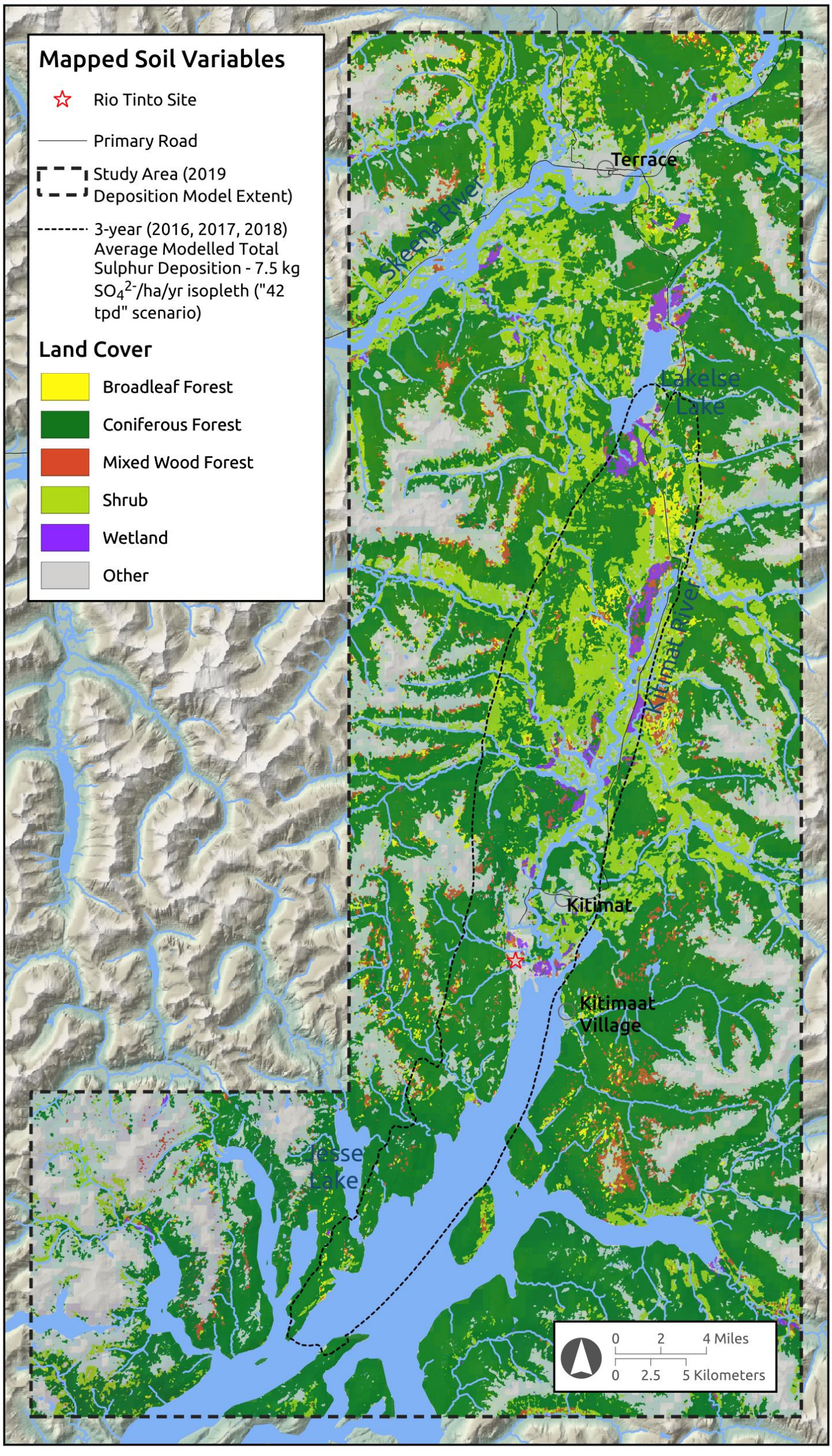


Figure 6-3. Map of the study area depicting the coverage of the receptor ecosystems used for the determination of critical loads of acidity (sulphur). Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleth.

6.2.4 Analyses we conducted: long-term soil plots

Soil chemistry data from the primary long-term plots at Coho Flat and Lakelse lake were summarised by plot (mean or geomean based on the distribution of the data) and over cumulative soil depths, i.e., 0–5 cm, and weighted-averages (weighted by depth and bulk density) for 0–15 cm and 0–30 cm. Each plot has 20 observations (for each depth), i.e., for the top 0–30 cm of soil, summary data are expressed as the average of the 20 observations, each of which represents the weighted-average soil chemistry over three depths. Exchangeable base cations (BC) were estimated as the sum of exchangeable Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}. Cation Exchange Capacity (CEC) was estimated as the sum of base cations and exchangeable acidity, this is technically termed effective CEC (CECe) as CEC was not directly measured (Tamminen and Starr 1990). Base saturation (%) was estimated as the percentage of effective CEC made up of base cations (BSe). Exchangeable base cations pools in soil were estimated by multiplying the concentrations of base cations in each layer by the corresponding soil bulk density and depth; pools were estimated for the cumulative depths of 0–5 cm, 0–15 cm and the 0–30 cm for the mineral soil. Organic soil horizons (e.g., LF and H) were not measured because they are highly influenced by internal base cation cycling through uptake and litterfall. See Terrestrial Ecosystems (Soils) Appendix 6.11 Tables 6.7 to 6.9 and Tables 6.11 to 6.13 for soil observations by plot and depth.

The measure of central tendency (MCT, i.e., average) in soil chemistry for each primary plot was calculated as a mean or geometric mean with untransformed or log10 transformed data, respectively. Variability in soil chemistry was described by the coefficient of variation (or relative standard deviation), which was estimated as the standard deviation/average × 100 (units of %). Statistical differences in soil chemistry between plots or depths was evaluated using an unpaired t-test. Further, comparison of soil properties between 2015 and 2018 was carried out using a one-sided t-test assuming equal or unequal variances according to a Levene's test for equal variances ($\alpha = 0.05$) and testing for a decrease in values for 2018. Statistical comparisons were conducted using untransformed or log10 transformed data depending on the normality of the residuals determined from a Shapiro-Wilk's test ($\alpha = 0.05$). The magnitude of difference in the MCT was calculated as (2018–2015)/2015 × 100 (units of %).

The multiple observations per depth (n = 20) define the variation in soil properties, which influence our ability to detect statistical changes in the soil properties following repeat sampling. The Minimum Detectable Difference (MDD) is the minimum change in a soil property over a given period of time required to be considered statistically significant, i.e., soil data collected during plot establishment can be used to determine how much change must occur to be considered statistically significant and not an artifact of system variability. The MDD was conducted using a t-test power analysis (α=0.05, $\beta = 0.1$) using the standard deviation in 2015 and the pooled standard deviation (2015 and 2018) and accounting for unequal variances where appropriate. MDD was expressed as a percent decrease from 2015 (–MDD/MCT2015). For transformed data, power analysis was conducted with log transformed data, but back-transformed to raw scale for % MDD relative to 2015.

The time to base cation depletion (in years) is the buffering period of base cations under continued sulphuric acid deposition, i.e., the period of time (years) that exchangeable base cations in soil can buffer incoming acidity assuming no other sources of base cations (such as

weathering or deposition) or acidity, and linear exchange on the soil exchange complex. The time to depletion for the top 30 cm of mineral soil was calculated as the base cation pool (meq/m^2) measured in 2015 divided by observation-based estimates of wet and dry sulphur deposition ($meq/m^2/yr$). Estimates of current sulphur deposition are based on wet deposition observations from the closest (or most representative) NADP precipitation chemistry monitoring station, and air concentrations from passive samplers or the nearest ambient continuous monitoring station (e.g., Whitesail was used for dry deposition at Coho Flats; see Section 3.1 for further details).

6.2.5 Assessment of acceptable or unacceptable impacts to terrestrial receptor

The assessment of impacts to terrestrial receptors is directly linked to the two KPIs, exceedance of critical loads of acidity and depletion of exchangeable base cation pools. Impacts are causally related to smelter emissions, as exceedance of critical loads is determined using CALPUFF modelled sulphur deposition, which is parameterised on smelter emissions only. In addition, if changes in exchangeable base cations above the KPI threshold are observed at the long-term soil plots, they are assessed with respect to changes in the control plot (at Kemano). There are three thresholds associated with each KPI leading to increased monitoring/modelling, receptor-based mitigation and facility-based mitigation, depending on the level of impact. The first two thresholds are associated with acceptable impacts.

If sulphur deposition, causally related to KMP emissions, exceeds critical loads in > 1% of semi-natural upland forest soils in the study area, this will trigger the threshold for increased modelling, i.e., uncertainties in the regional critical load mapping will be re-evaluated and the critical load model will be re-run with new data where required. During the EEM program, the critical loads modelling approach was expanded to be consistent with the Kitimat and Prince Rupert assessments (ESSA et al. 2014b, 2015). These revisions include the addition of non-forest ecosystems (wetlands) and the determination of proportional exceedance with reference to the modelled 7.5 kg SO_4^{2-}/ha/yr deposition isoline (see Terrestrial Ecosystems (Soils) Appendix 6.5 for model revisions; Technical Memo S05, 2017). The revisions directly influence the determination of acceptable / unacceptable impacts.

If a 40% decrease[32] in exchangeable cation pools for at least one element for one plot is observed between five-year[33] sampling events, and the decrease is causally related to emissions from the modernized smelter, the data from the regional soil survey will be used to assess (model) the spatial significance of observed base cation loss (i.e., are there wider issues over >1% of the study area?).

[32] Soil chemistry is highly variable in forests; chemical properties, such as exchangeable cations, typically vary by at least 40% (coefficient of variation) on local scale. To detect a statistically significant change in soil chemistry, the shift (increase or decrease) must be greater than the natural variation in the soil. A 40% decrease in exchange cation pools was selected as an indicator that could be reliably detected with statistical significance.
[33] To accommodate the comprehensive review reporting schedule, there was only three years between the initial (2015) and first resampling (2018).

6.3 What Did We Learn, and Did We Make Any Adjustments to the EEM Program?

The SO_2 EEM Program resulted in improved regional estimates of critical loads of acidity for the study domain. The EEM also provided information regarding the spatial variability on soil chemical properties and exchangeable base cation pools to identify the amount of change that could be significantly detected.

The results of the EEM Program directly support the two KPIs for soils: (a) atmospheric sulphur deposition and critical load exceedance risk, and (b) long-term soil acidification (rate of change of base cation pool) attributable to sulphur deposition. The improved estimates of regional critical loads provide for a direct assessment of the potential impacts of KMP emissions of SO_2 on soils within the study domain. Similarly, the repeated observations of soil chemistry at the long-term monitoring plots provide a direct measure of the rate of change in exchangeable base cations.

6.3.1 Knowledge gained: critical loads

The study domain was 3653.5 km^2, with receptor ecosystems covering 2377.8 km^2 (~65%). Soil properties (organic matter content, bulk density, coarse fragment, clay and sand) were mapped across the entire terrestrial study area (Appendices 6.3 and 6.4). Organic matter content in mineral forest soils (top 50 cm) was estimated to range from <1.0 % to 35% (average: 10.5%) across the study area (Terrestrial Ecosystems (Soils) Appendix 6.4 Figure 6.5). In general, the lowest values (< 5% LOI) were observed north of Lakelse Lake associated with fluvial, glaciofluvial and marine surficial deposits (covering ~14% of the mapped receptor ecosystems). In contrast, the highest values (> 15% LOI) were predicted to occur in mountainous regions in the west and south of the Kitimat Valley (covering 20% of the receptor area). Soil organic matter was used to predict and spatially define the gibbsite equilibrium constant (see Table 6-3 for further details).

Base cation weathering rate for mineral forest soils was estimated to range from 18.3 $meq/m^2/yr^1$ to 177.5 $meq/m^2/yr^1$ (average: 78.6 $meq/m^2/yr^1$) in the top 50 cm (Figure 6-4). The highest base cation weathering rates were predicted in southern parts of the Kitimat valley (surrounding Kitimat town) and further south-west (16% of the receptor ecosystems have weathering rates >100 $meq/m^2/yr^1$). In contrast, the lowest weathering rates (3.5% of the receptor ecosystems have weathering rates <50 $meq/m^2/yr^1$) were generally observed north, east and west of the Kitimat Valley corresponding with coarse texture mountain soils with low bulk density (Figure 6-4 and Terrestrial Ecosystems (Soils) Appendix 6.1). On average, sodium weathering (19.1 $meq/m^2/yr^1$) made up approximately 25% of estimated base cation weathering rate. Base cation weathering is a key parameter used to derive chemical criteria or indicators and determine critical loads of acidity (see Table 6-3). In general, estimated weathering rates were similar to the STAR (average: 88.6 $meq/m^2/yr^1$).

The spatial pattern of CL(A) (Figure 6-5) was similar to base cation weathering (Figure 6-4), although significantly greater in magnitude across the region (× ~2.85) owing to the dominance of the $ANC_{le(crit)}$ term, which was approximately twice the average weathering rate (see Table 6-2: Equation 1). The average critical load of acidity was 223.6 $meq/m^2/yr^1$ (range: 52.6–650 $meq/m^2/yr^1$). As such, much of the study region is considered to have moderate to

high critical loads of acidity, and consequently have moderate to low sensitivity to acidic deposition.

Exceedance of critical loads of acidity (S) was estimated under three emissions scenarios: 2016–2018 actual, 35 tpd and 42 tpd, presenting a range between current and maximum permitted emissions. The area of the receptor ecosystems (forests and wetlands) under the 7.5 kg SO_4^{2-}/ha/yr ranged from 271.1–398.4 km^2; the exceeded area under the three emissions scenarios was low, ranging from 0.97 km^2 (actual) to 2.33 km^2 (42 tpd). The greatest areal exceedance (under the 42 tpd scenario) represented 0.58% of the mapped receptor ecosystem within the effects' domain. Even though a relatively small area was predicted to be exceeded, the average exceedance was high; 149 meq/m2/yr under the 42 tpd scenario, indicating that a small area of receptor ecosystems will receive acidic deposition greatly in excess of their critical load (Table 6-4; see Terrestrial Ecosystems (Soils) Appendix 6.9 Figure 6.9 and Terrestrial Ecosystems (Soils) Appendix 6.10 Table 6.4). The exceeded area was located primarily south and north of the principal sulphur emissions sources in the Kitimat Valley, i.e., the Rio Tinto smelter (Figure 6-5). The area of exceedance outside the fence line ranges from 0.20 km^2 (actual) to 1.26 km^2 (or 0.32% under 42 tpd; see Terrestrial Ecosystems (Soils) Appendix 6.8).

The improved regional estimates of critical loads provide for a direct assessment of the potential impacts of KMP emissions on soil acidification within the Kitimat valley. The updated critical loads incorporated new site-specific observations of soil data, improved regionalisation methods, and updated model parameters. However, there is limited data or knowledge on the acid-base status of wetlands in the Kitimat valley, as such there is uncertainty in the chosen critical limit for wetlands (Table 6-3). Similarly, the gibbsite equilibrium constant (K_{gibb}), which plays a crucial role in the determination of ANC leaching (Table 6-2) is based on literature ranges, which may not be appropriate for the region. Observations of wetland geochemistry, wetland S storage capacity and aluminium solubility in mineral soils would reduce uncertainties in the regional assessment of impacts to terrestrial receptors.

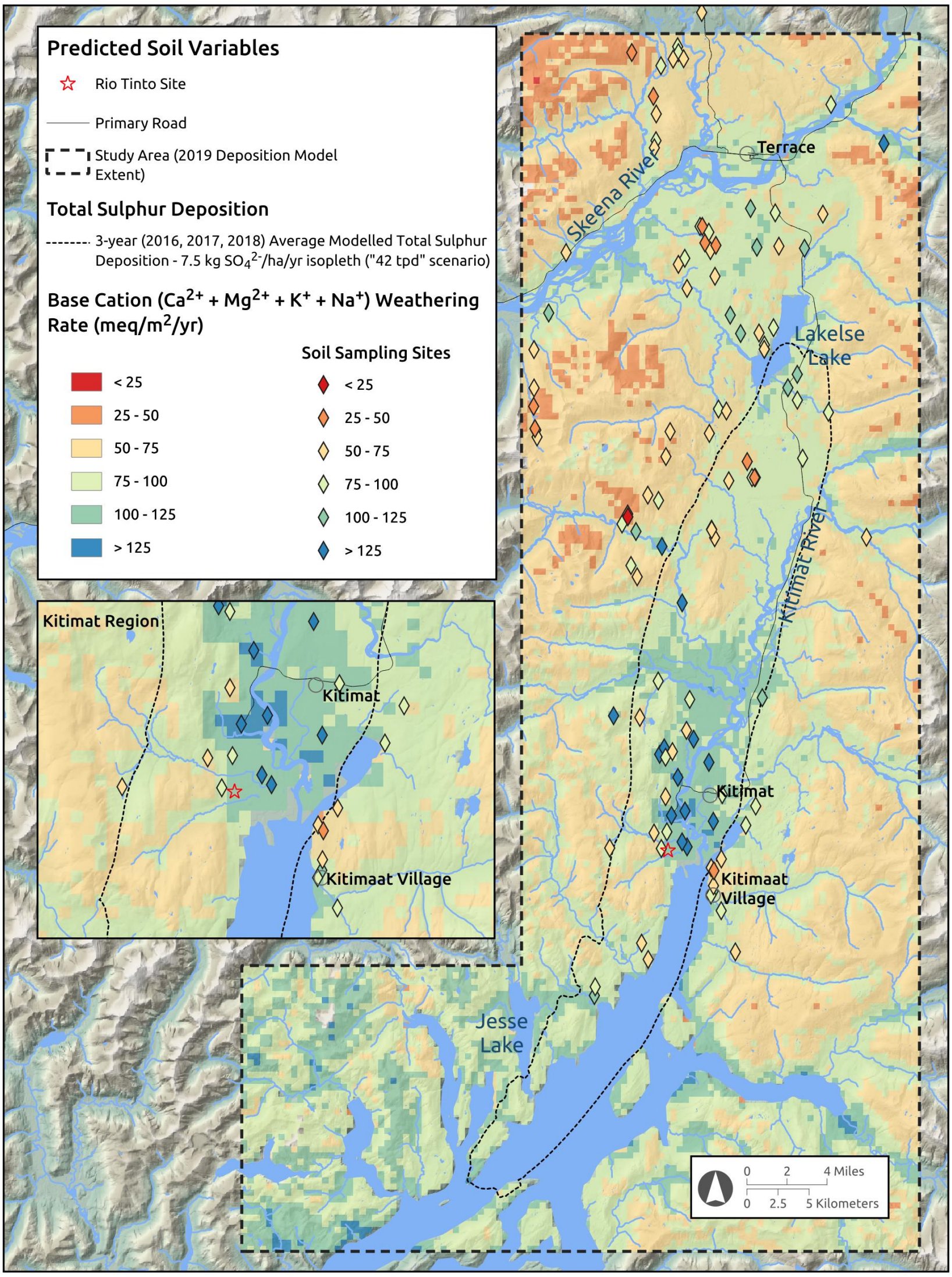


Figure 6-4. Predicted soil base cation (Ca^{2+} + Mg^{2+} + K^+ + Na^+) weathering rates (meq/m^2/yr) in the top 0–50 cm of mineral soil. Diamonds represent site-specific estimates of weathering rates used to develop the predictive map (through regression kriging). The dotted line indicates the isoline for total sulphur deposition > 7.5 kg SO_4^{2-}/ha/yr. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleth. See Terrestrial Ecosystems (Soils) Appendix 6.4 Figure 6.6 for base cation (Ca^{2+} + Mg^{2+} + K^+) weathering rates (meq/m^2/yr).

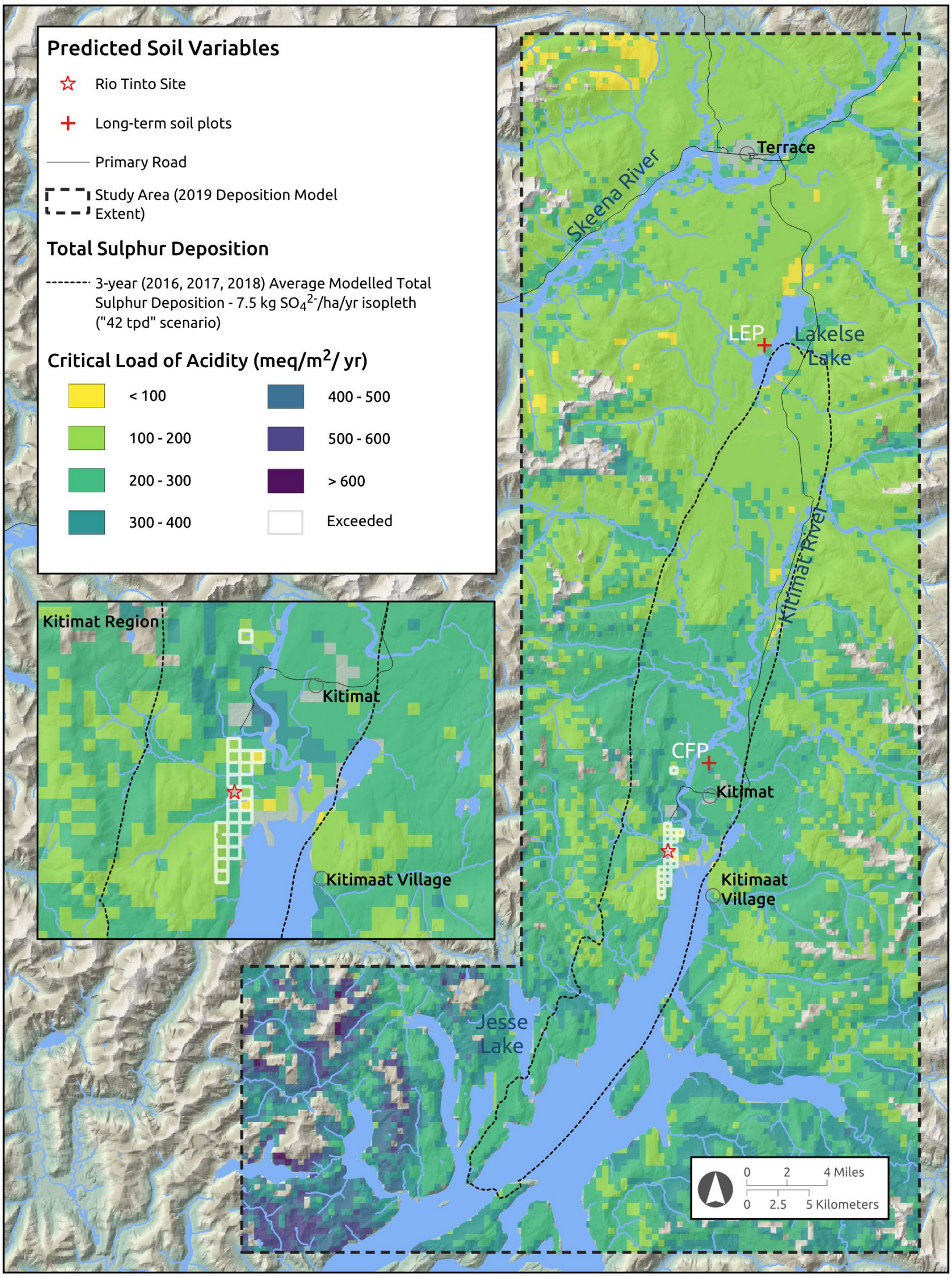


Figure 6-5. Predicted critical loads of acidity for forest and wetland soils (meq/m²/yr) and exceedance (grids cells with white outline; n = 21) under modelled total sulphur deposition, based on maximum permitted emissions of 42 tonnes of sulphur dioxide per day. The dotted line indicates the isoline for total sulphur deposition > 7.5 kg SO_4^{2-}/ha/yr. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleth. The location of the long-term soil plots, Coho Flats Primary (CFP) and Lakelse Lake Primary (LEP), are also shown (+).

Table 6-4. Exceedance of critical loads of acidity for forest soils and wetlands under three sulphur emissions scenarios. The values within brackets refer to areas outside of the Rio Tinto fence line.

Exceedance	Deposition		
	Actual	35 tpd	42 tpd
Average exceedance (meq/m^2/yr)	119.9 (97.9)	140.0 (116.13)	149.6 (97.9)
Exceeded area (km^2)	0.97 (0.20)	1.26 (0.40)	2.33 (1.26)
Exceeded area wetland (km^2)	0.40 (0.16)	0.44 (0.16)	0.58 (0.30)
Exceeded area (%) *	0.36 (0.07)	0.39 (0.13)	0.58 (0.32)
Exceeded grids (n)	12 (5)	15 (6)	23 (11)
Mapped receptor area (km^2)	271.1	321.4	398.4

* as a percentage of the mapped receptor area under the 7.5 kg SO_4^{2-}/ha/yr deposition isoline

6.3.2 Knowledge gained: long-term soils plots

The average concentration of exchangeable base cations (Ca^{2+} + Mg^{2+} + K^+ + Na^+) in the top 0–30 cm of mineral soil at the primary plots was 1.2 meq/100g at Coho Flats and 1.5 meq/100g at Lakelse Lake during 2015. Exchangeable Ca^{2+} was the dominant cation at both plots (0.7 meq/100g at Coho Flats and 1.0 meq/100g at Lakelse Lake; Table 6-5, compare Figure 6-7 with Terrestrial Ecosystems (Soils) Appendix 6.11 Figure 6.12) followed by Mg^{2+} (0.26 meq/100g at Coho Flats and 0.30 meq/100g at Lakelse Lake). Base saturation in the top 0–30 cm of mineral soil was 15% at Coho Flats compared with 47% at Lakelse Lake, which was primarily driven by the higher CECe at Coho Flats. The higher CECe at Coho Flats is a result of the higher exchangeable acidity, which is driven by the higher organic matter content (estimated as LOI, 17.7% at Coho Flats compared with 5.5% at Lakelse Lake).

There was no statistical difference in the concentration of exchangeable base cations in the top 0–30 cm of mineral soil at both primary plots (Coho Flats and Lakelse Lake; Table 6-5). In contrast, the exchangeable base cation pools are statistically different between plots (see Terrestrial Ecosystems (Soils) Appendix 6.11 Table 6.11; 1,708 meq/m^2 Coho Flats versus 4,041 meq/m^2 Lakelse Lake) owing to the difference in soil bulk density (0.466 g/cm^3 Coho Flats versus 0.890 g/cm^3 Lakelse Lake). The lower bulk density at Coho Flats is related to the higher organic matter content. It should be noted that, the deep organic soil layer (LFH) at Coho Flats makes it difficult to accurately sample mineral soils.

Soil chemistry was highly variable among the 20 observation points (weighted average of three depths) at both sites. The coefficient of variation for average soil chemistry in the top 0–30 cm of mineral soil ranged from 21.6% (exchangeable acidity) to 74.5% (exchangeable Ca^{2+}) at Coho Flats and from 26.8% (exchangeable acidity) to 50.6% (exchangeable Mg^{2+}) at Lakelse Lake during 2015. Variation in the concentration of exchangeable base cations ranged from 42–56% (Lakelse Lake to Coho Flats); soil base cation pools showed a similar variation of ~52% for both primary plots (Figure 6-5).

The variability in soil chemistry influences our ability to detect statistical differences (decreases) in exchangeable base cations between sampling periods (see Table 6-5). The

minimum detectable difference[34] (decrease) based on the variability in soil chemistry during 2015 ranged from 20% (exchangeable acidity) to 50% (exchangeable Ca^{2+}) at Coho Flats, and from 23% (base saturation) to 44% (exchangeable Ca^{2+}) at Lakelse Lake in the top 0–30 cm of mineral soil. The minimum detectable decrease in exchangeable base cations is 40% at Coho Flats and 37% at Lakelse Lake, i.e., to detect a statistical decrease between sampling periods at Lakelse Lake, exchangeable base cations would have to decrease by 37%. However, the minimum detectable difference (decrease) is also influenced by the variability in soil chemistry during the second sampling period, i.e., detectable difference is influenced by the pooled variability of sampling events[35]. The minimum detectable difference (decrease) based on the variability in soil chemistry during 2015 and 2018 ranged from 29% (effective cation exchange capacity) to 68% (exchangeable Mg^{2+}) at Coho Flats, and from 29% (base saturation) to 46% (exchangeable Ca^{2+}) at Lakelse Lake in the top 0–30 cm of mineral soil (Table 6-5). The minimum detectable decrease in exchangeable base cations increased to 45% at Coho Flats and 42% at Lakelse Lake based on pooled variability during 2015 and 2018 compared with 2015 only. At Coho Flats, the minimum significant decrease in base saturation that can be statistically detected based on the variability in the soils during 2015 is 34%. Considering the variability in soil during the second sampling period (2018), the minimum significant decrease that can be statistically detected is 38% (Table 6-5). These levels of change are both below the KPI threshold of 40%, suggesting that base saturation is a better (more reliable) indicator of long-term soil acidification under the EEM.

There was no statistical decrease in exchangeable soil chemistry between 2015 and 2018 in the top 0–30 cm of mineral soil at both plots. For example, there was no statistical decrease in exchangeable Ca^{2+} between 2015 and 2018 in the top 0–30 cm of mineral soil at both plots; at Coho Flats a slight increase (13%) was observed in exchangeable Ca^{2+} between 2015 and 2018 (Table 6-5). There was a statistical decrease in pH at Coho Flats between 2015 (mean = 4.34) and 2018 (mean = 4.02) in the 0–30 cm of mineral soil but not at Lakelse Lake (mean pH 2015 = 5.11 and 2018 = 5.07). However, this decrease was driven by the higher organic matter content of the soil samples during 2018 at Coho Flats (Figure 6.12 in Terrestrial Ecosystems (Soils) Appendix 6.11); the average content was 17.7% in 2015 compared with 21.1% in 2018. As noted above, the LFH at Coho Flats made it difficult to accurately sample mineral soils; the observed difference in organic matter content reflects a change in sampling depths between years. The only soil variable that consistently showed a statistical decrease at lower cumulative depths (i.e., 0–15 cm and 0–5 cm) was exchangeable acidity, suggesting that there was a decrease in acidity between 2015 and 2018, despite the increase in acidic deposition (see Section 3). This was likely driven by differences in organic matter content between sampling periods (Figure 6.12 in Terrestrial Ecosystems (Soils) Appendix 6.11).

[34] Minimum Detectable Difference was conducted using a t-test power analysis (α=0.05, β = 0.1), i.e., the level of significance is 0.05 and the power is 0.9 (=1 – β). A power of 0.9 means that there is a 90% probability that a test of significance will pick up on an effect that is present.

[35] It is important to note that the KPI, *long-term soil acidification (rate of change of base cation pool) attributable to sulphur deposition*, is defined with respect to changes since the establishment of the soil monitoring plots during 2015. Therefore, MDD (2015) should be used to set the threshold for statistical detection. Nonetheless, it is important to recognise that soil variability during the repeat sampling periods may influence (positively and negatively) the statistically significant level of detection.

The time to base cation depletion (in years), i.e., the buffering period of soil exchangeable base cations under current sulphuric acid deposition in the top 0–30 cm ranged from 115 years (Coho Flats) to 373 years (Lakelse Lake) during 2015. The current observation-based estimates of acidic deposition for both sites ranged from 12.2 meq/m^2 at Lakelse Lake to 16.8 meq/m^2 at Coho Flats; observation-based estimates were derived from annual average wet deposition during 2016–2018 (from the nearest, or most appropriate, NADP station) and dry deposition estimated from air concentrations (from passive samplers or the nearest ambient continuous station) and modelled deposition velocity. However, the critical load of acidity was not exceeded at either plot (see Figure 6-5) indicating that base cation weathering rate buffers incoming acidity and that depletion of base cation pools is unlikely.

We have primarily focused our analysis of soil chemistry at the long-term soil on the top 0–30 cm of mineral soil at both primary plots. However, the results are consistent for the other cumulative depths (0–5 cm and 0–15 cm). The chemistry for individual layers displays the expected relationships with depth, i.e., organic matter (estimated as LOI) and exchangeable cations decrease with depth, whereas bulk density and pH increase with depth (see Figure 6.12 in Terrestrial Ecosystems (Soils) Appendix 6.11). Base saturation (%) was the most sensitive parameter for detecting change in exchangeable base cations, i.e., it consistently had the lowest minimum detectable difference based on the variability in the soils during 2015 and the pooled variability for 2015 and 2018. This was generally consistent when considering cation concentrations (Table 6-5) or pools (Table 6.11 in Terrestrial Ecosystems (Soils) Appendix 6.11), and also between different cumulative depths (0–5, 0–15 and 0–30 cm). Average soil chemistry (concentrations) for the 0–30 cm had a slightly lower minimum detectable difference compared with other depths and compared with base cation pools. A disadvantage of using base cation pools is they also require measurements of soil bulk density.

The long-term monitoring plots provide systematic replicate random samples of soil chemistry to address the KPI of 'observed change in base cation pool over time'. The original KPI was based on a 40% decrease in exchangeable base cation pools; however, the study results indicate that base saturation is a more reliable indicator of long-term soil acidification as it was the only soil property (related to base cations) that had a minimum detectable difference less than 40%. While exchangeable acidity and cation exchange capacity also had minimum detectable differences less that 40% (Table 6-5 and Terrestrial Ecosystems (Soils) Appendix 6.11 Table 6.11), they do not provide any information on changes in base cations, which are essential nutrients for sustainable tree growth. The use of exchangeable base cation pools under the EEM adds uncertainty to the KPI, as their minimum detectable difference was generally above 40% (see Terrestrial Ecosystems (Soils) Appendix 6.11 Table 6.11).

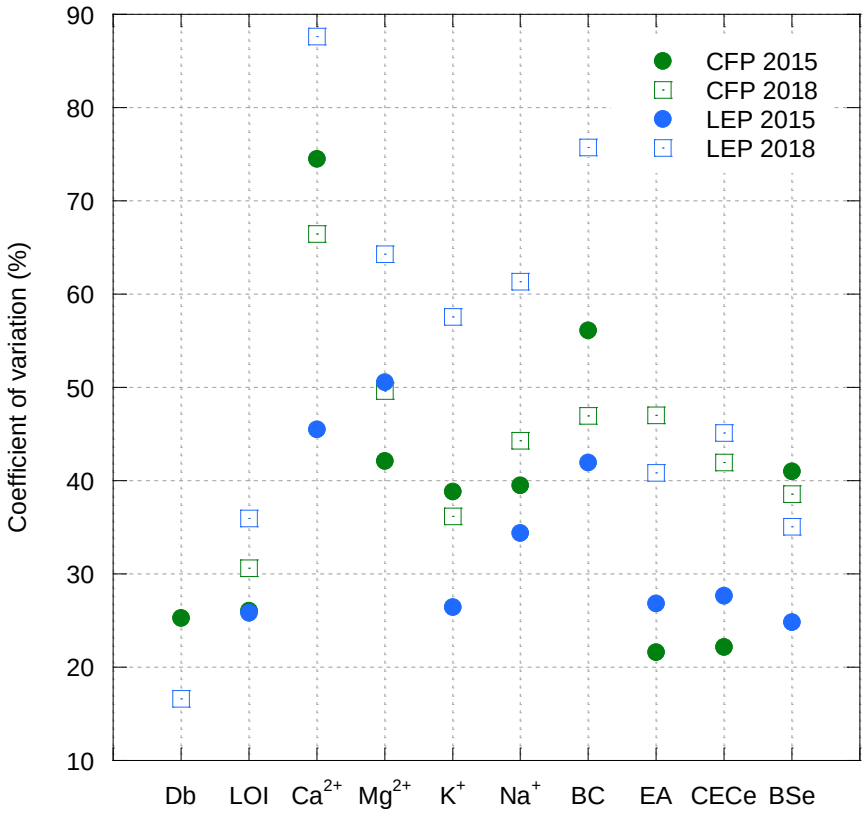


Figure 6-6. Coefficient of variation (%) in soil physico-chemical properties (20 observations for each variable) at Coho Flat Primary (CFP) and Lakelse Lake Primary (LEP) during 2015 and 2018. Soil properties: bulk density (Db), loss-on-ignition (LOI), exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), sodium (Na^{+}), base cations (BC), exchangeable acidity (EA), effective cation exchange capacity (CECe) and effective base saturation (BSe).

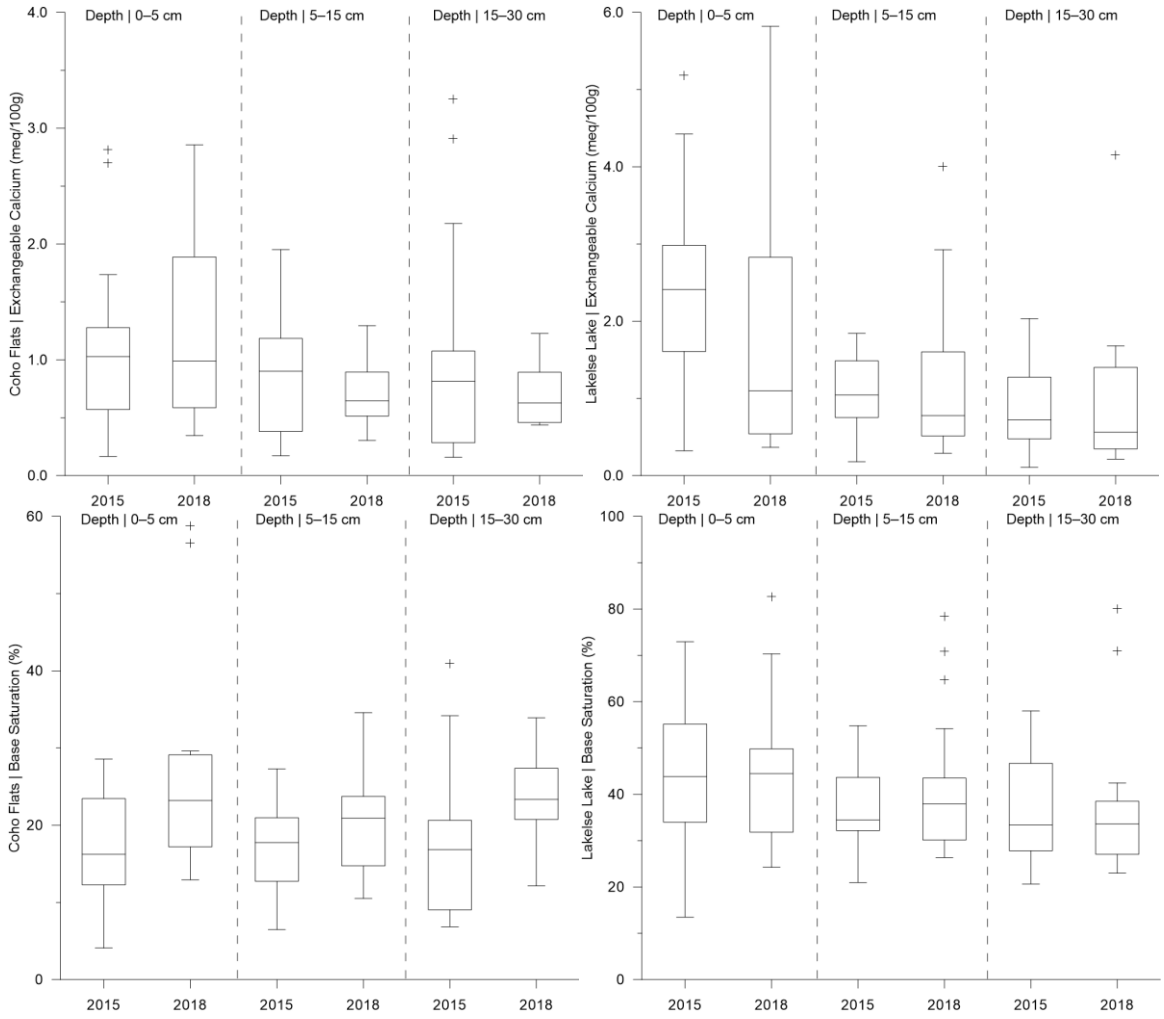


Figure 6-7. Boxplots showing exchangeable calcium (meq/100g) and base saturation (%) by depth during 2015 and 2018 at Coho Flats and Lakelse Lake long-term soil plots. There are 20 observations per depth. For the boxplot, the horizontal centre line represents the median concentration, the box represents the 75th (top, upper quartile) and 25th (bottom, lower quartile) percentiles and the whiskers represent 1.5 × the interquartile range, with any point that falls outside as an outlier (+).

Table 6-5. Average soil chemistry by depth during 2015 and 2018, probability of decrease between 2015 and 2018, magnitude of difference (MOD) and minimum detectable difference (MDD) based on the variability (pSD) during 2015 and pooled variability during 2015 and 2018 at Coho Flats Primary (CFP) and Lakelse Lake Primary (LEP) plots.

Plot	Depth	Param †	Unit	Test[a]	n 2015	Trans[b]	MCT[c] 2015	MCT[c] 2018	p-value	MOD[d] %	MDD[e] 2015	MDD[e] pSD
CFP	0–5	Ca^{2+}	meq/100g	tequal	19	Log10	0.87	1.0	0.737	15	-50	-52
		Mg^{2+}	meq/100g	tunequal	19	None	0.32	0.63	1.000	93	-37	-62
		BC	meq/100g	tequal	19	Log10	1.4	1.9	0.955	34	-43	-48
		EA	meq/100g	tunequal	18	None	7.8	6.2	0.006	-21	-16	-23
		CEC_e	meq/100g	tequal	18	None	9.4	8.3	0.074	-12	-18	-23
		BS_e	%	tequal	18	Log10	15	24	0.999	62	-38	-43
LEP	0–5	Ca^{2+}	meq/100g	tequal	20	Log10	2.2	1.2	0.007	-46	-45	-51
		Mg^{2+}	meq/100g	tequal	20	Log10	0.62	0.36	0.010	-42	-38	-48
		BC	meq/100g	tequal	20	Log10	3.0	1.7	0.006	-43	-39	-48
		EA	meq/100g	tequal	20	None	3.7	2.9	0.012	-24	-27	-30
		CEC_e	meq/100g	tequal	20	None	7.1	5.2	0.003	-27	-23	-28
		BS_e	%	tequal	20	None	47	41	0.150	-11	-31	-32
CFP	0–15	Ca^{2+}	meq/100g	tequal	19	Log10	0.80	0.84	0.597	5	-44	-46
		Mg^{2+}	meq/100g	tunequal	19	None	0.30	0.53	1.000	76	-36	-57
		BC	meq/100g	tequal	19	Log10	1.3	1.6	0.873	18	-36	-38
		EA	meq/100g	tunequal	18	None	7.1	5.9	0.030	-17	-18	-25
		CEC_e	meq/100g	tequal	18	None	8.6	7.7	0.101	-11	-18	-24
		BS_e	%	tequal	18	Log10	16	22	0.995	40	-32	-34
LEP	0–15	Ca^{2+}	meq/100g	tequal	20	Log10	1.3	1.0	0.071	-27	-42	-46
		Mg^{2+}	meq/100g	tequal	20	Log10	0.40	0.29	0.053	-27	-35	-44
		BC	meq/100g	tequal	20	Log10	1.9	1.4	0.076	-24	-37	-43
		EA	meq/100g	tequal	20	None	3.0	2.5	0.042	-18	-31	-31
		CEC_e	meq/100g	tequal	20	None	5.1	4.3	0.067	-16	-26	-30
		BS_e	%	tequal	20	None	41	39	0.389	-3.0	-28	-31
CFP	0–30	Ca^{2+}	meq/100g	tequal	19	Log10	0.70	0.79	0.726	13	−50	−57
		Mg^{2+}	meq/100g	tunequal	19	None	0.26	0.49	1.000	87	−40	−68
		BC	meq/100g	tequal	19	Log10	1.2	1.5	0.909	23	−40	−45
		EA	meq/100g	tunequal	19	None	6.5	5.6	0.078	−15	−20	−30
		CEC_e	meq/100g	tunequal	19	None	7.9	7.2	0.176	−9.3	−21	−29
		BS_e	%	tequal	19	Log10	16	23	0.997	44	−34	−38
LEP	0–30	Ca^{2+}	meq/100g	tequal	20	Log10	1.0	0.84	0.166	−19	−44	−46
		Mg^{2+}	meq/100g	tequal	20	Log10	0.30	0.25	0.170	−17	−40	−44
		BC	meq/100g	tequal	20	Log10	1.5	1.2	0.132	−19	−37	−42
		EA	meq/100g	tequal	20	None	2.6	2.2	0.095	−13	−25	−30
		CEC_e	meq/100g	tequal	20	None	4.3	3.8	0.148	−12	−26	−32
		BS_e	%	tequal	20	None	39	39	0.479	−0.51	−23	−29

† Soil parameters (Param) included exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), base cations (BC), exchangeable acidity (EA), effective cation exchange capacity (CEC_e) and effective base saturation (BS_e). [a] One-sided t-test assuming equal variances (tequal) or not (tunequal) according to a Levene's test for equal variances ($\alpha = 0.05$) and testing for a decrease in values for 2018. [b] Statistical comparisons were conducted using untransformed (None) or log10 transformed (Log10) data depending on the normality of the residuals determined from a Shapiro-Wilk's test ($\alpha = 0.05$). [c] The measure of central tendency (MCT) was calculated as a mean or geometric mean with untransformed or log10 transformed data, respectively. [d] The magnitude of difference was calculated as 2018 – 2015/ 2015 × 100% using the MCT. [e] The Minimum Detectable Difference (MDD) was conducted using a t-test power

analysis (α=0.05, β = 0.1) using the standard deviation in 2015 and the pooled standard deviation (2015 and 2018) and accounting for unequal variances where appropriate. MDD was expressed as a percent decrease from 2015 (–MDD/MCT2015). For transformed data, power analysis was conducted with log transformed data, but back-transformed to raw scale for % MDD relative to 2015.

6.3.3 Comprehensive synthesis and conclusions ('pulling all the pieces together')

The thresholds for the two terrestrial KPIs were not reached, i.e., the area of critical load exceedance was < 1% and there was no statistical change (decrease) in soil base cations at the long-term soil plots between 2015 and 2018.

In general, the areal extent of exceedance was similar to the STAR, i.e., areas with exceedance under the 42 tpd deposition scenario were close to the smelter. If exceedance is limited to areas outside the fence line, then areal exceedance drops by 55%. It is important to note that exceedance is not driven by sensitive soils, rather it is driven by high modelled sulphur deposition close to the smelter. As such, the limitations and uncertainties in the modelling and mapping of critical loads are unlikely to greatly influence the overall results of this KPI.

The long-term soil plots at Coho Flats and Lakelse Lake show no statistically significant decrease in exchangeable base cations or base saturation between 2015 and 2018 in the 0–30 cm depth. In general, the minimum detectable difference is lower for soil base cation compared with pools (note: base cation pools are specified in the KPI *long-term soil acidification attributable to sulphur deposition*). In addition, pools have the added requirement that soil bulk density be measured. Our results indicate that soil base saturation (a soil property related to base cations) provides the most reliable detectable difference of 40% in the top 0–30 cm of mineral soil. In contrast, it is highly uncertain that a statistically significant decrease of 40% in exchangeable base cations can be detected.

Exchangeable base cations in soil at Coho Flats and Lakelse Lake showed a range of changes between 2015 and 2018 in the 0–30 cm depth, e.g., there was an increase in exchangeable Ca^{2+} and Mg^{2+} at Coho Flats in the 0–30 cm depth but decrease at Lakelse Lake (Table 6-5). However, there were no statistically significant changes in soil chemistry between 2015 and 2018 in the 0–30 cm depth. The only consistent statistically significant change (decrease) at lower soil depths was observed for exchangeable acidity suggesting soils became less acidic between 2015 and 2018. In general, the size of the base cation pools and the level of base saturation at Coho Flats and Lakelse Lake are consistent with forest soils elsewhere in North America. The results for the long-term soil plots suggest that there were no impacts to sensitive receptors. In contrast, exceedance of critical load was predicted for a small area, indicating that growth of tree roots or stem biomass will likely be impacted (reduced by > 5%). However, the areal exceedance was < 1% and did not exceed the KPI threshold.

6.4 What Do We Recommend for the EEM Program Going Forward?

We recommend that both of the KPIs for soils under the EEM Program (atmospheric S deposition and critical load exceedance risk, and long-term soil acidification attributable to S deposition) be maintained going forward as they are both well-established and widely used indicators of the impacts from S deposition. Further, we recommend no changes to the critical loads KPI and suggest that critical loads of acidity for terrestrial ecosystems only need to be revised if new data or revised critical limits become available. We recommend that exceedance

continues to be routinely estimated for any updated S (and N) deposition scenarios, primarily to allow for the early detection of potential impacts from the smelter.

1. Nonetheless, there were several uncertainties in the regional assessment of impacts to terrestrial receptors. To address these uncertainties, we recommend that:
   a. A survey of wetland geochemistry and sulphur storage capacity be carried out; wetlands make up almost 25% of the exceeded area, yet there is no chemical information on wetlands in the Kitimat valley. This information will provide support for the critical limit for wetlands.
   b. An assessment of aluminium solubility in mineral soils be carried out; aluminium solubility is a key parameter in the determination of critical loads, associated with the critical limit and $ANC_{leaching}$[36] (see Terrestrial Ecosystems (Soils) Appendix 6.10). This information will help to confirm the current estimates on ANC leaching.
   c. If feasible, at least one of the (newly) proposed plant biodiversity plots (see Section 5: Review Results for Vegetation) be established within the exceeded areas south of the smelter. Further, as noted in Section 5.4.1, a Terrestrial Ecosystem line of evidence should be established to integrate the vegetation and soil lines of evidence.

2. We recommend that the assessment of changes in exchangeable base cation at the long-term soil plots be revised to:
   a. Use a change (decrease) in base saturation (%) to calculate the KPI rather than a change in exchangeable base cation pools; base saturation was the most sensitive parameter in detecting a change of 40% in exchangeable cations between two sampling periods (accommodating the variability in soil chemistry during both sampling events).
   b. Use soil concentrations in the top 0–30 cm (rather than 0–5cm or 0–15 cm) of mineral soil rather than pools to assess changes in soil chemistry.
   c. The minimum detectable difference should be further analysed to evaluate the potential of an early warning change in soil base saturation using a lower level of significance and / or lower power. While this decreases the probability of detecting a true statistical change, it may identify a potential influence at a lower level of change, e.g., a reduction in power may allow for the detection of a significant decrease in base saturation of 20% rather than 40%.
   d. Carry out the next sampling of long-term plots during 2025 (to move back to a five-year period) and measure trees (DBH) at time of soil sampling. Further, if the KPI is triggered, then tree chemistry should be measured to assess base cation update by trees.

[36] $ANC_{leaching}$ is a major component of the critical load (~70%) in this region owing to the high runoff.

7 Review Results for Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)

7.1 What Did We Set Out to Learn?

The STAR predicted that under the maximum post-KMP deposition (i.e., associated with emissions of 42 tpd), the pH would decrease by greater than 0.1 pH in 7 of the 41 lakes sampled. Five of these lakes with potential significant declines in pH were also predicted to exceed their critical loads under such deposition conditions. The rest of the 34 sampled lakes (including Lakelse Lake, which is the largest lake in the area and important to local communities and First Nations because of the fisheries it supports) and all 20 of the sampled stream sites were predicted to decline by less than 0.1 pH units in response to KMP. The STAR concluded that the impact on the aquatic ecosystems receptor under maximum permitted post-KMP emissions was **moderate**, as per the defined assessment framework. The approval of the permit acknowledged that this level of impact was acceptable but would require monitoring through the EEM program to assess any early warnings, potential impacts, and additional monitoring or mitigation actions as appropriate. The STAR assessment also concluded that the change in pH due to KMP would not be enough to have regional impacts on lakes or streams of importance to the public, or on fish production or on wildlife dependent on aquatic biota.

For this receptor, the STAR identified four critical uncertainties (ESSA et al. 2013), framed as questions to be addressed through the EEM program (Table 7-1).

Table 7-1. Critical questions for the aquatic ecosystems component of the EEM Program.

#	Question
W1	How do uncertainties in deposition and surface water models affect the predicted extent and magnitude of critical load exceedance post- KMP?
W2	How many of the 7 to 10 potentially vulnerable lakes actually acidify, and to what extent? a. Have any of the sensitive lakes exceeded their KPI thresholds? b. Does the weight of evidence suggest that any of the lakes have actually acidified and that such acidification is due to KMP (examining changes in all relevant water chemistry parameters)? c. What is the water chemistry of the four less sensitive lakes? Do any of them show any evidence of acidification and/or impact from KMP? d. How many lakes have actually acidified due to KMP and exceeded their KPI thresholds? e. Are additional sites suggested by ENV (i.e., lakes MOE-3 and MOE-6, Cecil Creek, and Goose Creek) at risk of acidification under KMP?
W3	What is the current status of the fish community in the potentially vulnerable lakes that can be safely accessed for fish sampling?
W4	If some of the potentially vulnerable lakes that can be safely sampled for fish show an acidifying trend, then do these lakes also show changes in their fish communities?

For each critical uncertainty, we developed at least two hypotheses (Table 7-2) representing alternative outcomes and identified the information that would be required (measured or modelled) to provide the evidence required to test these hypotheses.

Table 7-2. Critical uncertainties, hypotheses and modelling or monitoring needs for the aquatic receptor, as initially identified in the STAR (Table 10.3-1 in ESSA et al. 2013).

Critical uncertainties	Hypotheses	Modelling and monitoring needs
W1. How do uncertainties in deposition and surface water models affect the predicted extent and magnitude of critical load exceedance post-KMP?	**H1.** Predicted extent and magnitude of exceedances are reasonable or are overestimates. **H2.** Predicted extent and/or magnitude of exceedances are underestimates.	Assess uncertainties in SSWC and modified ESSA/Fisheries and Oceans Canada (DFO) models (estimates of deposition, F-factor) and analyses.
W2. How many of the 7 to 10 potentially vulnerable lakes actually acidify, and to what extent?	**H1**. Changes in water chemistry post-KMP (acidification) are similar to the Steady State Water Chemistry (SSWC) model and modified ESSA/DFO predictions. **H2.** Changes in water chemistry post-KMP are less than predicted. **H3.** Changes in water chemistry post-KMP are greater than predicted.	Slightly smaller set of parameters than sampled in 2012; survey 7-10 potentially vulnerable lakes. Seven high priority lakes are Lakes LAK006 (End Lake), LAK012, LAK022, LAK023 (West Lake), LAK028, LAK042, LAK044. For 2 of the lakes with good road access (West Lake – LAK023 and End Lake – LAK006), could also examine water chemistry after snowmelt and storm events to assess if acidic episodes are occurring. Focus on seven lakes with predicted pH change >0.10 pH units, sampling annually during KMP ramp-up until lake chemistry stabilized (probably within 2-3 years), then once every 3 years for 2 more cycles.
W3. What is the current status of the fish community in the potentially vulnerable lakes that can be safely accessed for fish sampling?	Establish baseline conditions of fish communities prior to implementation of KMP.	Establish baseline biological conditions prior to KMP start-up in safely accessible lakes (which could include Lakes LAK023 (West Lake), LAK006 (End Lake), LAK012, LAK042 and LAK044, to be confirmed by reconnaissance). Resample if pH declines by 0.30 pH units or more relative to 2012 pH. Of the other five lakes, one is an alpine lake inaccessible to fish (LAK047), and the other four lakes have no safe means of access for fish sampling (LAK022, LAK028, LAK054 and LAK056).
W4. If some of the potentially vulnerable lakes that can be safely accessed for fish sampling show an acidifying trend, then do these lakes also show changes in their fish communities?	**H1.** No effects. **H2.** Some loss of diversity but community is still functional. **H3.** Major loss of diversity and function.	Repeat monitoring of fish contingent upon detecting chemical change >0.30 pH units relative to 2012 sample[37]. If pH change is <0.30 pH units, then there would be no resampling of lake fish communities.

[37] Gill netting was used to define the baseline. However, additional gill netting could itself lead to depletion of small fish populations in fish lakes, therefore it will be important to apply discretion and/or alternative monitoring methods if individual lakes require resampling.

7.1.1 EEM Key Performance Indicators

For each receptor, the EEM Plan identifies KPIs that comprise an important metric of potential change, quantitative thresholds associated with that metric, and decision rules that trigger increased monitoring and/or mitigation actions. The 2014 SO_2 EEM Plan (ESSA et al. 2014a) includes two types of KPIs: prediction- and observation-based indicators. The aquatic ecosystems receptor has one observation-based KPI that tracks water chemistry data to determine the pH changes in sensitive lakes (as defined in Table 7-3). The results were designed to reveal the magnitude of impact (i.e., how large the pH change is in lakes expected to be affected). The three critical indicators monitored in the program are SO_4^{2-}, pH and Gran ANC (the capacity of a solution to neutralize strong acids, determined by titration to the inflection point of the pH-alkalinity titration curve). Increases in SO_4^{2-} due to smelter emissions were predicted in the STAR and are not a problem for lake biota provided that pH and Gran ANC do not decrease below threshold levels (e.g., pH 6.0) and by amounts (e.g., decrease ≥ 0.30 pH units) which would be expected to cause biological effects.

The EEM Plan establishes receptor- and facility-based mitigation actions when certain thresholds in the KPIs are reached. For aquatic receptors, the threshold for increased monitoring was defined as an observed pH decrease ≥ 0.30 pH units below the pre-KMP baseline pH level that is causally linked to KMP. If further water chemistry evidence confirms a pH decrease greater than 0.3 pH units linked to KMP, the identified receptor-based mitigation measure involves liming the lake (subject to feasibility and necessary approvals). Studies of acidification impacts on biota in Sweden (Fölster et al. 2007) provided an operational rule for the protection of surface waters, namely that lakes should be maintained within 0.4 pH units of their original, pre-industrial pH. For the Kitimat Airshed Emissions Effects Assessment (ESSA et al. 2014b; page 152), ENV used two criteria for the protection of aquatic ecosystems: 1) avoiding exceedance of critical loads; and 2) if critical loads are exceeded, limiting pH declines to less than 0.30 pH units, adapted from the work of Fölster et al. 2007. As the Kitimat Airshed Assessment was underway at the same time as finalization of the EEM Plan, ENV adopted similar criteria (KPIs) for the EEM Plan.

If the KPI threshold for receptor-based mitigation is reached and receptor-based mitigation is applied but proves ineffective or unfeasible, then facility-based mitigation would be implemented to reduce SO_2 emissions.

Table 7-3. KPI and thresholds for the aquatic receptor (ESSA et al. 2014a).

Key performance indicator	Threshold for increased monitoring	Threshold for receptor-based mitigation	Threshold for facility-based mitigation	Indicators to be jointly considered
Water chemistry – acidification	Observed pH decrease ≥ 0.30 pH units below mean baseline pH level measured pre-KMP and is causally related to KMP. Action: additional monitoring to determine seasonal variation in pH and SO_4^{2-}	Lake is rated Medium or High (based on relative lake rating) and shows a decrease causally related to KMP of > 0.30 pH units below measured baseline pre-KMP and liming is feasible given access. Action: liming to bring the lake back up to pre-KMP pH, subject to approval by B.C. ENV/DFO prior to implementation.	More than 2 lakes rated Medium or High (based on relative lake rating) with decrease causally related to KMP of > 0.30 pH units below measured baseline pre-KMP (prior to liming). Action: reduction in SO_2 emissions	Aquatic biota: fish presence / absence per species on sensitive lakes ratings Evidence that pH decrease is causally related to KMP SO_2 emissions.

7.1.2 EEM informative indicators

The EEM Plan also identified "informative indicators", which may have decision rules for increased monitoring or modelling, but they do not have decision mitigation actions on their own. The purpose of the informative indicators is to provide additional evidence in support of the KPIs.

The SO_2 EEM Plan (ESSA et al. 2014a) identified seven informative indicators (Table 7-4) that provide evidence in support of the lake acidification KPI. The first informative indicator for this receptor is prediction-based: measured water chemistry data and measured S deposition data are used as inputs for updated modelling of critical loads and expected exceedance of those critical loads. Results will reveal the extent of expected impact (i.e. how many lakes might be affected) and will guide where sampling should occur. The informative indicator "*evidence that pH is causally related to KMP SO_2 emissions*" involves the analysis of changes in Gran ANC, SO_4^{2-}, dissolved organic carbon (DOC), base cations, Cl, in combination with the application of the evidentiary framework. These topics are covered in greater detail in later sections. The methods used for collecting data pertaining to these indicators are briefly described in Table 7-4 and discussed in more detail in Section 7.2.1.

Table 7-4. Informative indicators and thresholds for the aquatic receptor (ESSA et al. 2014a).

Informative indicators	Threshold for increased monitoring	Indicators to be jointly considered
Atmospheric S deposition and CL exceedance risk	CL exceeded in more than the 10 acid-sensitive lakes identified in the STAR as having either CL exceedance or predicted to acidify by more than 0.1 pH units. Action: expand the monitoring to include newly identified lakes with predicted exceedance.	• Predicted steady state pH versus current pH (if predicted change > 0.1 pH units then level of concern is higher than if predicted change < 0.1 pH units) • Water chemistry – acidification
Predicted steady state pH versus current pH	Seven lakes with predicted pH change >-0.10 units are included in the set of lakes that are monitored annually each October.	• Surface water model inputs, as described in Section 8.6.3.4 of ESSA et al. (2013)
Estimates of natural variability in pH and other indicators	If the fall index sample is below the pH threshold for any lake, the EEM Program will then obtain four chemistry samples during the fall index period of the following year to better estimate the mean index value and natural variability of pH and other parameters.	• Baseline estimates of natural variability in pH and other indicators from End Lake (LAK006), Little End Lake (LAK012) and West Lake (LAK023) • These estimates will be used to assess whether observed pH values (and other indicators) are within or outside the range of natural variability
Evidence that pH decrease is causally related to KMP SO_2 emissions	Used in application of all three KPI thresholds	• Trends and levels of SO_2 emissions, SO_4^{2-} deposition, N deposition • Trends and levels of lake ANC, SO_4, • NO_3^-, Cl^- and DOC in both individual lakes and across all seven acid-sensitive lakes
Aquatic biota: fish presence / absence per species on sensitive lakes	Decrease in pH ≥0.30 units confirmed by more intensive sampling in the fall index period. Action: resample the fish community in lakes that can be safely accessed for fish sampling	• None
Episodic pH change	NA	• None
Amphibians	NA	• Atmospheric S deposition

7.1.3 Other questions that have emerged

Other questions that arose during the STAR and/or the development of the EEM Program

- **How do the observed changes in SO_4, Gran ANC and pH compare to the steady-state predictions from the STAR?**
  The STAR included predictions of future lake chemistry properties based on the current lake chemistry and maximum increases in deposition that could occur under the prospective permit. One of the most basic questions to address with the water chemistry data collected after the smelter increased emissions is how the observed changes compare to the initial predictions (after accounting for the fact that post-KMP emissions have been significantly below the permit levels assessed in the STAR – i.e., approximately 30 vs 42 tpd SO_2).

- **Can we estimate F-factors[38] from the empirical sampling results?**
  As more years of data are collected on the water chemistry of each of the lakes, and if there is sufficient change within the data, it may be possible estimate the F-factor for individual lakes based on the actual observed changes in total base cations and SO_4^{2-}.

- **Do we see any evidence of regional acidification if we analyze the lakes as a group rather than individuals?**
  In contrast to many or most freshwater acidification monitoring and assessment programs, the EEM Program is explicitly designed to assess the potential impacts on individual lakes. Usually regional acidification monitoring programs focus on regional trends and patterns. This gives the program greater power to detect regional patterns in water chemistry. However, in the development of the EEM Program, concerns were raised that a regional assessment could mask changes of concern at individual lakes of interest, which is why the program is focused on patterns of change for individual lakes.

Other questions that have emerged since the development of the EEM Program

During the implementation of the EEM Program (2013-2018), new questions that were not originally identified in the EEM Program emerged as data were collected and analyzed.

- **Is there a benefit to adding appropriate control lakes to the EEM?**
  The EEM Program did not originally include control lakes. Four less sensitive lakes in the Kitimat Valley were included in the EEM Program, to provide contrasts in responsiveness to acidic deposition (i.e., these lakes would be expected to show changes in lake [SO_4] if exposed to increased S deposition, but would not show biologically significant changes in pH or Gran ANC). However, early monitoring results suggested that the variability in the lake chemistry was greater than anticipated, which raised the question of whether appropriate control lakes

[38] The F-factor is equal to the ratio of the change in base cations to the change in sulphate in a lake (i.e., F-factor = $\Delta BC / \Delta SO_4^{2-}$). It is a simple way to represent cation exchange processes, specifically the proportion of incoming acidity accompanying sulphate that is exchanged in the soil for base cations. The F-factor is an important parameter for both the Steady-state Water Chemistry model (critical loads and exceedances) and the ESSA-DFO model (future steady-state pH).

could be identified in areas of very low S deposition, and whether adding them to the EEM could improve the program's ability to detect and interpret changes in the EEM lakes.

- **Is there a benefit to more intensive water sampling?**
  The sampling frequency was increased for multiple EEM lakes in response to initial indications that the variability in the lake chemistry properties might be much greater than anticipated during the STAR and the design of the EEM Plan. It is important to understand the benefit of more frequent sampling in order to determine the value of continuing such monitoring.

- **Is there a benefit to collecting other data on the EEM lakes?**
  Bathymetric data would allow a more accurate estimation of lake volume, and thus water residence time. Water residence time is a factor that influences water chemistry variability in lakes. Lake level information could provide information on changes in inflows prior to sampling events. Increased runoff can influence the concentration of different ions in the lake and lead to short-term decreases in pH.

- **Will increased emissions result in immediate (i.e., same year) changes to lake chemistry or will there be a lag?**
  Much of the modelling done in the STAR was based on analyses of future, steady-state conditions. However, it was not known whether the changes predicted under steady-state conditions would occur quickly or slowly after emissions increased.

- **How important will it be to consider multiple metrics in our evaluations of the data?**
  From the beginning of the EEM Program, we have been considering multiple metrics in our quality assurance, modelling, and statistical analyses of water chemistry data. The EEM Plan included a multi-metric evidentiary framework for determining if changes in lake chemistry were caused by the smelter, considering the various processes that can affect lake chemistry; we apply that framework in this report in Table 7-12. In completing this report, we have simplified the EEM evidentiary framework, presented as a decision flowchart with three key questions, focused on SO_4^{2-}, pH and Gran ANC (see Section 7.2.4). This decision flowchart examines the evidence for chemical change in each lake, beginning with changes in SO_4^{2-} (the link to the smelter), and then assessing the evidence for changes to pH and Gran ANC (indicators of acidification). Other ions are used to help explain observed patterns of change in lake chemistry.

7.1.4 Complexity and causality of changes in lake chemistry

7.1.4.1 *Complexity of lake chemistry; separating anthropogenic and natural changes*

The complexity of watershed-lake ecosystems makes it difficult to clearly identify what caused all observed changes in lake chemistry. Fortunately, that isn't required. The EEM Program is not intended to be a comprehensive research program to evaluate the causes and effect of all observed changes in lake chemistry. However, it is important to be able to confidently separate natural and anthropogenic changes. The focus of the aquatic component of the EEM Program is to identify and understand whether increases in emissions from the smelter are contributing to acidification of any lakes through increased SO_4^{2-} deposition. However, even in the absence of the smelter emissions (either at stable or increased levels), lake chemistry properties are not static. Changes in ANC, pH, organic acids, Cl, SO_4, base cations, and other ions are subject to a suite of

natural drivers that lead to daily, monthly, seasonal, and annual variability in lake chemistry. For example, concentrations of ions tend to decrease during wet periods due to dilution effects, and increase during droughts due to concentration effects. While these factors make it more difficult to understand trends in lake chemistry, the focus of the analysis is on a simpler question – have smelter emissions and associated S deposition caused acidification of the sensitive lakes?

7.1.4.2 *Evidentiary Framework*

The EEM Evidentiary Framework was developed to provide a structured approach for evaluating the causes of any acidification observed in the lakes. The EEM Plan provided the following description of the context and purpose of the Evidentiary Framework (EEM Plan, p. 42-44):

> Proving causality (i.e., acidification of lakes related to KMP) requires following the cause-effect chain in the source-pathway-receptor diagram (Figure 7), and evaluating multiple lines of evidence for alternative causal pathways. Weight of evidence analyses (Burkhardt-Holm and Scheurer 2007, Marmorek et al. 2011) rely on four types of evidence: 1) a plausible mechanism; 2) exposure to the pollutant; 3) correlation of pollutant exposure and chemical / biological response in space and time; and 4) experimental evidence from the region or other published studies. The pathways and plausible mechanisms of acidification of surface waters are well understood (Marmorek et al. 1989; Baker et al. 1991), so the focus of the proposed weight of evidence analysis is on exposure, correlation and experimental evidence.
>
> The evidentiary framework (Table 17) provides a series of questions and tests for various different lines of evidence that then need to be jointly evaluated to draw a conclusion regarding the likelihood that KMP has caused acidification.

The Evidentiary Framework is further discussed in Section 7.2.4 and applied in Section 7.3.4.5. We developed a simpler Evidentiary Framework for this report, and have applied both the simpler and more complex frameworks in Section 7.3.4.5.

7.1.4.3 *Multiple metrics, types of lakes and lines of evidence*

Separating smelter effects from natural changes requires multiple metrics (deposition, full lake chemistry, precipitation), control lakes that are outside of the plume (and therefore reflect only natural changes), and multiple lines of evidence (presented in this report and its appendices). In addition to the Evidentiary Framework, Appendix H of the EEM Plan provides further guidance on interpreting patterns of change across multiple lake chemistry metrics.

7.1.4.4 *Limitations of pH as a KPI*

Although pH is the primary metric upon which the aquatic KPI is based, it would not be appropriate to rely solely upon observed changes in pH. First, there are many natural processes which can change pH, such as increases in precipitation (decreases pH) and increases in primary production (increases pH). The EEM Plan recognized this explicitly by defining the KPI based on changes in pH that are *causally related* to the increased smelter emissions. Assessing that causal linkage implicitly requires evaluation of other changes in lake chemistry, especially ANC and SO_4, as outlined in the Evidentiary Framework and Appendix H of the EEM Plan. However, there are

still some additional limitations and concerns with the pH-based KPI that were not well understood at the time the EEM Plan was developed. First, the natural variability in the pH of the EEM lakes is much greater on average than for other North American lakes for which lake chemistry data sets were available in the literature. Even within the EEM lakes, the variability in pH is much greater than the variability in ANC, which will be an important consideration if new KPIs are developed for the next phase of the EEM. Second, over the course of the EEM sampling program, we have learned that measuring pH in lakes with low ionic strength is difficult and not all laboratories and instruments can achieve consistent, stable measurements. Third, even for instruments and laboratory processes able to achieve stable measurements of pH, the measurement uncertainty is still relatively large compared to the effect size of interest.

7.2 What Methods Did We Use?

This section provides a high-level summary of the major methods applied for the collection, processing, and analysis of data for implantation of the aquatic ecosystems component of the EEM Program. The methods applied are briefly introduced in terms of identifying the method (or suite of methods) and the purpose. The detailed specifications of how each method was implemented are reported in the appendices (e.g., primarily Aquatic Appendices A, F, and G).

7.2.1 Data we collected

7.2.1.1 *Water chemistry data*

We focused on biologically-relevant water chemistry as the primary indicator (i.e., pH, ANC, SO_4, DOC, and other major ions), because it provides the earliest possible indication of potential impacts to aquatic biota. Water chemistry data are needed to assess the form, rate and magnitude of changes that may be occurring in lake chemistry. Water chemistry data also provide the inputs necessary for predictive modelling of changes that may occur in the future under different emissions scenarios. Limnotek implemented the water sampling program, including collecting samples, conducting some field measurements, sending samples for laboratory analyses and performing Quality Assurance/Quality Control (QA/QC) analyses on the results (see Limnotek's annual technical reports). We performed additional QA/QC checks on the data and then converted the data into equivalent concentration values. As described in the STAR, we applied an adjustment factor to the measured concentration of SO_4^{2-} and base cations to correct for the influence of marine sea salts (i.e., marine-adjusted concentration), as is conventional practice in acidification analyses. Throughout the comprehensive review we always use and/or present the marine-adjusted values unless explicitly noted.

7.2.1.2 *Sampling locations*

The EEM Program includes sampling of the following sets of lakes:

- **EEM Sensitive Lakes[39]:** Seven lakes that were predicted in the STAR to decrease in pH >0.1 units under maximum future emissions levels.
- **EEM Less Sensitive Lakes[40]**: Two moderately sensitive lakes, one highly insensitive lake, and one lake of high public value (also highly insensitive). 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 or Gran ANC due to their greater ability to neutralize acidic deposition.
- **EEM Control Lakes:** Three control lakes, which are sensitive lakes located well outside of the deposition plume. These were added to the program in 2015 but already had sampling data from 2013 from the KAEEA program

The STAR sampled 41 lakes (all lakes greater than 1 ha in the study area which fulfilled the selection criteria), and 20 stream sites. The selection of the seven sensitive and four less sensitive lakes was based on the analyses of the full set of lakes and streams in the STAR. As part of the updated analyses of critical loads and exceedances in the comprehensive review, we also included any lakes from the KAEEA program that are located within the CALPUFF modelling domain. Figure 7-1 shows the location of all the lake and stream sites within the study area, as sampled during the STAR, KAEEA and/or EEM programs. Figure 7-2 focuses on the locations, frequency and types of sampling implemented as part of the EEM Program specifically.

An incidental outcome of having selected the lakes based on chemical criteria (i.e., acid sensitivity properties) rather than geographic criteria is that the lakes are unevenly distributed across the study area. As shown in Figure 7-2, the EEM lakes are located in three distinct groupings. Three of the EEM lakes (two sensitive lakes and one less sensitive lake) are located in a cluster in the northernmost part of the study area. Six of the EEM lakes (four sensitive lakes and two less sensitive lakes) are located in a cluster to the south and southwest of Lakelse Lake (itself a less sensitive lake), which is roughly halfway between the smelter and the northern boundary of the study area. Only one EEM lake (LAK028, a sensitive lake) is located fairly close to the smelter and is in fact the only lake in the southern half of the study area. From the perspective of minimizing potential environmental effects, it is fortuitous that there is only one sensitive lake relatively close to the smelter.

This uneven distribution of lakes evokes a couple of obvious questions: 1) are there any other lakes close to the smelter that should have been included in the EEM?, and 2) why does the EEM

[39] The methodology and criteria by which the sensitive lakes were selected is explained in detail in the STAR (refer to Sections 9.4.1.4, 9.4.2.5) and the EEM Plan (refer to Section 6.2.1, Appendix D, and Appendix H).
[40] The rationale for the inclusion of less sensitive lakes and the methodology and criteria by which they were selected is explained in detail in Appendix H of the EEM Plan. Note that these lakes were initially included in the design as "control lakes" that were located within the deposition plume but not predicted to exhibit any changes in chemistry associated with increased deposition. However, this characterization was revised early in the EEM Program. Further consideration concluded that equally sensitive lakes located well outside the plume would provide better controls. Such control lakes were added to the EEM Program in 2015 but the initial control lakes were retained as "less sensitive" lakes for potential comparisons to the sensitive lakes.

not include any lakes south of the smelter? The answer to both of these questions is that, as described above, the STAR assessed the acid sensitivity of all of the candidate lakes within the study area and did not find any other lakes that should be included in the EEM program. The details of these conclusions are expanded upon below.

Other STAR lakes close to the smelter
In the STAR, there were only two other lakes south of the Little Wedeene River and in relative proximity to the smelter, which were LAK027 and LAK030. LAK027 (Bowbyes Lake) had a pH of 6.6, Gran ANC of 70 µeq/L, an estimated critical load of 248 meq/m^2/yr, and a predicted future pH change of 0.0 pH units. LAK030 was even more insensitive, with a pH of 7.4, Gran ANC of 390 µeq/L, an estimated critical load of 802 meq/m^2/yr, and a predicted future pH change of 0.0 pH units. These two lakes are not acid sensitive and did not need to be included in the EEM Program.

Other STAR lakes south of the smelter
There were five STAR lakes to the southwest of the smelter in the 2019 modelled deposition area (LAK053, LAK054, LAK055, LAK056, and LAK057) and 9 KAEEA lakes (see Aquatic Appendix G, Table 2-2). The STAR and KAEEA concluded that these lakes were all at a low risk of acidification (i.e., predicted pH decreases of less than 0.1 pH units in the STAR and 0.3 pH units in the KAEEA). Three of the five STAR lakes (LAK053, LAK055, LAK057) show no critical load exceedances and a predicted pH change of 0.0 (Aquatic Appendix G, Tables 2-2 and 3-2). Two of the five STAR lakes (LAK054 and LAK056) are naturally acidified with high DOC and very low critical loads (0 and 1.2 meq/m^2/yr respectively), therefore showing exceedances under all deposition scenarios (Aquatic Appendix G, Table 2-2), but with predicted pH decreases of less than 0.1 pH units under the STAR's 42 tpd scenario (Aquatic Appendix G, Table 3-2).

Seven of the nine KAEEA lakes to the southwest of the smelter showed no critical load exceedances under any of the new deposition estimates (Aquatic Appendix G, Table 2-2). Two of the KAEEA lakes (DCAS07A and DCAS07B) have a CL of 0.0 so they show CL exceedance under all emissions scenarios, but the predicted change in pH under the highest KAEEA emissions (Scenario H_82.6, with 55.8 tpd of SO_2; 26.8 tpd of NO_x) was only -0.03 pH units for both lakes (KAEEA unpublished analyses).

7.2.1.3 *Aquatic biota*

In the discussions leading up to the development of the EEM Plan, we discussed the pros and cons of monitoring aquatic biota directly (e.g., zooplankton, benthic organisms, fish). While biotic indicators do provide direct evidence of aquatic impacts, changes in such indicators (e.g., community structure or species diversity) lag behind changes in aquatic chemistry. Due to their public importance, we did take baseline estimates of fish density in 5 sensitive lakes (those that were safely accessible – End Lake (LAK006), Little End Lake (LAK012), West Lake (LAK023), Finlay Lake (LAK042) and LAK028, and three of the less-sensitive lakes – Clearwater Lake (LAK007), LAK016, and LAK034.

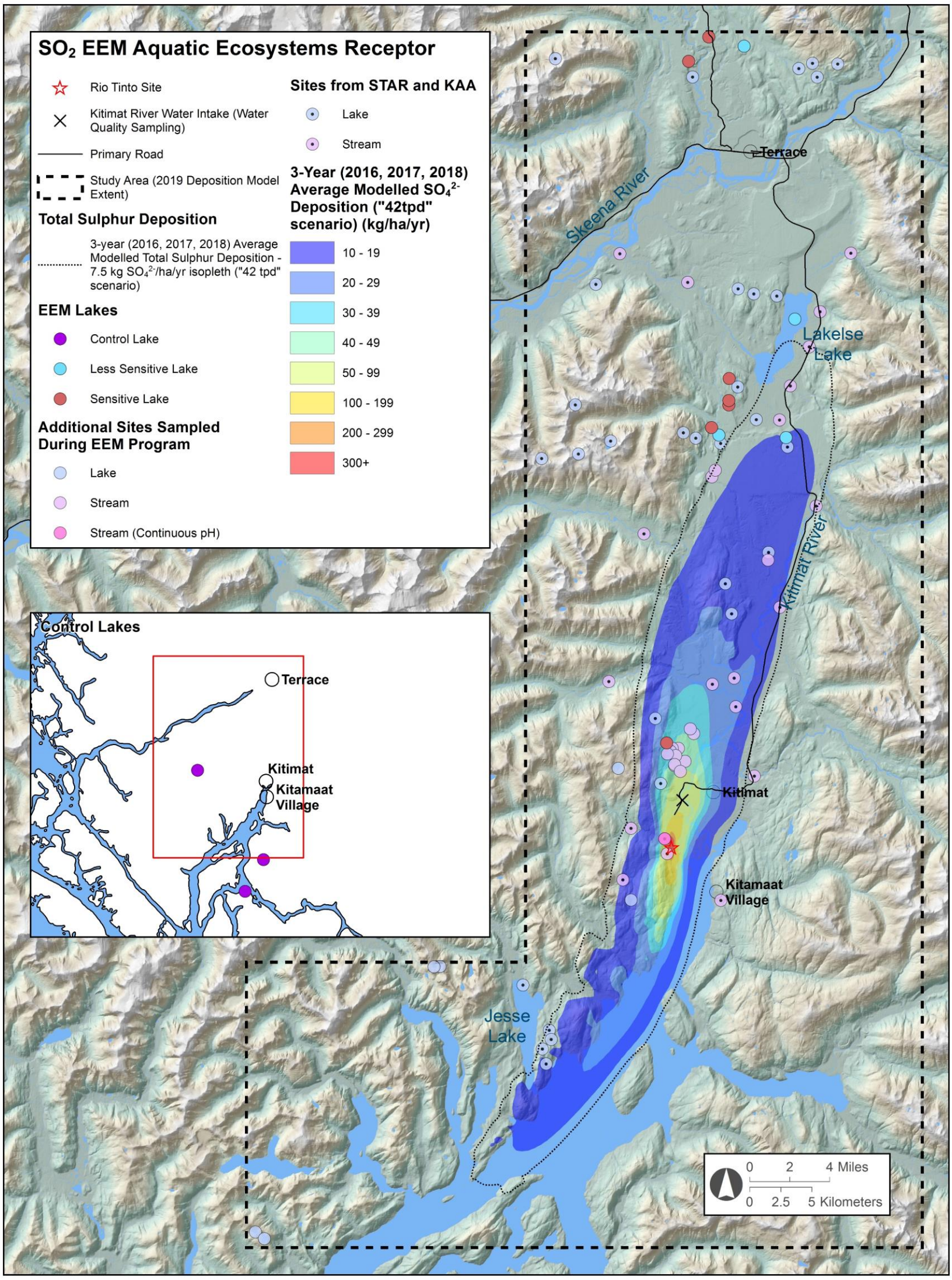


Figure 7-1. Locations of ongoing and existing monitoring and sampling for the aquatic receptor of the EEM Program. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleths.

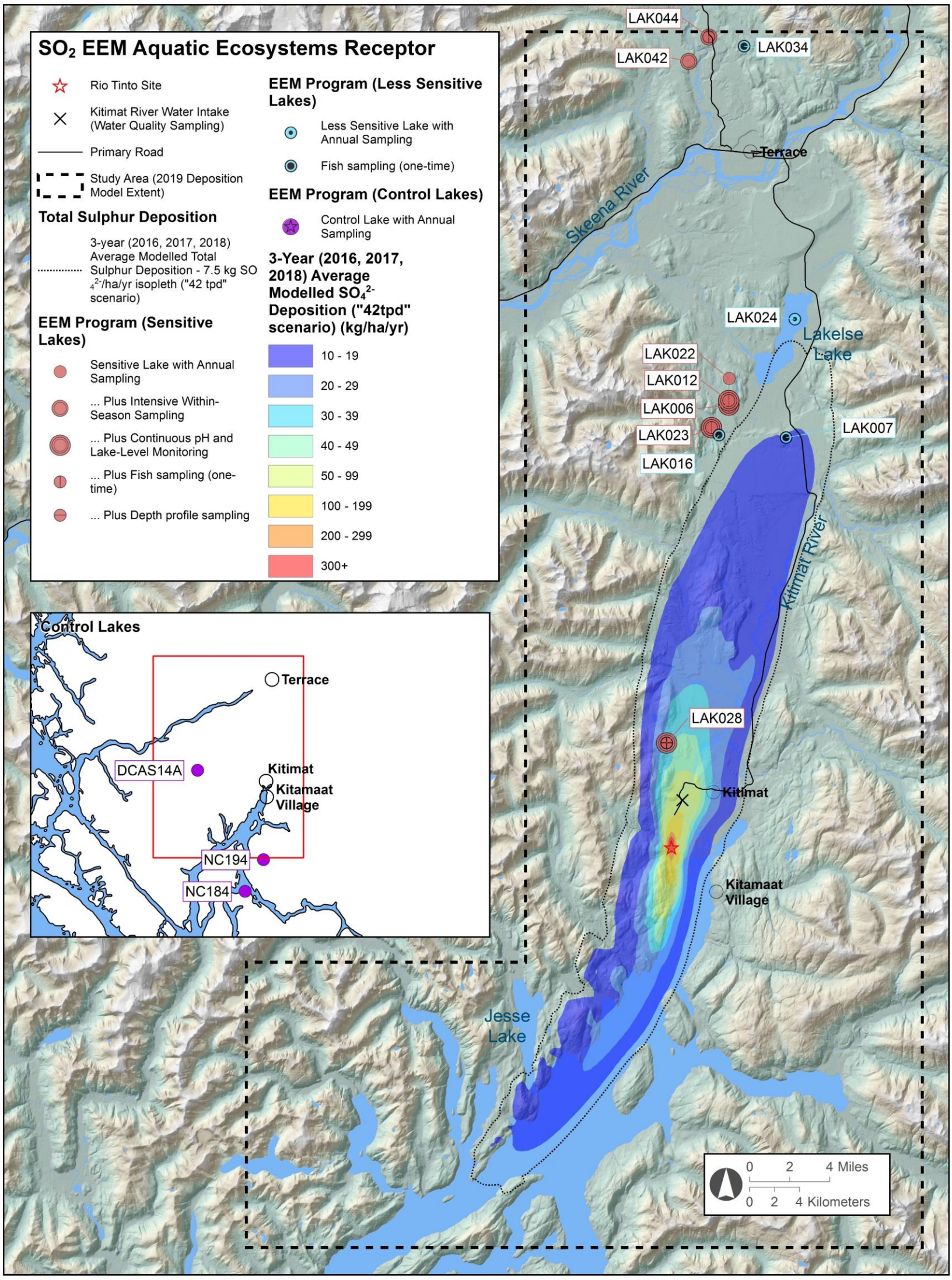


Figure 7-2. Locations of the study lakes of the EEM Program. Lakes are grouped by their classification as sensitive lakes, less sensitive lakes and control lakes. The map also shows the frequency and type of monitoring conducted at each of the lakes. The plume shows the estimated deposition under the maximum emissions rate. The estimated deposition values for each watershed under current emissions are documented in Table 2-2 of Aquatic Appendix G. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleths.

7.2.2 Quality of water chemistry data

The methods utilized in the collection of water samples, field measurements, storage and transport of samples, and laboratory analyses of water chemistry properties are subject to rigorous quality control and quality assurance procedures, as described in the annual technical reports prepared by Limnotek, who are responsible for the implementation of the EEM aquatic ecosystems monitoring program.

Once the water chemistry data are received, we conduct additional checks to ensure the data do not appear to have any data quality deficiencies that would raise any concerns regarding their use in our analyses. A reasonable balance between cations and anions and relatively small differences between the measured and estimated conductivity provides assurance that there are no concerns with the laboratory analyses (or data management procedures) and that all of the major constituents of the water chemistry are accurately represented within reasonable bounds of uncertainty expected in these types of data. Aquatic Appendix A provides addition information.

7.2.3 Analyses we conducted with these data

This section provides a high-level summary of the major types of analyses we conducted. Specific details of the implementation of these analyses are described in Aquatic Appendices A and F.

7.2.3.1 *Variable organic charge density*

The contribution of organic anions to the charge balance is estimated as a function of the measured DOC and an assumed charge density. In the STAR and EEM, we have applied the Oliver et al. (1983) function. In the STAR we used a uniform organic charge density with an assumed value based on the literature. In the comprehensive review we explored whether using alternative values for the organic charge density would improve the charge balance – i.e., thus indicating a more accurate characterization of the contribution of organic anions. We used two different approaches. First, we continued to use a uniform value across all sites and found the organic charge density value that resulted in the best charge balance across the entire data set. Second, we allowed organic charge density to vary by site (but with a single value for each lake across years) and found the value that resulted in the best charge balance for each individual lake.

7.2.3.2 *Exploration of ANC values and metrics*

There are multiple ways of measuring and/or estimating the ANC of a particular water sample. In the STAR and EEM we have primarily used Gran ANC in our analyses of both the observed and predicted changes in lake chemistry. Gran ANC is the capacity of a solution to neutralize strong acids, including the buffering effect of organic anions. However, measuring Gran ANC requires specialized laboratory equipment that is not widely accessible.

Charge balance ANC (CBANC) is an alternative estimation of the capacity of a solution to neutralize acidity. It is generally calculated as the equivalent difference between the total base cations and strong acid anions. CBANC is widely used in acidification studies because it is estimated from easily measured ions, but it does not account for the buffering effect of organic anions. Additional alternatives are based on modifying the estimate CBANC to explicitly account for the effect of organic anions. The two we compared are the Lydersen et al. (2004) method for

estimating an organic anion adjusted ANC (ANC_{oaa}) and the Lawrence et al. (2007, 2013) method for making a conceptually similar adjustment to ANC, but termed Base Cation Surplus (BCS).

7.2.3.3 *Temporal patterns in water chemistry*

Table 7-5 outlines the key questions of interest, the rationale for these questions, and the methods used to address these questions. These analyses are presented in detail in the Aquatic Appendix F and summarized below in Section 7.3.2.3.

Table 7-5 Analyses of temporal patterns in water chemistry: questions, rationale and methods.

Questions of Interest / Rationale	Methods Used
How long does it take to reliably assess whether or not key water chemistry parameters (SO_4, pH, ANC) have changed relative to pre-KMP conditions, and (for pH and ANC) whether those changes exceed the 0.3 unit threshold established in the EEM Plan for pH, and the lake-specific thresholds established subsequently for Gran ANC? Water chemistry varies naturally, both within and between years, due to changes in weather and lake productivity. We are interested in detecting the signal of long-term chemical change against the noise created by natural variability. We would like to avoid two types of errors: false positives (concluding that changes in lake chemistry exceed a threshold, when in fact they don't) and false negatives (not detecting a true exceedance of a threshold). Appendix H of the EEM Plan describes the general types of responses that could be observed in different lakes, depending on the degree of sensitivity and level of exposure. Aquatic Appendix C of the report shows the time series of empirical observations, which show that the changes have generally been gradual.	• In 2015 we conducted a power analysis of the data collected to date (i.e., 2012-2014), to assess our ability to detect changes in water chemistry for SO_4, pH and ANC. Having now collected data for seven years (2012-2018) we have better estimates of year-to-year and within-year variability.
What are the general patterns of variability and change over time in key water chemistry parameters? These graphs are meant to simply examine general patterns, independent of any assignment of causality, quantitative statistical analysis or application of the evidentiary framework. The patterns of interest include variability across and within years within each lake, differences in the magnitude of variability across different lakes, and differences in water chemistry between different groups of lakes (e.g., sensitive, less sensitive, control).	• Simple graphs of changes over time of each variable of interest for each lake (as included in previous EEM reports).
Do the values of key water chemistry parameters vary with the magnitude of recent precipitation? The EEM is designed to detect long term trends, not episodic changes in water chemistry. Eight lakes are sampled annually during the fall index period, while six lakes are sampled four times during this period. We are, however, interested in understanding the extent to which late summer and fall storms may affect lake chemistry, and the apparent trends over multiple	• Scatter plots to look at relationships among water chemistry variables of interest (i.e., SO_4, ANC, pH, DOC, BC, Cl, Al) and recent precipitation (during the last 3 days, and last 14 days) at the Haul Rd monitoring site. • Inclusion of precipitation covariates in statistical analyses (Sections 7.6.4.2.6,

Questions of Interest / Rationale	Methods Used
years. Snowmelt and rainstorms may affect water chemistry through a number of natural and anthropogenic mechanisms, including dilution, nitrification, organic acid production and the sea salt effect (Wigington et al. 1996). Snowmelt and rainstorms could create a spurious long-term trend. For example, if big storms occurred prior to the annual sampling later in the 7-year time series (i.e., 2017 or 2018), and increased SO_4, due to washout of atmospheric or watershed SO_4, this might generate a false long-term pattern of increasing SO_4^{2-} over multiple years. Conversely, if major storms occurred prior to annual sampling early in the time series (i.e., 2012 or 2013), and increased SO_4, this might generate a false long-term pattern of decreasing SO_4^{2-} over multiple years.	7.6.4.3.6 and 7.6.4.4.6 of Aquatic Appendix F).
Do the values of key water chemistry parameters vary with emissions? The absence of any positive correlation between lake SO_4^{2-} concentrations and recent increases in SO_2 emissions (or the lack of any trend of increasing SO_4^{2-}) is evidence against the new smelter being a cause of changes in a lake's $[SO_4^{2-}]$. However, the lack of a correlation could also reflect the fact that emissions are only a proxy indicator of the actual deposition at each lake. Estimates of lake-specific deposition are only available with the revised CALPUFF model for the period from 2016 to 2018, and therefore cannot provide contrast between the pre-KMP and post-KMP period. While the presence of a positive correlation between lake $[SO_4^{2-}]$ and SO_2 emissions is consistent with the hypothesis of the new smelter causing changes in lake SO_4, such a correlation is not by itself incontrovertible evidence that smelter emissions caused the increase in lake SO_4. For example, drought conditions can cause SO_4^{2-} that was historically stored in a reduced form in wetlands to be re-oxidized and then (once the drought is over) washed into the lake, causing an increase in SO_4^{2-} and decreased pH (Yan et al. 1996).	• Scatter plots to look at relationships among water chemistry variables of interest (i.e., SO_4^{2-}, ANC, pH, DOC, BC, Cl, Al) and average emissions of SO_2 from the smelter (in tpd). • Inclusion of smelter emissions as a covariate in statistical analyses (Sections 7.6.4.2.6, 7.6.4.3.6 and 7.6.4.4.6 of Aquatic Appendix F).
How much change has occurred in key water chemistry parameters (SO_4, pH, ANC) between the pre-KMP period (2012) and the post-KMP period (2016-2018)[41], within each lake? For pH and ANC, how likely is it that the changes exceed the EEM thresholds? Figures 11 and 12 in Volume 1 of the STAR demonstrate the expectation in 2012 that the new smelter would result in both a higher level of sulphur deposition, and a different spatial pattern of deposition. We are therefore interested to learn which lakes experienced an increase in SO_4^{2-} concentrations, and which lakes experienced a decrease. Critical to the EEM Plan is the evaluation	We applied seven frequentist methods: 1. Two-sample Before-After t-test using mean values for 2012 and 2016-2018 (all lakes) 2. Two-sample Before-After t-test using individual samples (for the six sensitive lakes with four fall samples during each year) 3. Before-After Control-Impact (BACI), using mean values (all lakes)

[41] Data from 2013 to 2015 is not included in these temporal analyses because it represents a period in which emissions were decreasing as production was ramped down prior to the transition to the new smelter. The pre-KMP baseline year for the aquatic analyses is 2012. The new smelter was ramped up in late 2015, therefore 2016 onwards represents "post-KMP".

Questions of Interest / Rationale	Methods Used
of whether lake pH changed by more than 0.3 pH units, and whether ANC decreased by more than the lake-specific thresholds for ΔANC.	4. BACI, using individual samples (six sensitive lakes) 5. BACI, assuming no change in mean of the control lakes between the before and after period. 6. BACI, using covariates for emissions and precipitation to explain inter-annual variation 7. Temporal Trend Analyses – Mann-Kendall non-parametric test for monotonic trend detection. We also applied two Bayesian approaches: 1. Bayesian Estimation Supersedes the T-Test (BEST; using a range of informative priors) 2. Bayesian analysis with uninformative priors The Bayesian approaches provide a "percent belief" in chemical changes of interest (e.g., SO_4^{2-} increases, Gran ANC or pH decreases beyond thresholds).
Based on the three intensively monitored lakes (End Lake, Little End Lake, West Lake), are there are seasonal and long-term trends in pH?	We applied a Seasonal Mann-Kendall test, using average values for each season per year to reduce auto-correlation. Spring = [April, May, June]; Summer = [July, Aug], Fall = [Sept, Oct., Nov]).

7.2.3.4 *Assessing observed changes in water chemistry relative to STAR predictions*

The STAR included predictive analyses of future changes in water chemistry under increased deposition at maximum emissions levels (i.e., the permitted level of 42 tpd SO_2). We compared the changes that have been observed thus far to those predicted changes, after accounting for the fact that average post-KMP emissions (i.e., 29.3 tpd SO_2) have been much lower than the maximum permitted level of 42 tpd. We therefore adjusted the STAR predictions based on current emissions to facilitate an equivalent comparison.

7.2.4 Weight-of-Evidence approach for assessing causality

Table 17 of the 2014 SO_2 EEM Plan (ESSA et al. 2014a) laid out nine questions which would jointly be helpful in determining if lakes were acidifying due to emissions from KMP, or whether other factors might be responsible for observed changes in lake chemistry. We called this table an "evidentiary framework", since it laid out multiple lines of evidence. In Section 7.3.4.2, we address these nine questions as written in the EEM Program Plan, and have also developed a simpler evidentiary framework (Figure 7-3), which provides a clearer categorization of lakes into different types. The primary advance in Figure 7-3 is that it first filters out types of lakes which are not a concern (i.e., lakes which have shown no change in $[SO_4^{2-}]$ or strong evidence of a

decrease in in [SO_4^{2-}]), which aligns with the focus of the EEM in determining whether or not the lakes have experienced any smelter-driven acidification. The next filter is for lakes which have shown an increase in [SO_4^{2-}] but no evidence for decreases in either pH or ANC. The focus then turns to lakes which are the greatest concern (i.e., lakes with an increase in [SO_4^{2-}] and some support for a decline in either ANC or pH), to determine if the magnitude of decline exceeds the defined thresholds. The simplified evidentiary framework assumes that any lake with strong support for a post-KMP increase in lake SO_4^{2-} reflects contributions of S to that lake from SO_2 emitted from the new smelter. This assumption reflects the fact that there are not any other major sources of regional S emissions which changed over the period of interest[42] and that the smelter emissions do not include enough N to have a meaningful impact on aquatic acidification. The KAEEA included N in its acidification analyses because it included other types of facilities with significantly different emissions profiles (e.g., higher N oxides from LNG facilities); however, the smelter emits only a small amount of N oxides (~1 tpd). This is corroborated by the fact that the observed changes in nitrate (NO_3^-) concentrations in the EEM lakes have been roughly an order of magnitude less than the observed changes in SO_4^{2-} concentrations (see Figures 7.23 and 7.24 in Aquatic Appendix A), Lakes could acidify naturally by increases in organic acids, but that would not be related to the smelter. That is, sulphur is the only potential driver of acidification that is causally associated with smelter activity and that is present in sufficient quantity to influence lake chemistry. Furthermore, the smelter is the only major source of sulphur emissions in the region. Therefore, the first question of the simplified evidentiary framework is an appropriate screen to eliminate lakes from further consideration if they do not have evidence of an increase in lake [SO_4]. Explaining changes in lake chemistry that are unrelated to the smelter is not within the scope of the EEM Program.

The simplified evidentiary framework also more easily incorporates the results of the statistical analyses and permits conclusions to be drawn with respect to which lakes are or are not of current concern. However, for sake of completeness and alignment with the original EEM Plan, we have still worked through the full nine questions of the detailed evidentiary framework (Section 7.3.4.2, Table 7-13).

[42] This assumption could cause an over-estimate of smelter impacts, as increases in lake sulphate could be due to climatic fluctuations that release S stored in wetlands (i.e., droughts followed by storms; see discussion in fourth row of Table 7-5). However, the most notable drought occurred in the summer of 2018, and there is not any evidence of a broad increase in sulphate concentrations in the samples taken in the fall of 2018, as shown in Section 7.6.2.1.1 of Aquatic Appendix G.

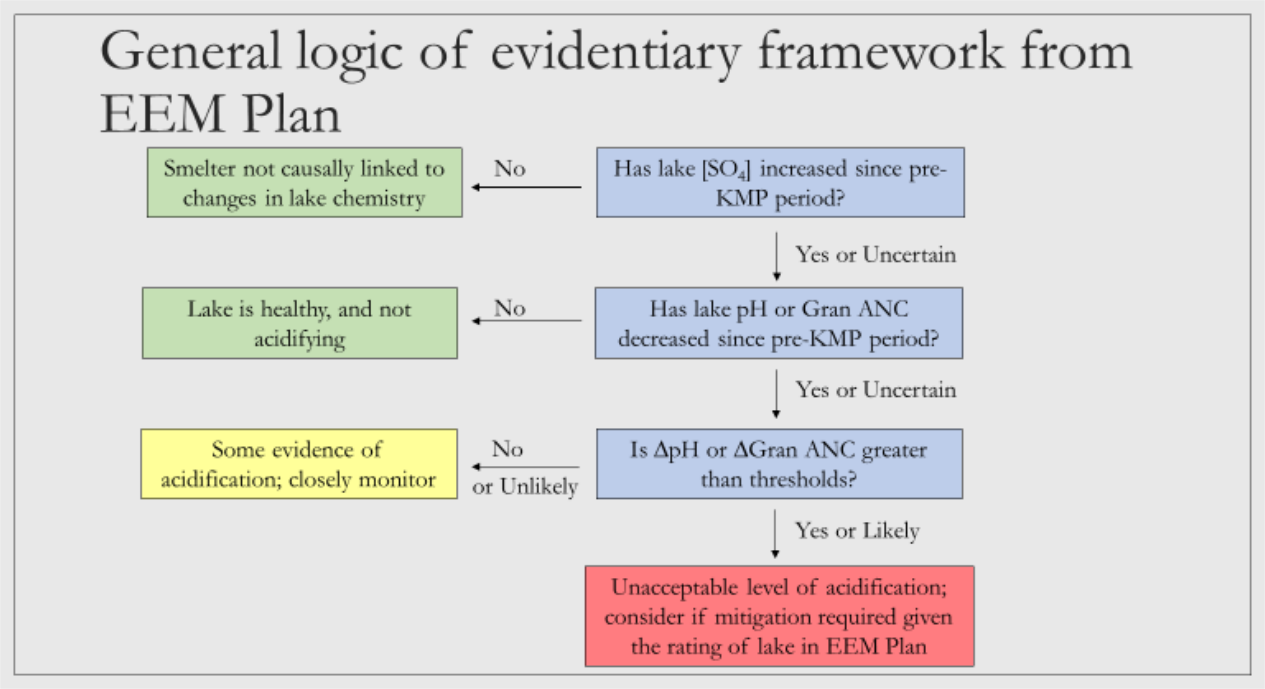


Figure 7-3. Simplified evidentiary framework, building on Table 17 in the EEM Plan. Note that within the Evidentiary Framework, "some evidence of acidification" (i.e., the yellow box) represents lakes that show some evidence of any level of acidifying change but have not exceeded their EEM thresholds, whereas "unacceptable level of acidification" (i.e., the red box) represents lakes that show strong evidence of having acidified beyond their EEM thresholds.

7.2.5 Episodic acidification studies

As discussed in EEM Annual Reports, the two sources of information intended to provide the inputs for exploring this topic were the continuous pH data from LAK006, LAK012 and LAK023 as well as the results of an independent, parallel research project being conducted by Dr. Paul Weidman to determine (among other research objectives) the extent of episodic acidification within the Kitimat watershed. However, as described more fully in Aquatic Appendix A, Limnotek (2019) concluded that due to concerns with the ability of the continuous pH monitors to accurately and consistently measure pH in lakes with low ionic strength, the data have not been of sufficient quality for conducting such studies. Although not ideal, the inability to use these data for their original purpose is not a significant detriment to the program because the pH and ANC thresholds for chronic chemistry were designed to be sufficiently conservative to protect aquatic biota. Additionally, the results of Dr. Weidman's work are not yet available for review. Therefore, we are unable to report on any studies of episodic acidification.

However, Aquatic Appendix F includes analyses of the temporal trends of the pH sampling associated with the bi-weekly field visits required to calibrate the continuous monitors over the years they were installed. Furthermore, new instruments better suited to measuring pH in waters of low ionic strength have been piloted in 2018.

7.2.6 Critical loads, exceedances and predicted changes in pH

We applied the same methodologies as used in the STAR for estimating critical loads and predicting exceedances of those critical loads and future steady-state pH under different deposition levels. Critical loads and exceedances were assessed using the Steady State Water Chemistry Model and future pH was assessed using the ESSA-DFO model. These methods are described in detail in the STAR and KAEEA. Details on the updated and/or revised data inputs available for the comprehensive review, the model scenarios and sensitivity analyses, and all the results from all the different model runs are documented in Aquatic Appendix G.

7.2.6.1 *Critical Loads and Exceedances*

We performed analyses of critical loads and exceedances at two different spatial-temporal scopes. Firstly, we conducted analyses on the entire set of all the lakes within the study area for which we have lake chemistry data – i.e., all of the STAR lakes, any KAEEA lakes within the study, plus additional non-EEM lakes sampled during the course of the EEM program. For this data set we used the original estimates of their critical loads, calculated the predicted exceedances under *current* deposition, and compared these results to the STAR. We also conducted some sensitivity analyses on the original estimates of critical loads with model inputs for which we now have additional or improved data *across all of the lakes*, as well as higher levels of deposition. Secondly, we conducted analyses on the EEM lakes, for which we have much more extensive data. For this data set we developed new estimates of their critical loads based on the best, most defensible data inputs currently available, calculated the predicted exceedances under *maximum future* deposition, and compare the results to the STAR. We also conducted extensive sensitivity analyses on the critical loads and exceedances for the EEM lakes across multiple data inputs, different emissions scenarios, and potential uncertainty in the CALPUFF model estimates of deposition.

7.2.6.2 *Future steady-state pH*

For the modelling of future steady-state pH and changes from 2012 levels, there is not an analogous analysis that can be applied across the first data set (all lakes) using the updated deposition estimates – the ESSA-DFO model requires before/after estimates of deposition levels and the updated modelling did not include a pre-KMP scenario within the same CALPUFF modelling framework (e.g., meteorological years and models used) as the actual emissions (29.3 tpd), 35 tpd and 42 tpd scenarios. However, there were a couple sensitivity analyses performed with the STAR modelling (which applies the pre-KMP and post-KMP modelled deposition estimates) on a couple of model inputs for which we now have additional or improved data *across all of the STAR lakes.* However, for the EEM lakes, we developed new predictions of their future steady-state pH based on the best, most defensible data inputs to characterize current, post-KMP (2016-2018) lake chemistry and the change in deposition from *current* (i.e., actual emissions scenario, based on 29.3 tpd) to *maximum future* (i.e., 42 tpd scenario). We then compared these results to the baseline pH values in 2012 and conducted a series of sensitivity analyses across multiple data inputs, different emissions scenarios, and potential uncertainty in the CALPUFF model estimates of deposition.

7.2.7 Kitimat River water quality

Rio Tinto voluntarily conducts water sampling at their intake on the Kitimat River. This voluntary sampling was initiated following a request from a concerned citizen over perceived impacts of the

smelter's SO_2 emissions on the District of Kitimat's potable water supply. As these water supplies have a high capacity to neutralize acidity (Gran ANC), have shown no changes over time, and remain well within all B.C. objectives for drinking water, Rio Tinto will discontinue sampling water quality in the Kitimat River at the end of 2019.

7.2.8 Other data and/or analyses previously reported

As reported through the Annual Reports, other monitoring activities and analyses outside the core water chemistry sampling program for EEM lakes have been conducted during the course of the EEM program in support of the aquatic ecosystems component. These activities have included fish sampling in EEM lakes, a literature review of the potential effects of acidification on amphibians, lake level monitoring, bathymetric analyses and estimation of water residence time for lakes, and sampling of non-EEM sites. These activities are summarized in Aquatic Appendix A and have been described in detail in previous Annual Reports, technical appendices, and/or technical memos.

7.2.9 Assessment of acceptable or unacceptable impacts to aquatic receptor

The assessment of the impacts to the aquatic receptor as "acceptable" or "unacceptable"[43] is directly linked to the KPI, as currently defined in the EEM Plan (ESSA 2014a). If the KPI threshold associated with facility-based mitigation in the EEM is exceeded, this is identified as an "unacceptable" impact for the aquatic receptor. Impacts to the aquatic receptor that do not exceed the KPI threshold associated with facility-mitigation in the EEM are identified as "acceptable".

7.3 What did we learn, and did we make any adjustments to the EEM Program?

7.3.1 Empirical data from lake chemistry monitoring program

It is worth emphasizing that the goal of the analyses of changes in lake chemistry is to determine whether the smelter has caused lake acidification, and if so, whether the magnitude of acidification exceeds thresholds for biological effects. While it may be of scientific interest to understand the causes of all chemical changes in each lake, that is beyond the scope of the EEM Program, the comprehensive review, and this analysis.

The measured changes in major water chemistry properties between the baseline period (2012) and the post-KMP period (average of 2016-2018) are summarized in Table 7-6 and Table 7-7. The three-year average is used because the mean of the post-KMP period is a better indication of longer-term changes than individual years that are subject to multiple sources of variability that do not reflect longer-term changes. Long term changes are the focus of the EEM. Increasing the statistical power to detect an effect requires multiple years of data whereas using post-KMP years individually reduces statistical power. Although the results presented in this section are simply comparisons of the empirical observations rather than statistical analyses (see Section 7.3.2.3 and Aquatic Appendix F), the principles of statistical power still apply. The empirical observations

[43] Section 4.2.6 of the P2-00001 permit, dated March 15, 2016, states "If any unacceptable impacts are determined through the use of the impact threshold criteria pertaining to emission reduction, then the maximum SO_2 daily discharge limit shall revert back to 27 Mg/d, unless the Director amends the discharge limit."

show that sulphate has increased in four of the seven sensitive EEM lakes and in two of the four less sensitive lakes, but none of these lakes show decreases in Gran ANC or pH. Detailed statistical analyses of the changes in water chemistry are in Aquatic Appendix F, and summarized below in Section 7.3.2.3. The only lake with a decrease in Gran ANC is LAK007, which is highly insensitive and has Gran ANC levels that are two orders of magnitude higher than the sensitive lakes (LAK007 also has shown a small decrease in SO_4^{2-} concentrations). The only lake with a decrease in pH is LAK034 but this change cannot be driven by sulphur emissions from the smelter because its sulphate concentration has decreased to essentially zero. These results are also mapped in Figure 7-4.

However, given the known variability in these data, measurement error, low power, and the limited number of years of post-KMP observations, any interpretation of these results must take into consideration the results of the rigorous statistical analyses of the data (see Section 7.2.3.3 for the statistical methods and Section 7.3.2.3 for a summary of results, with full details in Aquatic Appendix F). However, statistical power will increase with more years of observations (see Section 7.3.2.2).

Additional visualization of these results is included in Aquatic Appendix A. Time series of the inter-annual changes in these lake chemistry properties (and intra-annual variation for lakes with additional sampling during the fall index period) across the period of record from 2012 to 2018 are presented for all of the EEM lakes in Aquatic Appendix C. The underlying data (in microequivalents and raw, unconverted values) are reported in Aquatic Appendix D.

Table 7-6. Changes in pH, Gran ANC and SO_4^{2-} from baseline conditions (2012) to the post-KMP period (2016-2018). Green cells indicate increases and red cells indicate decreases. * = corrected for marine influence. Statistical analyses of changes in these parameters are in Aquatic Appendix F, and are summarized in Table 7-9.

	pH			Gran ANC (µeq/L)			SO_4^{2-}*(µeq/L)		
EEM sensitive lakes	2012	Post-KMP	ΔpH	2012	Post-KMP	ΔANC	2012	Post-KMP	ΔSO_4^{2-*}
LAK006	5.8	6.0	0.24	25.7	27.7	2.0	11.4	14.0	2.5
LAK012	5.6	6.2	0.52	57.0	58.3	1.3	6.1	12.9	6.8
LAK022	5.9	6.1	0.15	27.8	33.0	5.1	30.2	38.8	8.6
LAK023	5.7	5.9	0.22	19.8	26.4	6.7	19.0	12.3	-6.7
LAK028	5.0	5.0	0.02	-4.0	-3.5	0.5	56.9	128.4	71.5
LAK042	4.7	5.2	0.54	-20.4	5.6	26.1	6.2	5.4	-0.8
LAK044	5.4	5.6	0.15	1.3	5.0	3.7	6.2	4.4	-1.9
Total lakes with increase			**7**			**7**			**4**
Total lakes with decrease			**0**			**0**			**3**

EEM less sensitive lakes	2012	Post-KMP	ΔpH	2012	Post-KMP	ΔANC	2012	Post-KMP	ΔSO_4^{2-*}
LAK007	8.0	8.0	0.03	1437.6	1385.9	-51.6	51.4	47.0	-4.4
LAK016	6.3	6.7	0.34	68.7	89.8	21.1	39.0	44.5	5.4
LAK024	7.1	7.5	0.36	299.5	463.2	163.7	24.8	38.9	14.1
LAK034	6.7	6.4	-0.29	99.4	139.6	40.2	24.1	0.1	-24.0
Total lakes with increase			**3**			**3**			**2**
Total lakes with decrease			**1**			**1**			**2**

Control lakes	2013	Post-KMP	ΔpH	2013	Post-KMP	ΔANC	2013	Post-KMP	ΔSO_4^{2-*}
DCAS14A	6.5	6.6	0.2	50.6	55.9	5.4	33.4	36.4	3.0
NC184	5.7	5.8	0.1	16.2	27.0	10.8	5.7	6.2	0.5
NC194	6.6	6.4	-0.2	28.0	22.4	-5.6	3.6	2.5	-1.1
Total lakes with increase			**2**			**2**			**2**
Total lakes with decrease			**1**			**1**			**1**

Table 7-7. Changes in dissolved organic carbon (DOC), total base cations (∑BC), and chloride (Cl^-) from baseline conditions (2012) to the post-KMP period (2016-2018). * = corrected for marine influence. Green cells indicate increases and red cells indicate decreases.

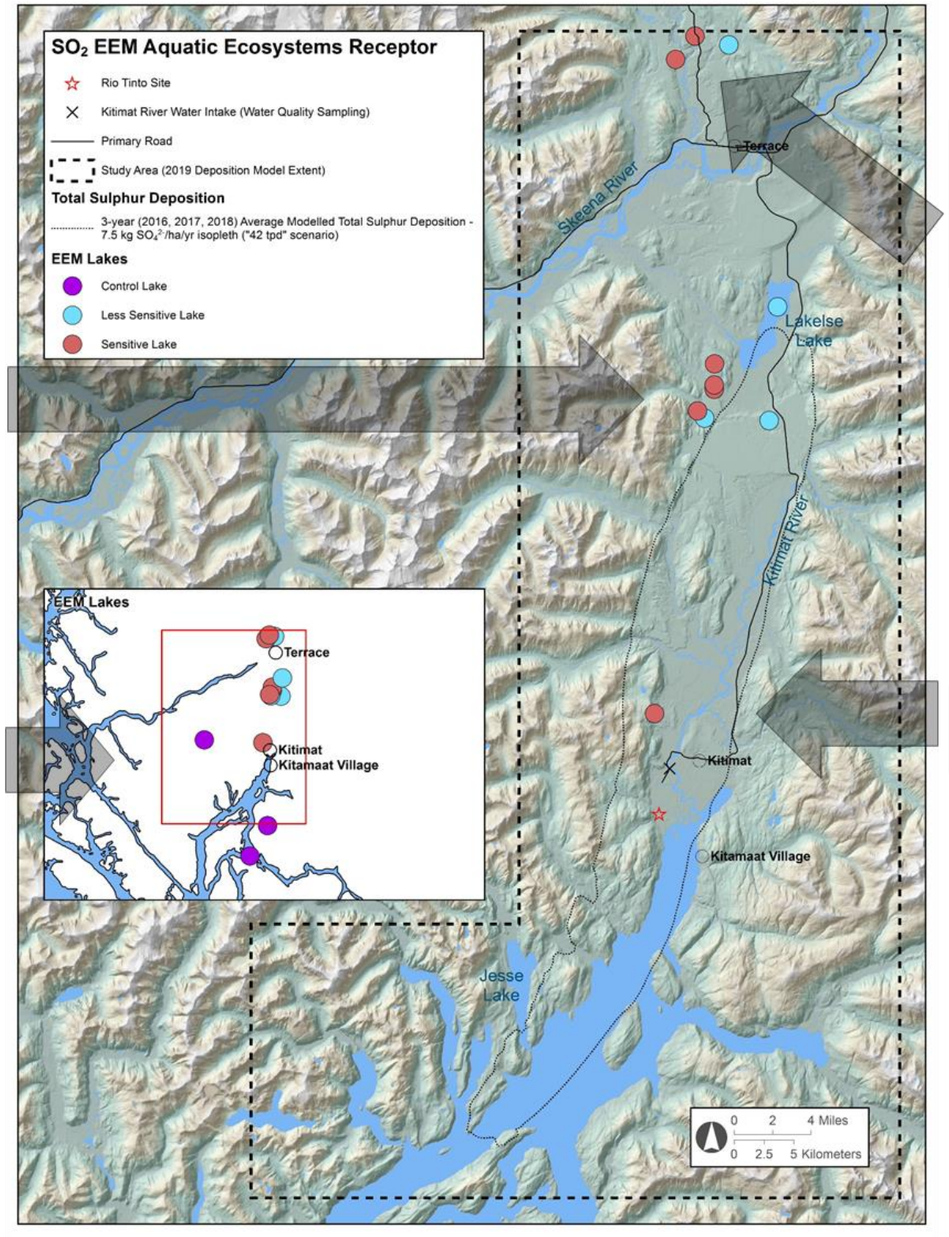
	DOC (mg/L)			∑ BC (µeq/L)			Cl (µeq/L)		
EEM sensitive lakes	2012	Post-KMP	ΔDOC	2012	Post-KMP	ΔBC*	2012	Post-KMP	ΔCl
LAK006	3.6	3.9	0.4	60.6	72.1	11.5	5.8	5.7	-0.1
LAK012	4.6	5.0	0.3	120.6	111.5	-9.1	4.2	6.3	2.1
LAK022	5.3	6.1	0.7	98.1	114.7	16.5	6.9	7.4	0.5
LAK023	4.2	5.6	1.5	65.9	72.8	6.9	4.5	4.7	0.2
LAK028	4.9	6.6	1.7	72.9	136.7	63.8	6.1	8.4	2.4
LAK042	13.2	10.7	-2.5	53.4	64.8	11.4	6.1	6.7	0.5
LAK044	1.7	1.8	0.1	14.2	18.1	3.9	5.6	6.2	0.6
Total Lakes with Increase			**6**			**6**			**6**
Total Lakes with Decrease			**1**			**1**			**1**

EEM less sensitive lakes	2012	Post-KMP	ΔDOC	2012	Post-KMP	ΔBC*	2012	Post-KMP	ΔCl
LAK007	0.6	0.4	-0.2	1503.9	1494.3	-9.6	24.6	26.4	1.8
LAK016	3.7	4.6	0.9	166.3	179.5	13.2	6.3	7.7	1.4
LAK024	1.4	2.1	0.7	340.0	558.5	218.4	27.3	68.3	41.0
LAK034	4.5	6.2	1.7	201.7	191.2	-10.5	5.8	4.5	-1.3
Total Lakes with Increase			**3**			**2**			**3**
Total Lakes with Decrease			**1**			**2**			**1**

Control lakes	2013	Post-KMP	ΔDOC	2013	Post-KMP	ΔBC*	2013	Post-KMP	ΔCl
DCAS14A	1.4	1.3	-0.0	90.6	109.7	19.1	9.2	7.1	-2.0
NC184	11.6	10.3	-1.3	86.2	94.8	8.6	24.0	17.5	-6.5
NC194	0.7	1.0	0.3	39.2	45.8	6.6	7.6	5.9	-1.7
Total Lakes with Increase			**1**			**3**			**0**
Total Lakes with Decrease			**2**			**0**			**3**

LAKE	2012 to 2016-18 ΔSO_4^{2-}	ΔANC	ΔpH
Lak006	2.5	2.0	0.2
LAK012	6.8	1.3	0.5
LAK022	8.6	5.1	0.1
LAK023	-6.7	6.7	0.2
LAK007	-4.4	-51.6	0.0
LAK016	5.4	21.1	0.3
LAK024	14.1	163.7	0.4

LAKE	2013 to 2016-18 ΔSO_4^{2-}	Δ ANC	Δ pH
DCAS14A	3.0	5.4	0.2
NC184	0.5	10.8	0.1
NC194	-1.1	-5.6	-0.2



LAKE	2012 to 2016-18 ΔSO_4^{2-}	Δ ANC	Δ pH
LAK042	-0.8	26.1	0.5
LAK044	-1.9	3.7	0.2
LAK034	-24.0	40.2	-0.3

LAKE	2012 to 2016-18 ΔSO_4^{2-}	Δ ANC	Δ pH
LAK028	71.5	0.5	0.0

Figure 7-4. Observed changes in SO_4^{2-}, Gran ANC and pH from the baseline period (2012) to the post-KMP period (2016-2018). Green cells indicate increases and red cells indicate decreases. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleth.

7.3.1.1 *Observed increases versus predicted decreases in pH*

As shown above, pH increased from 2012 to the post-KMP period for all of the EEM sensitive and less sensitive lakes except one less sensitive lakes, which may at first seem to contradict the predictions in the STAR of future decreases in pH. However, there are multiple factors that may collectively contribute to this perceived contradiction:

1. **Maximum vs. Actual Emissions:** The STAR predictions of future pH were based on estimated deposition levels under the maximum permitted emissions (42 tpd) whereas actual emissions have been much lower (29.3 tpd).
2. **Deposition**: Deposition has been less than expected in 6 of the 7 sensitive lakes (LAK028 being the exception). Therefore, the changes in lake SO_4^{2-} have been less than predicted in the sensitive lakes, even after accounting for emissions at ~30 tpd rather than 42 tpd. See Aquatic Appendix A (Section 7.1.2.3.4, Assessing observed changes in water chemistry relative to STAR predictions). Some lakes have shown a decrease in SO_4^{2-} rather than an increase, which likely reflects changes in the spatial distribution of deposition since pre-KMP conditions.
3. **Long-term vs. Short-term Changes**: The STAR analyses of changes in pH were based on predictions of future, *steady-state* pH – i.e., predictions of long-term change rather than short-term. It may take a number of years to reach steady-state under the new deposition levels.
4. **Lake Sensitivity:** For sensitive lakes which have shown an increase in SO_4^{2-} (i.e., LAK006, LAK012, LAK022, LAK028), but no decrease in ANC or pH, it appears that their F-factor is higher (less sensitive to acidification) than what we had assumed in the STAR. The only lake for which we can compare assumed vs observed F-factors is LAK028, where the observed F-factor (0.65 to 0.89) was higher than what was estimated in the STAR (0.44) (see Aquatic Appendix G, Section 2.3.3).
5. **Precipitation:** It is possible that environmental conditions (e.g., drier summers than historically) could have led to a concentration effect, increasing base cations, ANC and pH. As shown in Aquatic Appendix G (Section 2.3.2), average annual precipitation was 9% lower during 2016-2018 compared to the climate reference period of 1960-1990. Furthermore, when compared to the 3-year period prior to the STAR sampling (i.e., 2010-2012) the relative difference is even greater because those years were on average slightly wetter than the climate reference period – i.e., relative to that period, the average annual precipitation for 2016-2018 was 13%, 9% and 25% less for the three stations with data (though the 25% decline applies only to 2018). However, statistical analyses of the correlations between lake chemistry and precipitation (on both short term and seasonal time scales) have not revealed any statistically significant relationships (Aquatic Appendices F and I).
6. **Natural Variability and Measurement Error**: In addition to precipitation, there are variations from year to year in watershed processes (e.g., wetland releases of organic acids and stored sulphate), and in-lake processes (e.g., photosynthesis, sulphate reduction), which add noise to observed patterns and trends in lake chemistry. While the quality of data has been very high (see Section 7.2.2), there are measurement errors, which add additional noise to the observed patterns and trends. As the EEM program gathers more years of data, these sources of variation become less important, and it becomes easier to see if there is in fact a long-term trend.

7.3.2 Knowledge gained

7.3.2.1 *Measuring pH*

During the EEM Program we have learned that pH is more highly variable than expected. Those expectations were based on literature and data from other regions. We have also learned that it is difficult to measure pH well in lakes with low ionic strength. The low ionic strength means that a long time is needed to get stable readings – longer than factory settings for some instruments or laboratory protocols at some facilities. Not allowing sufficient time for readings to stabilize results in less reliable pH data. Furthermore, even when allowing sufficient time for stabilization, the measurement error for the different instruments (± 0.2 pH units) is high relative to the effect size of interest (0.3 pH units).

7.3.2.2 *Ability to detect changes in water chemistry*

In 2015 we conducted a power analysis of the data collected to date (i.e., 2012-2014), to assess our ability to detect changes in water chemistry for SO_4, pH and ANC. Our analyses revealed that lakes in the EEM program had a higher level of year-to-year variability in SO_4^{2-} and ANC over 2012-2014 than did lakes in the Georgia Basin sampled by Environment Canada from 2005 to 2014 (Figure 3 in EEM Technical Memo W05, 2016). The data from 2012-2014 likely overestimates the year-to-year variability in lake chemistry, because there were significant changes in smelter emissions of SO_2 during this period (from an average of 16.1 tpd in 2012 to 11.6 tpd in 2014). Other key findings from the power analyses completed in 2015 included the following:

- On average, the statistical power to detect changes in pH that exceed the KPI threshold is quite low (<0.1 for LAK012 and LAK042), due to high within-year and between-year variability, as well as measurement error.
- The power to detect changes in ANC and SO_4^{2-} is however quite high (>0.8 after a 5-year period) for four of the seven sensitive EEM lakes (LAK006, LAK012, LAK022, LAK023), indicating the benefit of using multiple metrics.
- The ability to detect changes in all three variables increases over time, and with multiple samples per year.
- Gran ANC provided the most reliable indication of long-term changes in acid-base chemistry (i.e., highest statistical power to detect changes of biological significance), but required ≥ 3 years of annual measurements to obtain acceptable statistical power in five of the sensitive lakes.
- Two of the seven sensitive lakes (LAK028 and LAK042) showed low statistical power (<0.1) to detect biologically significant changes in Gran ANC even after 10 years of annual measurements, due to high natural variability.

Since 2014, the intensively monitored lakes (End Lake – LAK006, Little End Lake – LAK012, West Lake LAK023) have included Rio Tinto's voluntary continuous monitoring of pH (including biweekly measurements of field pH during calibration of the continuous monitors) and four samples of full chemistry during the month of October. Our observations from the power analysis (i.e., high year-to-year variability and low statistical power in several EEM lakes) led us to increase the number of lakes with four fall samples, adding 3 of the remaining 4 sensitive lakes (LAK028, LAK042, LAK044) in 2016. It is not feasible to access LAK022 for multiple samples in the fall index period.

In general, at least five years of post-KMP data are required to reach adequate statistical power for Gran ANC, with significantly more years required for three of the lakes. For this report, we have only three years of post-KMP data. Therefore, at least two more years of post-KMP data are required to attain adequate statistical power for Gran ANC, preferably three more years of data (see Recommendations, Section 7.4). The inter-annual and intra-annual variability in pH is much higher than the variability in Gran ANC, and therefore it is more difficult to detect changes in pH than changes in Gran ANC. More information on the power analyses is provided in Aquatic Appendix F, Section 7.6.3. The statistical analyses included in Aquatic Appendix F and Aquatic Appendix I (sensitivity analysis of alternative baselines) have the benefit of more years of data than were available for the 2015 power analysis, allowing for better estimates of variability in lake chemistry both within and between years.

A weakness of the EEM Program is that for pH and ANC, we have only one measurement in August 2012 as a baseline. In the statistical analyses for pH and ANC using 2012 as the baseline, we have assumed that the year-to-year variability observed in 2016-2018 is representative of the year-to-year variability during the baseline year of 2012 (see Aquatic Appendix F). In the EEM plan, we had assumed that we could include 2012-2014 as an expanded baseline period. Over time, we realized that the period from 2012-2014 was better described as a *transition period* with the decommissioning of the old smelter, and not as a pre-KMP baseline. We did not apply an expanded baseline period (2012-2014) to pH and Gran ANC, because doing so would increase two risks: 1) the risk confounding baseline water chemistry conditions with the effects of smelter decommissioning; and 2) the risk of a Type I error (a false positive) in testing for exceedances of pH and ANC thresholds. Including pH and ANC observations from 2013 and 2014 in the estimates of mean pre-KMP pH and mean pre-KMP Gran ANC would increase those metrics to a level that is not representative of the pre-KMP period prior to and including 2012, and increase the risk of a false exceedance of the thresholds for changes in pH and Gran ANC. Changes in lake [SO_4] are an important part of the simplified and full evidentiary frameworks (Section 7.3.4.5). Using 2012-2014 as a baseline also could increase the risk of a false positive for detecting an increase in lake [SO_4], if a lake's [SO_4] decreased during 2013-3014 due to the decommissioning of the old smelter and reduced emissions of SO_2. Therefore, both the draft comprehensive review report and the 2018 EEM Report used 2012 as a baseline for comparison.

In response to requests from reviewers of the draft comprehensive report, we have completed a sensitivity analysis to assess the effects of using 2012-2014 as an alternative baseline to 2012 (Aquatic Appendix I). While use of a 2012-2014 baseline does change some of the results of the statistical analyses, it does not change any of the overall conclusions regarding effects of the smelter on EEM lakes (see Table 7.82 and Figure 7.147 in Aquatic Appendix I).

7.3.2.3 *Spatial and temporal patterns in water chemistry*

There are multiple ways in which the spatial and temporal patterns in water chemistry have been explored, assessed and analyzed.

Comparison of August vs. October sampling

Sampling during the STAR (providing data for the baseline year of 2012) was conducted in August and sampling during the EEM program has been during October (see EEM Plan and EEM Annual Reports for addition discussion – in particular the 2013/2014 EEM Annual Report explored the

potential implications and sensitivities of the seasonal transition in the sampling period). As part of the comprehensive review, we further explored this issue with new data.

Based on analyses of the field pH, lab pH and Gran ANC data from samples collected during the calibration visits to the lakes with continuous pH monitors, it was not possible to detect a difference in the mean values for August and October. This provides some further support to work done in previous years to evaluate the potential effects of having sampled the baseline year of 2012 in August rather than during the fall index period used throughout the EEM Program. However, although this analysis could not detect a difference, the analysis is limited by the duration and sample size of the data available. For LAK006, LAK012 and LAK023, there were two or three field pH samples in August and an average of four for October during 2015-2018. For 2017 and 2018, these samples also include measurements of lab pH and Gran ANC. For LAK028, these analyses could only be done for 2018, when the lake was sampled once in August and four times in October. Aquatic Appendix A (Sections 7.1.2.3.3 and 7.1.3.2.3) provides further details on these analyses and results.

Observed Changes in Water Chemistry

This topic is predominantly addressed within Section 7.3.1. However, Aquatic Appendix A includes additional exploration of a) the relative changes in base cations and SO_4^{2-} and b) changes in the ion composition over time.

Magnitude of Changes in Nitrate

In the STAR, nitrate was excluded from analyses of potential acidification as it was assumed to represent a negligible contribution. Examination of the magnitudes of the changes in NO_3^- relative to changes in SO_4^{2-} over the observation period confirmed that the changes in NO_3^- have been negligible.

Statistical Analyses

The key results of the extensive statistical analyses of changes in lake chemistry across all the lakes in the EEM Program are summarized in Table 7-8 and Table 7-9. Table 7-9 uses results from Bayesian statistical analyses (Sections 7.6.4.2.9, 7.6.4.3.9 and 7.6.4.4.9 of Aquatic Appendix F) since this approach provides the greatest ability to assess the level of support for different hypotheses of chemical change. The logic of Table 7-9 reflects the logic of the simple evidentiary framework (Figure 7-3 and Figure 7-10). The control lakes are far outside of the plume of the smelter, and so changes which have occurred there are unrelated to the smelter. For the other lakes, the following logic applies:

- Lakes with a low percent belief in a sulphate increase (< 20%, or a strong belief in a sulphate decrease) can be eliminated from further consideration (as indicated by cells coloured green in the sulphate column of Table 7-9; this includes sensitive lakes LAK023, LAK044, and less sensitive lakes LAK007 and LAK034.
- Lakes with cells coloured red in the sulphate column (sensitive lakes LAK006, LAK012, LAK022, LAK028; less sensitive lakes LAK016 and LAK024) show strong evidence for a sulphate increase (>80% belief), and proceed on to evaluations of the next two columns (Gran ANC and pH). If there is a low percent belief (< 20%) that the ΔGran ANC and ΔpH for these lakes exceeded the identified thresholds, then the cells in those columns are

coloured green, indicating that these lakes show no evidence of smelter-induced acidification.

- Lakes coloured yellow in the sulphate column (sensitive lake LAK042) show an intermediate level of support for a sulphate increase (20% to 80% belief), and are also evaluated for their changes in Gran ANC and pH.
- The conclusions in the rightmost column of Table 7-9 reflect a consideration of both the statistical analyses and the magnitudes of changes in lake chemistry. Two lakes (LAK028 and LAK012) are shaded yellow because they show some evidence of acidification[44], but neither lake has exceeded its thresholds for ΔGran ANC and ΔpH.

Power or Minimum Effect Size

The power analyses completed in 2015 represent a comprehensive analysis of the power to detect differences based on the available data and statistical model applied at the time.

The Aquatic Appendix F quantifies the minimum detectable difference (MDD) values for the frequentist analyses performed (7.6.4.2 for SO_4^{2-}; 7.6.4.3 for pH; 7.6.4.4 for ANC). These sections of Aquatic Appendix F include sensitivity analyses of the MDD based on assumptions about variability in the pre-KMP period. The Bayesian analysis, which involves running 1,000 simulations to test each hypothesis, provides a more comprehensive assessment of the level of support (percent belief) for an increase or decrease in a chemical parameter, and for a decrease beyond the thresholds of concern. The Bayesian analysis provides useful insights for situations where the frequentist analysis was unable to determine whether or not the observed change exceeded the threshold.

Potential Lag Effects

There could be a lag between increased SO_2 emissions and increased SO_4^{2-} concentrations in lakes due to variability in winds and the plume, and due to temporary watershed storage of deposited SO_4^{2-} in wetlands. However, both of these potential lag effects are expected to be temporary (e.g., no longer than two years). Once additional SO_4^{2-} enters a lake, lake chemistry should adjust quickly (based on lake residence time), but the magnitude of change in lake pH depends on the sensitivity of the watershed and the lake to acidification. If a lake has higher ANC (lower sensitivity), there is not expected to be any decline in lake pH associated with higher SO_4^{2-}. If a lake is sensitive to acidification, then the magnitude of change will depend on concurrent changes in base cations and ANC (e.g., there might no decrease in pH if base cations went up concurrently). These different types of potential responses are also described in Appendix H of the EEM Plan.

Section 7.6.4.6 of Aquatic Appendix F summarizes the results of other statistical analyses of chemical change (e.g., frequentist methods) which are consistent with the results presented in Table 7-9. The full results of the statistical analyses are reported in Aquatic Appendix F. In response to requests from reviewers of the draft comprehensive review report, we have completed a sensitivity analysis to assess the effects of using 2012-2014 as an alternative baseline to 2012 (Aquatic Appendix I). While use of a 2012-2014 baseline does change some of the results

[44] LAK028 shows moderate support for *any level* of ANC and pH (34% belief and 46% belief, respectively) and LAK012 shows moderate support for a decline in ANC only (46% belief), but as shown in Table 7-9 there is no to low support for declines exceeding the EEM thresholds (i.e., no support in LAK012 for exceeding either the ANC or pH threshold; no support in LAK028 for exceeding the ANC threshold and low support for exceeding the pH threshold). The analyses of the level of support for *any level* of decline in ANC or pH, are shown in Section 7.6.4.6 of Aquatic Appendix F (see Tables 7.72 and 7.73).

of the statistical analyses, it does not change any of the overall conclusions regarding effects of the smelter on EEM lakes (see Table 7.82 in Aquatic Appendix I).

Figure 7-5 summarizes the patterns of change in water chemistry on a map of the study area, so as to elucidate any effects of lake location, specifically distance from the smelter. Six of the eight lakes to the south of Lakelse Lake showed strong evidence of increases in sulphate. It isn't clear why LAK023 and LAK007 were exceptions to this pattern – perhaps they are topographically more isolated from the path of the plume. None of the six lakes with strong evidence for increases in sulphate showed statistical support for changes in pH or Gran ANC beyond the thresholds, as evidenced by the low levels of % belief for such changes. Lakes to the north of Terrace (LAK034, LAK044, LAK042) are outside of the deposition isopleth for 7.5 kg SO_4^{2-} / ha / year, consistent with low to intermediate support for sulphate change (0%, 36% and 1% belief, respectively). The control lakes were selected to be well outside of the plume. Two of the control lakes showed intermediate levels of support for increases in sulphate between 2013 and 2016-2018, but the amount of change in sulphate concentrations was very small (Table 7-6).

Table 7-8. Key findings for each of the questions posed in Table 7-5.

Questions of Interest	Key Findings
How long does it take to reliably assess whether or not key water chemistry parameters (SO_4, pH, ANC) have changed relative to pre-KMP conditions, and (for pH and ANC) whether those changes exceed the 0.3 unit threshold established in the EEM Plan for pH, and the lake-specific thresholds established subsequently for Gran ANC?	This question was addressed by the power analysis, described above in Section 7.3.2.2, and in Section 7.6.3 of Aquatic Appendix F. We found that it takes less time to reliably detect changes in Gran ANC than to reliably detect changes in lake pH, as Gran ANC is less variable. We found that it would take at least 5 years of post-KMP monitoring to reliably detect changes of interest in Gran ANC within 4 of the 7 sensitive lakes, 10 years of monitoring for one other lake, and an uncertain amount of time in the other 2 lakes. These may be over-estimates of the time required as the variability of water chemistry was likely over-estimated from 2012-2014 data, due to declines in emissions during this time period. Nevertheless, we have only 3 years of post-KMP data so far, and more years of data will improve our ability to detect how much change has occurred.
What are the general patterns of variability and change over time in key water chemistry parameters?	See graphs in Section 7.6.2.1 of Aquatic Appendix F. The quantitative analyses of changes in water chemistry (summarized below, with details in Section 4 of Aquatic Appendix F) provide an assessment of what patterns of change are statistically significant.
Do the values of key water chemistry parameters vary with the magnitude of recent precipitation?	Sulphate, pH and Gran ANC show a negative correlation with the amount of precipitation over the past 3 and past 14 days, but these correlations are not statistically significant (Sections 7.6.4.2.6, 7.6.4.3.6 and 7.6.4.4.6 of Aquatic Appendix F).
Do the values of key water chemistry parameters vary with emissions?	Neither SO_4, pH or Gran ANC varied significantly with emissions over the time period of measurements. This could be because deposition varies considerably over space and time, and a single measure of emissions does not explain variability in observed water chemistry.
Based on the annual fall sampling, how much change has occurred in key water chemistry parameters (SO_4, pH, ANC) between the pre-KMP period (2012) and the post-KMP period (2016-2018), within each lake? For pH and ANC, how likely is it that the changes exceed the EEM thresholds?	The only lakes of concern (i.e., those with both an increase in SO_4^{2-} and decreases in either pH or Gran ANC) are sensitive lakes LAK012 and LAK028. Changes in pH and Gran ANC in these two lakes are less than thresholds. See Table 7-9 and Figure 7-5. LAK028, situated about 9 km north of the smelter, is the only lake with values of BCS[45] that are consistently less than 0 (true in 5 of the 7 years of the EEM program, including 2012 and 2013, during the pre-KMP period). Values of BCS < 0 µeq/L are indicative of water chemistry conditions potentially damaging to aquatic biota. The fact that LAK028 has consistently shown BCS values < 0 µeq/L is evidence of water chemistry likely to damage aquatic biota. EEM sampling in 2017 to establish a biological baseline found that LAK028 does not have any fish.

[45] Base cation surplus (BCS) is a measure of acid-neutralizing capacity that adjusts CBANC to account for the influence of strong organic acid anions. BCS also acts as a strong predictor for aluminium toxicity for aquatic organisms - a distinct threshold for inorganic aluminium (Al) mobilization occurs at a BCS value that closely approximates 0, therefore BCS values < 0 would indicate that acid-neutralization within the watershed is not sufficient to buffer acidic deposition without mobilization of toxic inorganic Al. Further details are provided in the literature review on ANC metrics and thresholds (Aquatic Appendix B). BCS is calculated and explored for the EEM lakes in Aquatic Appendix A.

Questions of Interest	Key Findings
Based on the three intensively monitored lakes (End Lake, Little End Lake, West Lake), are there are seasonal and long-term trends in pH?	As expected, field pH measurements were more variable than lab pH measurements (in the lab, samples are allowed to equilibrate with the atmosphere, which reduces a key source of variability, the degree of supersaturation of CO_2). Trends in field pH over 2015-2019 were negative in all three lakes, but this trend was only statistically significant in LAK023 (West Lake), with an estimated change in field pH of -0.12 over 2015-2019. West Lake showed strong evidence of a decrease in sulphate, so the decline in field pH within West Lake was unrelated to the smelter. Field pH values were generally lowest in the fall (in 9 out the 12 lake-years of data with spring, summer and fall measurements), and highest in the spring or summer. A key caveat on these trends is that as SO_2 emissions declined from 2012 to 2014, lab pH values increased in all three lakes, so the field pH values in late 2014 and early 2015 are not representative of pre-KMP conditions, and should not be used for calculations of ΔpH and comparisons to the 0.3 threshold. Season and time of day can have important effects on lake pH. During the summer, low ANC lakes can show substantial diurnal fluctuations in pH (e.g., one pH unit or more) due to photosynthetic activity, which does not cause negative biological effects as long as the pH remains within a tolerable range (Morgan 1985; Robertson-Bryan Inc. 2004).

Table 7-9. Summary of findings across all lakes monitored in the EEM Program. The % belief values are derived from the Bayesian version of Method 1, as described in Aquatic Appendix F. Values of % belief < 20% are coloured green, 20-80% yellow, and >80% red.

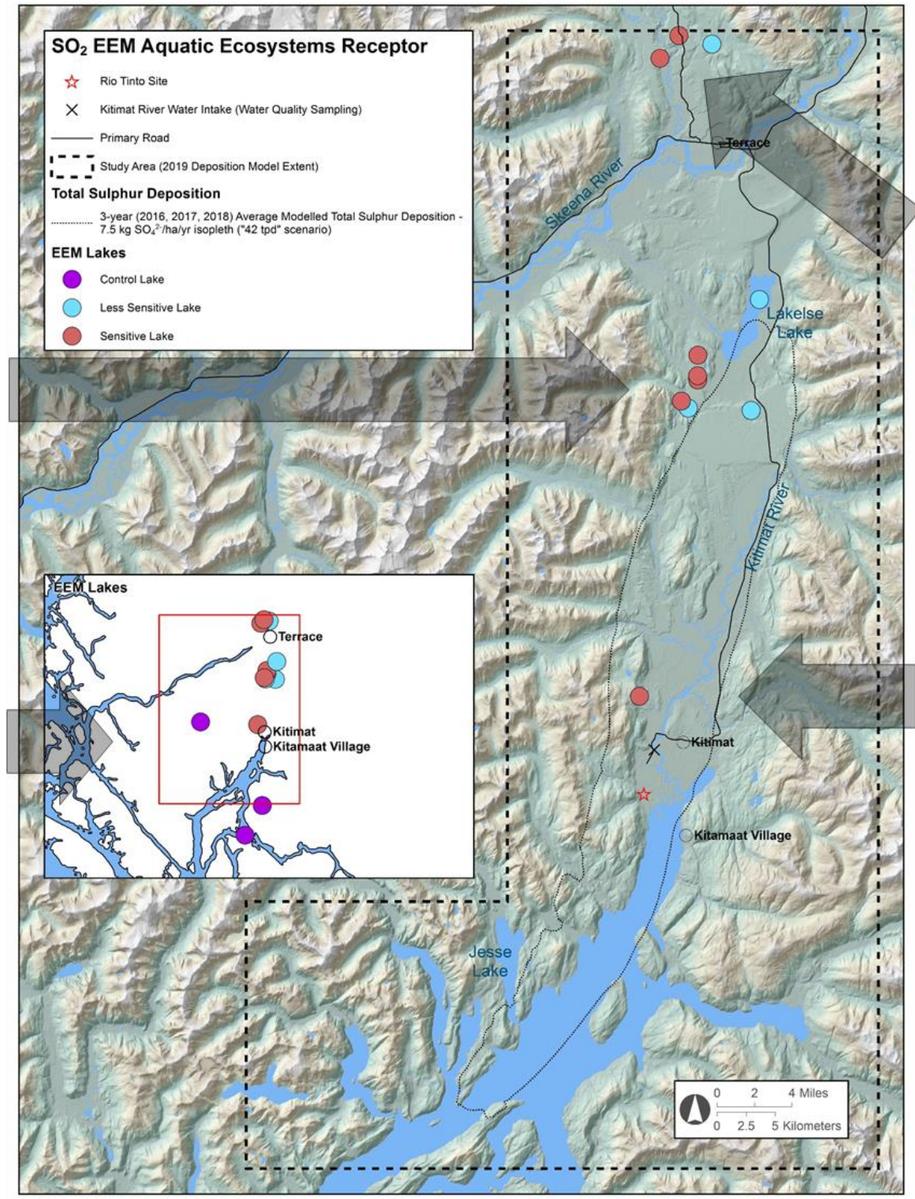
LAKE	Changes in SO_4^{2-} (% belief in SO_4^{2-} increase / decrease from Bayesian analysis - Method 1 violin plot)	Changes in Gran ANC (% belief that ANC threshold exceeded, from Bayesian analysis - Method 1 violin plot)	Changes in pH (% belief that pH threshold exceeded, from Bayesian analysis - Method 1 violin plot)	OVERALL INTERPRETATION[5]
Sensitive Lakes				
LAK006	83% belief in increase	0%	1%	SO_4^{2-} increase; no evidence of S-induced acidification
LAK012	91% belief in increase	1%	1%	SO_4^{2-} increase; some-evidence of S-induced acidification but no evidence of exceeding the ANC or pH thresholds established in the EEM Plan to protect aquatic biota
LAK022	88% belief in increase	0%	0%	SO_4^{2-} increase; no evidence of S-induced acidification
LAK023	5% belief in increase	0%	1%	SO_4^{2-} decrease; no evidence of S-induced acidification
LAK028	96% belief in increase	2%	18%	SO_4^{2-} increase; some evidence of S-induced acidification; low belief in exceeding the pH threshold and no evidence of exceeding its ANC threshold; conditions were potentially damaging to biota pre-KMP and remained so (see Section 7.3.4.2).
LAK042	36% belief in increase	0%	2%	No clear change in SO_4^{2-}; no evidence of S-induced acidification
LAK044	1% belief in increase	0%	0%	SO_4^{2-} decrease; no evidence of S-induced acidification
Less Sensitive Lakes				
LAK007	0% belief in increase	58%	2%	SO_4^{2-} decrease; no evidence of S-induced acidification
LAK016	97% belief in increase	0%	1%	SO_4^{2-} increase; no evidence of S-induced acidification
LAK024	96% belief in increase	1%	1%	SO_4^{2-} increase; no evidence of S-induced acidification
LAK034	0% belief in increase	0%	43% [2]	SO_4^{2-} decrease; no evidence of S-induced acidification
Control Lakes				
DCAS14A	68% belief in increase[3]	0%	6%	No clear change in SO_4^{2-}; no evidence of S-induced acidification
NC184	58% belief in negligible increase [3]	5%	28%[1]	No clear change in SO_4^{2-}; no evidence of S-induced acidification
NC194	1% belief in increase	TBD[4]	12% [1]	SO_4^{2-} decrease; no evidence of S-induced acidification

[1] Mean pH in NC184 changed from ~5.7 (2013) to ~5.8 (2016-18); Mean pH in NC194 changed from ~6.6 (2013) to ~6.4 (2016-18).
[2] Not related to S deposition as lake SO_4^{2-} has declined in LAK034.

[3] Magnitude of increase in [SO_4] between 2013 and 2016-2018 is very small in NC184 (0.5 µeq/L), and only 4 samples were available for statistical analysis.
[4] Lake NC194 did not have a lab titration from which we could determine an ANC threshold. It had a 55% belief in an ANC decline (about 6 µeq/L between 2013 and 2016-2018), though very low belief (1%) in a SO_4^{2-} increase, so the ANC decline was not related to SO_4^{2-}.
[5] The overall interpretation is also based in part on the level of support for *any level* of decline in ANC or pH, as are shown in Section 7.6.4.6 of Aquatic Appendix F (see Tables 7.72 and 7.73). Only two lakes show evidence of any level of decline in ANC or pH. LAK028 shows moderate support for declines in ANC and pH (34% belief and 46% belief, respectively) and LAK012 shows moderate support for a decline in ANC only (46% belief), but both of these lakes show no to low support for exceedance of the ANC and pH thresholds (as shown in the table). The coding of these two lakes in this table thus aligns with the results of the Evidentiary Framework.

LAKE	% belief in change		
	↑ SO_4^{2-}	↓ ANC	↓ pH
LAK006	83%	0%	1%
LAK012	91%	1%	1%
LAK022	88%	0%	0%
LAK023	5%	0%	1%
LAK007	0%	58%	2%
LAK016	97%	0%	1%
LAK024	96%	1%	1%

LAKE	% belief in change		
	↑ SO_4^{2-}	↓ ANC	↓ pH
DCAS14A	68%**	0%	6%
NC184	58%	5%	28%
NC194	1%	TBD	12%



LAKE	% belief in change		
	↑ SO_4^{2-}	↓ ANC	↓ pH
LAK042	36%	0%	2%
LAK044	1%	0%	0%
LAK034	0%	0%	43%

LAKE	% belief in change		
	↑ SO_4^{2-}	↓ ANC	↓ pH
LAK028	96%	2%	18%

Figure 7-5. Spatial distribution of percent belief in chemical change. Numbers show % belief in: a) SO_4^{2-} increase (no threshold), b) pH decrease below 0.3 threshold, and c) ANC decrease below lake-specific ANC threshold. The % belief values are derived from the Bayesian version of Method 1, as described in Aquatic Appendix F. NC194 does not have an estimated ANC threshold because it did not have appropriate titration data available. **The increase in SO_4^{2-} in control lake DCAS014A was only ~3 µeq/L, and only 0.5 µeq/L in NC184. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleth.

7.3.2.4 *Observed changes in water chemistry relative to STAR predictions*

The changes in SO_4, ANC and pH that were predicted in the STAR were initially modelled under the *maximum future* emissions of 42 tpd SO_2, as per the permit. In order to assess whether the observed changes have been more or less than the models predicted, we adjusted the STAR estimates based on the actual average emissions during 2016-2018 (i.e., 29.3 tpd[46], as compared to the maximum 42 tpd permitted levels under which the STAR predictions were made). The quantitative details of these analyses are presented in Aquatic Appendix A (Section 7.1.3.2.4).

The STAR modelling predicted that **sulphate** would increase in all lakes (even when adjusted for lower current emissions). For six of the seven EEM sensitive lakes and two of the three EEM less sensitive lakes, the observed changes in SO_4^{2-} have been lower than the predicted changes (five of the lakes have actually shown decreases). LAK024 had an observed increase in SO_4^{2-} that was greater than predicted. LAK028 had an observed increase in SO_4^{2-} that was many times greater than predicted.

The STAR predicted that **Gran ANC** would decrease for all of the sensitive lakes and decrease or remain unchanged for all of the less sensitive lakes. The observed changes have been less than the predicted changes insofar as Gran ANC has actually increased for all of the lakes except LAK007, which is highly insensitive and has a Gran ANC that is two orders of magnitude larger than the sensitive lakes.

The STAR modelling predicted that **pH** would decrease in all of the sensitive lakes (even when adjusted for lower current emissions) and remain unchanged for all of the less sensitive lakes. The observed changes in pH have been less than the predicted changes insofar as pH has actually increased for all of the lakes except LAK034. LAK034 was predicted to have no change in pH under increased emissions and although the observed change has been a decrease of 0.3 pH units, this cannot be associated with increased sulphur deposition from smelter emissions because SO_4^{2-} has decreased to essentially zero over the same period.

These results suggest that the STAR modelling predictions were cautious, since they have almost exclusively predicted changes of greater magnitude than have been observed. The one notable exception is the result for SO_4^{2-} at LAK028, that suggests that deposition levels close to the smelter have been much higher than the model estimates of deposition from the STAR. LAK028 is by far the closest lake to the smelter; all of the other sensitive lakes are much further north. The details of these comparisons (including the values of the initial STAR predictions, the STAR predictions adjusted for observed emissions, and the empirical observations) are reported in Section 7.1.3.2.4 of Aquatic Appendix A.

Deposition levels close to the smelter have been higher than the model estimates of deposition in the STAR. This raises the question of whether there could be some sensitive lakes that were not identified in the STAR, and were not included in the EEM but either would have been included based on these higher deposition levels, or could be more sensitive than their original assessment suggested. It is very unlikely that there were any lakes ≥1 ha in the study area that should have been included in the EEM

[46] Note: The underlying analyses described here were conducted based on actual emissions of 29.4 tpd rather than the correct 29.3 tpd. The difference was due to minor differences in 2016 data resulting from use of preliminary data that was later revised. However, the analyses have been retained as is because this difference would have a negligible impact on the results and therefore not affect the conclusions of these comparisons.

but were not. In the STAR, we did a sensitivity analysis on variation in sulphate deposition (from 50% to 200%; see Section 9.4.1.3.4, page 330 of the STAR) and found little change in the number of lakes with critical load exceedances. Doubling deposition only increased the number of lakes with exceedances from 8 to 10. The two additional lakes with exceedance under a doubling of deposition are LAK022 and LAK012, which were already included in the EEM due to predicted declines in future pH of greater than 0.1 pH units. Figure 7-9 shows which lakes had critical load exceedances, predicted changes in future pH > 0.1, or both, based on both the analyses of the STAR and in the present review. Other lakes in the vicinity of the smelter (e.g., Bowbyes Lake LAK027 (ANC = 70), and LAK030 (ANC=391)) do not show exceedance even with a doubling of STAR deposition (i.e., essentially equivalent to emissions of 84 tpd). Both of these lakes were predicted in the STAR to have a pH change of 0.0 pH units under 42 tpd of emissions. Furthermore, when we re-estimated critical load exceedances based on the updated deposition modelling as well as doubling the amount of deposition (i.e., equivalent to emissions of 84 tpd) we did not identify additional lakes which should have been included in the EEM program (Aquatic Appendix G, Sections 2.5.1 and 2.5.3). Based on the sensitivity analyses done in the STAR there were no other lakes ≥ 1 ha in size near the smelter which could potentially acidify. If we had found such lakes, they would have been included in the EEM Program.

7.3.2.5 *Critical loads, exceedances and predicted changes in pH*

The results of the primary scenarios – i.e., the base case (the original estimates of critical loads from the STAR and/or KAEEA under *current* deposition and the "best case" (new estimates with updated data inputs for the EEM lakes under *maximum future* deposition) – are shown below. Aquatic Appendix G contains the detailed results from all the sensitivity analyses conducted across multiple data inputs, different emissions scenarios, and potential uncertainty in the CALPUFF model estimates of deposition.

The control lakes are not included in the modelling of critical loads or future pH because we do not have deposition estimates for their watersheds. The three control lakes were chosen explicitly because they are located well outside the deposition plume (and thus the CALPUFF modelling domain).

Critical loads and exceedances

<u>All Lakes within Study Area</u>
We re-assessed the original critical loads for all the lakes within the study area against *current* deposition estimates from the updated CALPUFF modelling (i.e., current emissions are represented by the actual emissions scenario).

Of the 51 lakes in the entire data set, seven lakes show exceedances of those original critical loads. Of these seven lakes, five lakes have critical loads of zero (LAK044, LAK047, LAK054, DCAS09A, DCAS09B) and one lake has a critical load very near to zero (1.2 meq/m^2/yr; LAK056) (see Aquatic Appendix G for tabular, graphic and spatial summaries of these results).

The number of exceedances does not change when the higher emissions scenarios are applied. Under the STAR's "post-KMP" deposition estimates (based on the 42 tpd SO_2 emissions permit limit), there were three additional lakes with predicted exceedances that are no longer predicted to have exceedances. Even with the inclusion of background deposition (which was not accounted for in the STAR), these three lakes are not predicted to have exceedances under any of the new emissions scenarios.

The number of exceedances under current emissions did not change with any of the sensitivity analyses applied to the original critical loads. The sensitivity analyses on the CALPUFF modelled deposition estimates showed that the number of exceedances decreased by one lake when deposition under the actual (i.e., 29.3 tpd) emissions scenario was reduced by 50%, but remained unchanged when the deposition was doubled.

EEM lakes – new estimates of critical loads

We estimated new critical loads for the EEM lakes based on new or revised data and assessed them against *maximum future* deposition estimates from the updated CALPUFF modelling (i.e., the 42 tpd emissions scenario).

The new "best case" estimates for critical loads for the EEM lakes and exceedances under different emissions scenarios are summarized in Table 7-10 and mapped in Figure 7-6.

Only one lake (LAK044) shows an exceedance under the 42 tpd emissions scenario, and because it has a critical load of zero, it has an exceedance under all emissions scenarios. In the STAR, five of the EEM lakes were predicted to have exceedances under the "post-KMP" emissions scenario (i.e., also based on 42 tons SO_2 per day).

For eight of the 11 EEM lakes, the revised estimates of critical loads are quite similar to the original estimates in the STAR (see Aquatic Appendix G). The revised critical load estimates are higher than the STAR for LAK024 and LAK028 and lower for LAK012.

The exceedances of the revised critical loads under the 42 tpd emissions scenario are consistently smaller in magnitude than those predicted in the STAR (Figure 7-7). Since the revised estimates of critical loads are mostly similar to those in the STAR, the reduction in the magnitude of exceedances relative to the STAR primarily reflects lower estimates of deposition. Across the three new modelled emissions scenarios, the magnitude of exceedance increases as deposition increases but there are no additional exceedances – that is, the number of exceedances is not sensitive to the emissions scenario.

The number of exceedances under maximum future emissions increased by one lake (LAK028) when an alternate estimate of the F-factor was applied. Otherwise, the number of exceedances did not change with any of the other sensitivity analyses applied to the new estimates of the critical loads for the EEM lakes. The sensitivity analyses on the CALPUFF modelled deposition estimates showed that the number of exceedances remained the same (1 lake; LAK044) when deposition under the 42 tpd emission scenario was reduced by 50% but increased by two lakes (LAK006 and LAK028) when the deposition was doubled.

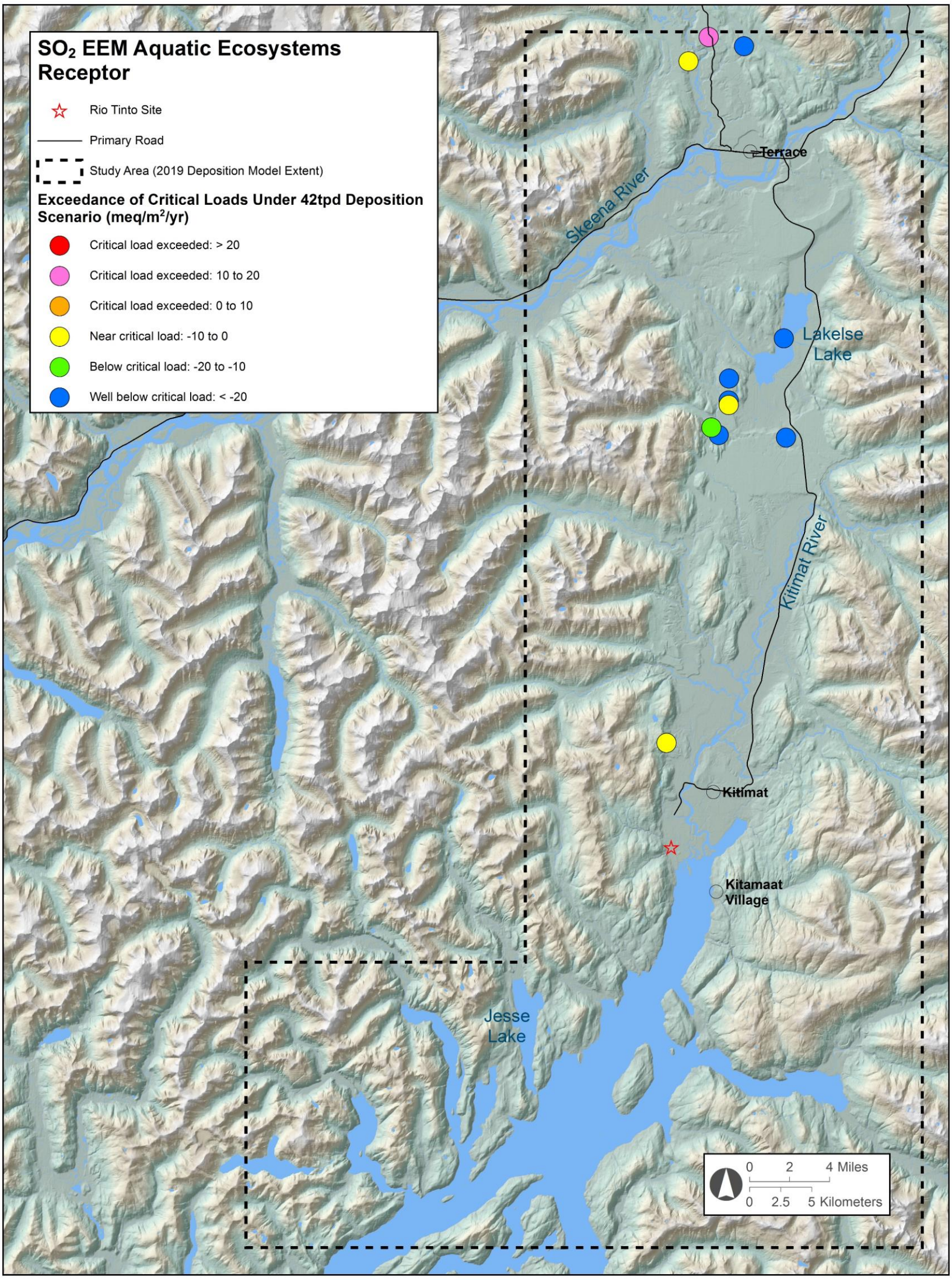


Figure 7-6. Exceedances of new critical loads for EEM lakes with modelled deposition under the 42 tpd emissions scenario.

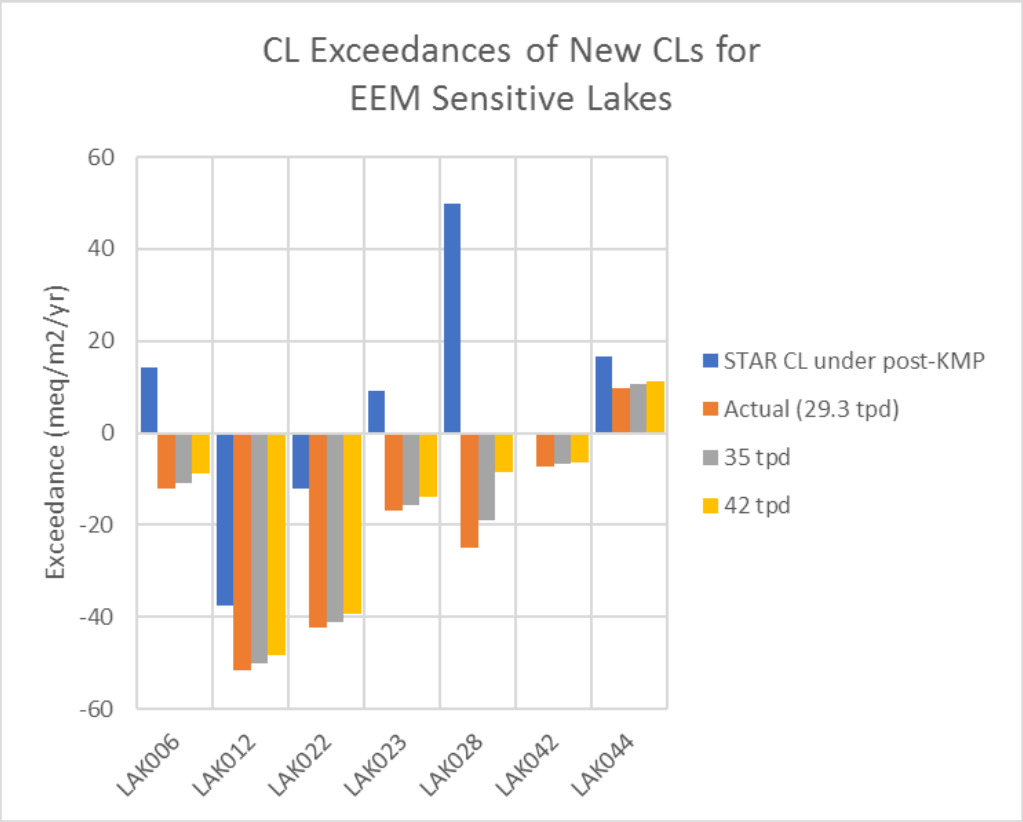


Figure 7-7. Critical load exceedances for the EEM lakes under different levels of deposition. Results from the STAR under the "post-KMP" emissions scenario are included for comparison. Results from the STAR "post-KMP" scenario did not include background deposition, whereas the exceedances estimated under the three new deposition scenarios do include background deposition of 7.5 meq/m2/yr. The exceedance for LAK042 from the STAR was smaller than perceptible on this graph (+0.2 meq/m²/yr).

Future steady-state pH

<u>EEM lakes – new predictions of future pH based on maximum future emissions vs. current</u>
We developed new predictions of future steady-state pH for the EEM lakes, using average lake chemistry conditions for the post-KMP period (2016-2018) and the change in deposition from the modelled current deposition (29.3 tpd) to the modelled maximum future deposition (42 tpd) (Table 7-10).

The new predictions for steady-state pH (i.e., based on post-KMP data, 2016-2018) show a decrease or no change for all EEM lakes relative to current condition; however, for the majority of the EEM lakes, these changes are substantially smaller than the observed *increases* in pH from 2012 to the post-KMP period. Given that the predicted decreases are predominantly much smaller than the observed increase thus far, this means that when expressed as a change relative to 2012 (relevant for comparing results

to the STAR and the baseline period defined in the EEM), the calculated changes show predicted increases in pH for many of the lakes from 2012 to steady-state conditions. However, this is an indirect effect of the changes observed so far and should not be interpreted as a prediction that increased deposition will drive increases in pH in these particular lakes.

Figure 7-8 shows the STAR and current predictions for steady-state pH relative to observed pH values for 2012 and the post-KMP period (2016-2018) for all the EEM lakes. This provides a visualization of the common patterns – i.e., that pH is predicted to decrease or remain unchanged for all of the EEM lakes relative to current pH, but because current pH is predominantly above 2012 pH levels, these steady-state predictions appear to show an increase in pH when compared to 2012.

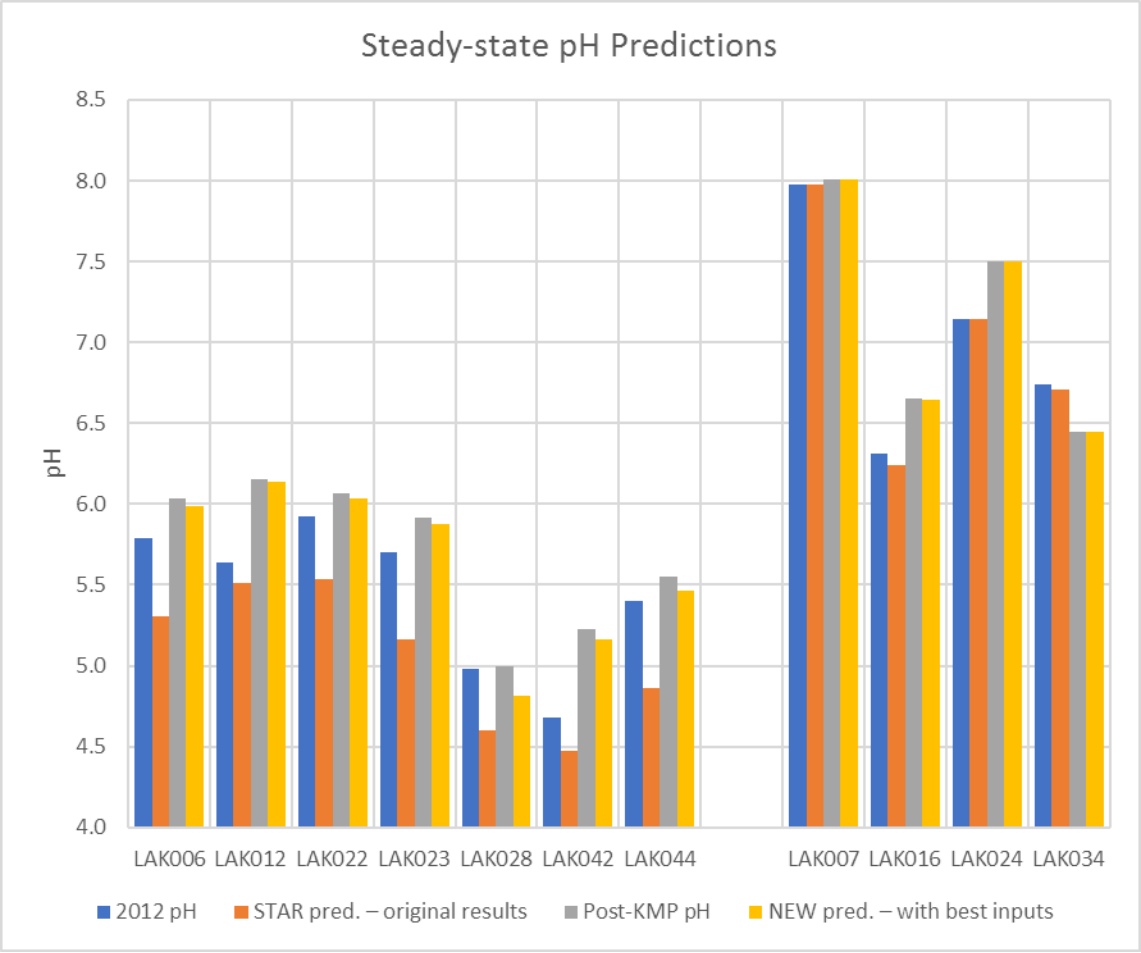


Figure 7-8. Observed pH and predicted steady-state pH for all of the EEM lakes. The STAR predictions were based on the change in deposition from the "pre-KMP" to the "post-KMP" modelled deposition. The new predictions are based on the increase in modelled deposition from current emissions (29.3 tpd) to the maximum future emissions level (42 tpd).

The applied sensitivity analyses did not change the number of lakes with predicted decreases in pH (relative to 2012) of greater than 0.1 pH unit (under maximum future emissions of 42 tpd). The sensitivity analyses on the CALPUFF modelled deposition estimates showed that for LAK028 the predicted pH change relative to 2012 was smaller than a 0.1 unit decrease when the 42 tpd emissions

scenario was reduced by 50% and increased to greater than a 0.3 pH unit decrease when the deposition was doubled – but none of the other lakes changed with respect to either of those thresholds.

Summary of critical loads, exceedances and future steady-state pH

The results from the "best case" analyses of the critical loads and steady-state pH for the EEM lakes are shown in Table 7-10. To be most conservative, these forward-looking analyses have been performed assuming the maximum level of emissions allowed under the permit (i.e., 42 tpd scenario). For each of the key metrics of interest (i.e., exceedances of critical loads, predicted changes in pH relative to the 2012 baseline, and predicted changes in Gran ANC thresholds relative to the 2012 baseline), there is only one lake that exceeds the reference threshold (as defined in the table caption):

Exceedance of critical loads
LAK044 has a critical load of zero and therefore shows a positive exceedance under all deposition scenarios. None of the other EEM lakes are predicted to show an exceedance of their critical loads (i.e., revised estimates based on the best data inputs) under the maximum predicted deposition levels (i.e., 42 tpd emissions scenario). Sensitivity analyses indicate that it is possible that the critical load for LAK028 could be exceeded under the 42 tpd scenario, but steady state predictions of future pH show that the expected future decline in pH under such a scenario is only 0.2 pH units.

Future changes in pH from baseline conditions
LAK034 is shown to have a predicted future pH that is 0.3 pH units below its 2012 level; however, this decline is unrelated to the smelter because sulphate has also decreased during the same period (as explained by the evidentiary framework). In fact, LAK034 is predicted to have zero change in pH from current (2016-18) levels, but these levels are already below 2012.

Future changes in Gran ANC from baseline conditions
LAK007 is shown to have a predicted change in Gran ANC that is greater than its lake-specific threshold; however, this result is an artifact of a change that has already occurred and is unrelated to the smelter. Gran ANC has declined since 2012 but because sulphate is also lower than 2012, the decline must not be driven by smelter emission (as per the evidentiary framework). LAK007 is highly insensitive to acidic deposition – it has very high Gran ANC and is predicted to have zero change in Gran ANC from current levels with higher deposition (even under the sensitivity analyses of 200% deposition). Furthermore, its pH has not changed since 2012 and is not predicted to change under any deposition scenario or sensitivity analysis.

The estimates of exceedances of critical loads and future changes in pH and Gran ANC are all based on steady-state modeling. Steady state models predict the eventual condition of lake chemistry under a sustained level of acidic deposition, but do not estimate the time frame over which the predicted changes will occur. We have used these models to assess the longer-term effects of the smelter. Dynamic models, which can provide predictions of changes over time, are not required for making decisions about the potential longer-term impacts of the smelter, and require much more intensive monitoring of hydrology, soils and lake chemistry.

Table 7-10. Summary of the estimated critical loads and the predicted exceedances, pH and Gran ANC under the 42 tpd emissions scenarios. Red cells indicate critical loads of zero, positive exceedances, predicted declines in pH of greater than 0.3 pH units, or predicted declines in Gran ANC that exceed the lake-specific threshold. Yellow cells indicate predicted declines in pH of greater than 0.1 pH units (but less than 0.3 pH units). The changes in LAK007 and LAK034 are unrelated to the smelter, as per the evidentiary framework and further explained in the text. Total sulphur deposition includes the CALPUFF estimate plus background deposition of 7.5 meq/m². NO_3^- leaching is a minor contribution to exceedance but included for clarity on how the exceedance is calculated.

	CALPUFF results		SSWC Model Results			ESSA-DFO Model Results								
	S Deposition (42tpd)		Total S Dep. + NO_3^- leaching	Critical load	Ex(A)	pH				Gran ANC (µeq/L)				
LAKE	meq/ m^2/yr	kg/ha / yr	meq/ m^2/yr	meq/ m^2/yr	meq/ m^2/yr	Baseline (2012)	Post-KMP (2016-18)	Future (steady-state)	ΔpH (from 2012)	Baseline (2012)	Post-KMP (2016-18)	Future (steady-state)	ΔANC (from 2012)	ANC threshold
EEM Sensitive Lakes														
LAK006	12.2	5.9	20.5	29.4	-8.9	5.8	6.0	6.0	0.2	25.7	27.7	24.7	-1.0	-10.8
LAK012	11.8	5.7	19.9	68.1	-48.3	5.6	6.2	6.1	0.5	57.0	58.3	56.0	-1.0	-16.3
LAK022	11.2	5.4	19.0	58.3	-39.3	5.9	6.1	6.0	0.1	27.8	33.0	30.4	2.6	-11.5
LAK023	11.1	5.3	19.4	33.3	-13.9	5.7	5.9	5.9	0.2	19.8	26.4	23.8	4.0	-10.5
LAK028	63.6	30.5	72.6	81.1	-8.5	5.0	5.0	4.8	-0.2	-4.0	-3.5	-9.3	-5.3	-13.4
LAK042	3.4	1.6	11.2	17.4	-6.3	4.7	5.2	5.2	0.5	-20.4	5.6	4.2	24.6	-24.4
LAK044	3.6	1.7	11.4	0.0	11.4	5.4	5.6	5.5	0.1	1.3	5.0	2.8	1.5	-6.2
EEM Less Sensitive Lakes														
LAK007	22.1	10.6	30.0	1383.4	-1353.5	8.0	8.0	8.0	0.0	1437.6	1385.9	1385.9	-51.6	-50.6
LAK016	13.2	6.4	21.5	118.1	-96.7	6.3	6.7	6.6	0.3	68.7	89.8	88.0	19.4	-25.6
LAK024	11.8	5.7	20.2	551.6	-531.4	7.1	7.5	7.5	0.4	299.5	463.2	463.2	163.7	-60.4
LAK034	4.7	2.2	12.5	138.4	-126.0	6.7	6.4	6.4	-0.3	99.4	139.6	138.7	39.3	-22.0

Reapplying the STAR Criteria for Inclusion in EEM

The STAR identified lakes with low pH (<6.0 pH units) and/or predicted exceedances of their critical loads and/or predicted declines in pH of greater than 0.1 pH units. The seven lakes identified for inclusion in the EEM program were those with a predicted pH decline of greater than 0.1 pH units. Lakes with existing pH<6.0 that did not have a predicted pH decline greater than 0.1 pH units were not included. Lakes with a positive exceedance and pH>6.0 would have been considered for inclusion but none of the STAR lakes met those criteria.

We used the same criteria from the STAR to position the lakes within the study area (Figure 7-9). The updated classification shows that of the seven lakes previously predicted to have a future pH decline greater than 0.1 pH units relative to 2012, only one of the lakes (LAK028) remains in that classification. Furthermore, of the eight lakes previously predicted to have an exceedance under the maximum level of emissions, only four of those lakes remain in that classification and all those lakes have critical loads of zero. It should be noted that two KAEEA lakes added to the present study (but outside the boundaries of the STAR study area) also have exceedances predicted, but similarly they also both have critical loads of zero, pre-KMP pH (i.e., 2013) less than 6.0 and also original pre-industrial pH less than 6.0. Therefore, had these two KAEEA lakes been included in the original STAR, they would have been identified as naturally acidic lakes with a negligible predicted change in pH and thus excluded for consideration as EEM lakes.

The results of the updated analyses of critical loads, exceedances and future pH suggest that the STAR did not omit any lakes that should have been considered for inclusion in the EEM. Additionally, it suggests that many of the lakes included in the EEM no longer match the inclusion criteria initially applied.

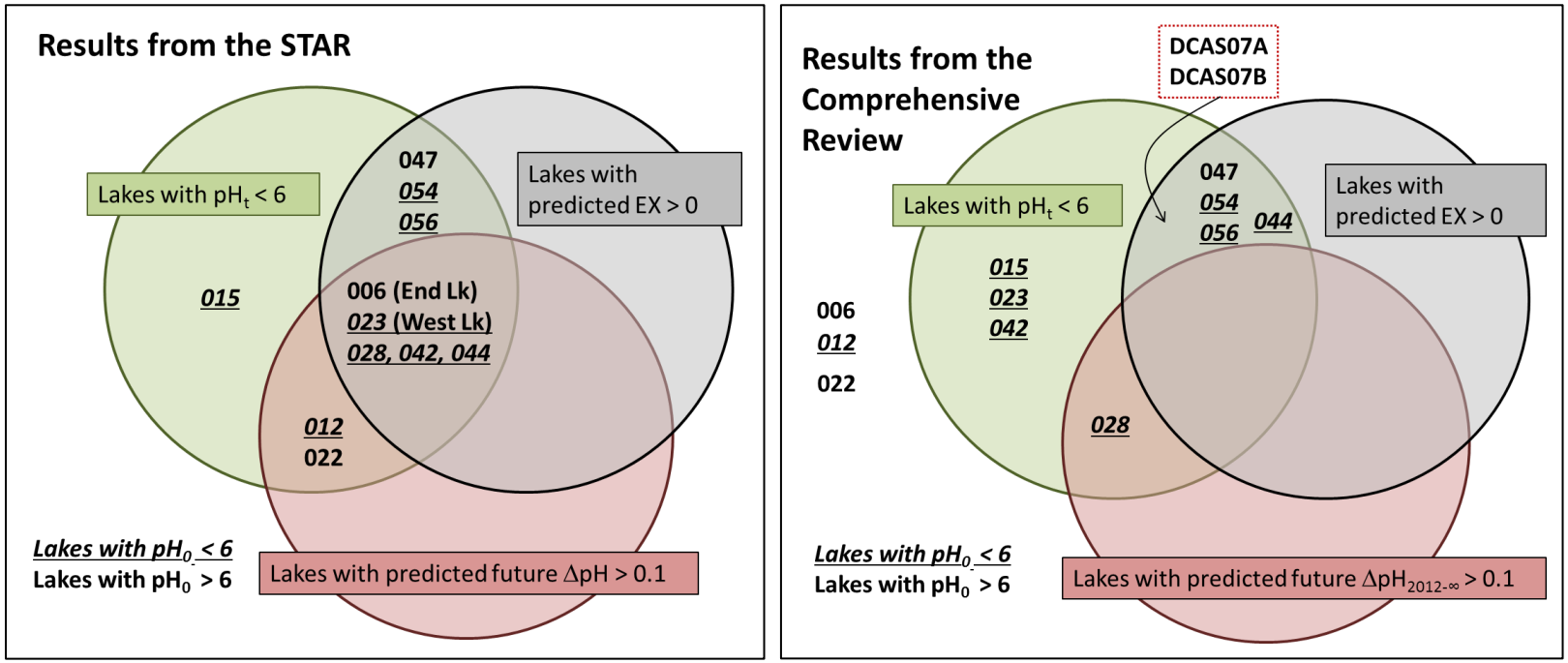


Figure 7-9. Application of the STAR criteria for identifying potential lakes for further monitoring using the new results available. The left panel shows the STAR results and the right panel shows the current results. Current pH (pH_t) and predicted change in pH are relative to 2012. DCAS07A and DCAS07B were from the KAEEA, therefore a) they were not included in the STAR classification, b) pH_t refers to 2013, and c) they do not have estimates of ΔpH (due to lacking deposition data for comparable emissions scenarios to the STAR). The results for LAK015, LAK047, LAK054, and LAK056 are based on their critical loads from the STAR (and do not have updated predictions of steady-state pH, as discussed elsewhere), whereas the results of LAK006, LAK012, LAK022, LAK023, LAK028, LAK042 and LAK044 (i.e., the EEM lakes) are based on the analyses using the most recent data.7

7.3.2.6 *Kitimat River water quality*

The results of the water quality sampling at the Rio Tinto intake on the Kitimat River are shown in Aquatic Appendix H. None of the results showed exceedances of the B.C. water quality objectives. The maximum measured sulphate concentration was less than 1% of the B.C. Drinking Water Guideline.

7.3.2.7 *Results from previously reported analyses*

Results from other, supporting analyses that have been previously reported during the EEM Program are summarized in Aquatic Appendix A. These assessments and/or analyses include: fish sampling in EEM lakes, a literature review of the potential effects of acidification on amphibians, lake level monitoring, estimation of water residence time for lakes, and sampling of non-EEM sites.

7.3.3 Modifications to the EEM Program

Modifications to the aquatic ecosystem component of the EEM Program during this phase (i.e., 2013-2018) have included: adding LAK024; adding three control lakes; increasing the frequency of water chemistry sampling to four times each fall for six of the seven sensitive lakes; and several Rio Tinto initiatives: adding continuous pH monitors to LAK006, LAK012 and LAK023 (End Lake, Little End Lake and West Lake) and LAK028 more recently, adding water level monitoring, conducting bathymetric surveys, improving the method for defining watershed area, adding a commercial laboratory, and, for LAK028, developing a depth profile and conducting depth sampling. These modifications and other improvements are further described in Aquatic Appendix A.

7.3.4 Comprehensive synthesis ('pulling all the pieces together')

7.3.4.1 *Synthesis across four lines of evidence*

We have synthesized four lines of evidence in Table 7-11: statistical analyses of changes over time in SO_4, pH and ANC; observed changes in pH, modelling of CL exceedance; and modelling of future changes in pH. Statistical analyses of data from the EEM Program have revealed patterns of change in lake chemistry, and allowed hypothesis testing for key questions despite natural variability in water chemistry. As the EEM program continues, we will have more years of post-KMP data, which will increase the statistical power to detect changes in lake chemistry. The overall conclusions are as follows:

- Of the 14 lakes in the EEM program (seven acid-sensitive lakes, four less sensitive lakes, three control lakes), 12 lakes show no evidence of sulphur-induced acidification causally related to the Kitimat smelter.

- LAK028, a 1 ha fishless lake[47] close to the Kitimat smelter, shows some evidence of sulphur-induced acidification causally related to the smelter, but the data indicate a low percentage belief that thresholds for ΔpH and ΔANC have been exceeded (18% and 2% respectively). Chemical conditions in LAK028 were potentially damaging to aquatic biota pre-KMP (i.e., in 2012 and 2013) and have remained so post-KMP (2016-2018); see Section 7.1.2.3 of Aquatic Appendix A. LAK028 is the only sensitive lake with a predicted future pH below 2012 levels under a 42 tpd emission scenario (0.2 units below 2012 levels, still less than the KPI threshold of 0.3 units).
- LAK012 (Little End Lake), a 2.3 ha lake to the southwest of Lakelse Lake, has shown increased concentrations of sulphate and some evidence of a decline in ANC, but no evidence of sulphur-induced acidification causally related to the smelter that exceeds the ANC or pH thresholds established in the EEM Plan to protect aquatic biota.

The design of the EEM program, and the set of analytical methods outlined in the TOR, provide valuable insights for assessing trends in lake chemistry.

[47] LAK028 is the headwater to Goose Creek, where fish have been found. However, all the samples taken from the many tributaries collectively known as Goose Creek (15 samples, over 2014, 2015 and 2018, across 11 sites) were found to be insensitive to acidification (see Aquatic Appendix A Sections 7.1.2.8 and 7.1.4.2).

Table 7-11. Synthesis of evidence from water chemistry analyses, critical loads (CL) models and ESSA-DFO model. Shading in the table: green – evidence against past or future acidification; yellow – situation worth close monitoring; red – exceedance of CL or decrease in observed / predicted pH (see Section 7.3.4.2). With respect to the rightmost column, average emissions over 2016-2018 have been 29.3 tpd. The 0.3 pH decline in LAK034 is not related to SO_4, which declined from 2012 to 2016-2018. The control lakes do not have results from the CL modelling or the ESSA-DFO model because they are located outside the CALPUFF model area and therefore do not have estimates of deposition. Note: Future pH is predicted to be similar or less than current pH for all lakes, but this is still higher than 2012 due to increases observed since 2012 (see Section 7.3.2.5).

Lake	Insights from Water Chemistry Analyses[48]	Observed ΔpH from 2012 to mean of 2016-2018	Insights from CL Modelling (exceedance under 42 tpd, in meq/m²/yr)	Insights from ESSA-DFO Modelling under 42 tpd
Sensitive Lakes				
LAK006	**SO_4^{2-} increase**; no evidence of S-induced acidification	0.2 unit pH increase	No exceedance predicted (-9)	Predicted future pH > 2012
LAK012	**SO_4^{2-} increase**; some evidence of S-induced acidification; no evidence of exceeding pH and ANC thresholds	0.5 unit pH increase	No exceedance predicted (-48)	Predicted future pH > 2012
LAK022	**SO_4^{2-} increase**; no evidence of S-induced acidification	0.1 unit pH increase	No exceedance predicted (-39)	Predicted future pH > 2012
LAK023	*SO_4^{2-} decrease*; no evidence of S-induced acidification	0.2 unit pH increase	No exceedance predicted (-14)	Predicted future pH > 2012
LAK028	**SO_4^{2-} increase**; some evidence of S-induced acidification; no evidence of exceeding ANC threshold; low belief in exceeding pH threshold[49]	0.0 unit pH change	No exceedance predicted (-9)	Predicted future pH is 0.2 pH units below 2012
LAK042	No clear change in SO_4^{2-}; no evidence of S-induced acidification	0.5 unit pH increase	No exceedance predicted (-6)	Predicted future pH > 2012
LAK044	*SO_4^{2-} decrease*; no evidence of S-induced acidification	0.2 unit pH increase	Zero CL; Exceedance predicted (11)	Predicted future pH > 2012
Less Sensitive Lakes				
LAK007	*SO_4^{2-} decrease*; no evidence of S-induced acidification	0.0 unit pH change	No exceedance predicted (-1354)	Predicted future pH > 2012
LAK016	**SO_4^{2-} increase**; no evidence of S-induced acidification	0.3 unit pH increase	No exceedance predicted (-97)	Predicted future pH > 2012

[48] See Table 7-9 for additional information on this line of evidence.
[49] Conditions in LAK028 were potentially damaging to biota pre-KMP and have generally remained so (Section 7.1.2.3 of Aquatic Appendix A)

Lake	Insights from Water Chemistry Analyses[48]	Observed ΔpH from 2012 to mean of 2016-2018	Insights from CL Modelling (exceedance under 42 tpd, in meq/m²/yr)	Insights from ESSA-DFO Modelling under 42 tpd
LAK024	**SO_4^{2-} increase**; no evidence of S-induced acidification	0.4 unit pH increase	No exceedance predicted (-531)	Predicted future pH > 2012
LAK034	*SO_4^{2-} decrease*; no evidence of S-induced acidification	-0.3 unit pH decrease (not related to smelter)	No exceedance predicted (-126)	Predicted future pH is 0.3 pH units below 2012 *(zero additional change predicted)*
Control Lakes		*Change from 2013*		
DCAS14A	No clear change in SO_4; no evidence of S-induced acidification	0.2 unit pH increase	Outside CALPUFF model area	Outside CALPUFF model area
NC184	No clear change in SO_4; no evidence of S-induced acidification	0.1 unit pH increase	Outside CALPUFF model area	Outside CALPUFF model area
NC194	SO_4^{2-} decrease; no evidence of S-induced acidification	-0.2 unit pH decrease	Outside CALPUFF model area	Outside CALPUFF model area

7.3.4.2 *Changes to and/or confirmation of the STAR results and assumptions*

Emissions / deposition**:** Post-KMP emissions have been well below the maximum permit emissions that were applied in the STAR (42 tpd). The steady-state analyses of critical loads, exceedances and future pH are still based on deposition levels under the maximum future emissions (i.e., 42 tpd) but the estimated deposition at each of the EEM lakes under that maximum scenario (as based on the updated CALPUFF modelling framework) is less than was previously estimated in the STAR. Therefore, deposition values under both current and future maximum emissions are less than predicted in the STAR. See Chapter 3 for further details on the changes in the atmospheric modelling framework.

F-factor: LAK028 was the only lake with a sufficient change in lake sulphate to permit an empirical estimate of the F-factor to compare against the model-based estimates used in the STAR (see Section 2.3.3 of Aquatic Appendix G). The revised empirically-based estimates of the F-factor for LAK028 are in the range from 0.65 to 0.85, compared to an initial estimate of 0.44 in the STAR. This indicates that over the period of the EEM program approximately 65% to 85% of the deposited acidity associated with sulphur deposition was neutralized by exchanges for base cations in the watershed of LAK028. Thus, LAK028 was able to neutralize a larger fraction of the deposited acidity than had been assumed in the STAR.

Critical Loads and Exceedances: Fewer lakes are predicted to have exceedances under the maximum future emissions of 42 tpd than were predicted in the STAR. Only one lake (LAK044) shows an exceedance under the 42 tpd emissions scenario. Because LAK044 has a critical load of zero, it has an exceedance under all emissions scenarios. In the STAR, five of the EEM lakes were predicted to have exceedances under the "post-KMP" emissions scenario (i.e., also based on emissions of 42 tons SO_2 per day). For eight of the 11 EEM lakes, the revised estimates of critical loads are quite similar to the original estimates in the STAR. The revised critical load estimates are higher than the STAR for LAK024 and LAK028 and lower for LAK012. The exceedances of the revised critical loads under the 42 tpd emissions scenario are consistently smaller in magnitude than those predicted in the STAR (Figure 7-7). Since the revised estimates of critical loads are mostly similar to those in the STAR, the reduction in the magnitude of exceedances relative to the STAR primarily reflects lower estimates of deposition. See Section 7.3.2.5 and Aquatic Appendix G.

Predicted Future Steady-state pH: The updated predictions of future pH are higher than the predictions from the STAR for all of lakes except LAK034, which has already decreased below its STAR prediction and is not predicted to change further. We developed new predictions of future steady-state pH for the EEM lakes, using average lake chemistry conditions for the post-KMP period (2016-18) and the change in deposition from the modelled current deposition (29.3 tpd) to the modelled maximum future deposition (42 tpd). The pH is predicted to decrease or remain unchanged for all of the EEM lakes relative to current pH, but because current pH is predominantly above 2012 pH levels, these steady-state predictions appear to show an increase in pH when compared to 2012. By comparison, the STAR predicted that future pH would be lower than 2012 values for all of the sensitive EEM lakes and one of the less sensitive EEM lakes, and would remain unchanged for the other three less sensitive EEM lakes. See Section 7.3.2.5 and Aquatic Appendix G.

7.3.4.3 *Summary of observed changes in lake chemistry, 2012-2018*

The statistical analyses of empirical observations of the changes in lake chemistry between 2012 and the average of the post-KMP years (2016-2018), summarized in Table 7-9 show the following patterns for the seven sensitive EEM lakes, four less sensitive EEM lakes and the three control lakes:

- There was a high percent belief in increases in $[SO_4]$ in four of the sensitive lakes (LAK006, LAK012, LAK022, LAK028) and two of the less sensitive lakes (LAK016 and LAK024). There was an intermediate percent belief in SO_4^{2-} increases within two of the control lakes (DCAS14A and NC184) and one of the sensitive lakes (LAK042). The other 5 lakes had no support for increases in $[SO_4]$.
- All but one of the 14 lakes (LAK007) showed a low percent belief in Gran ANC declines below the lake specific threshold; (LAK007) showed an intermediate level of support for such a decline, but is a very insensitive lake with very high Gran ANC.
- All but two of the 14 lakes (less sensitive lake LAK034 and control lake NC184) showed a low percent belief in pH declines of 0.3. LAK034 had an intermediate percent belief in a pH decline of 0.3, but since $[SO_4]$ in this lake declined to essentially zero, this change was unrelated to the smelter. Control lake NC184 also showed an intermediate percent belief in a pH decline of 0.3, but this reflects a small data set (just 4 samples); the mean pH changed from 5.7 in 2012 to 5.8 over 2016-18.

See Sections 7.3.1 and 7.3.2.3 and Aquatic Appendices A, C, D and F for full details.

7.3.4.4 *Exceedances of EEM indicators*

Based on the KPIs and thresholds in the EEM Plan (for pH), as well as those added for Gran ANC, there have been no exceedances of these thresholds. This is also the case when using the alternate baseline of 2012-14, as described in Aquatic Appendix I.

7.3.4.5 *Application of the Evidentiary Framework*

Applying the simplified evidentiary framework from Figure 7-3 to the 14 lakes, we obtain Figure 7-10. The results of applying this decision tree are as follows:

- At the first blue decision box (*Has lake $[SO_4]$ increased since pre-KMP period?*), six lakes are eliminated from further consideration of smelter effects, as there is strong evidence of decreases in their sulphate concentrations: Sensitive lakes LAK023 and LAK044; Less Sensitive lakes LAK007 and LAK034; Control lakes NC194 and NC184. Control lake DCAS14A is also eliminated from further consideration, as all of the control lakes are well outside of the smelter's plume (see Figure 7-1), and therefore any changes in lake sulphate were not associated with the smelter. In addition, observed increases over time in sulphate were negligible in both NC184 (0.5 µeq/L), and DCAS14A (i.e., 3 µeq/L); Table 7-6. Control lake NC194 showed an observed decrease in sulphate concentrations of 1.1 µeq/L (Table 7-6).
- At the second blue decision box (*Has lake pH or Gran ANC decreased since pre-KMP period?*), five more lakes are eliminated from further consideration of smelter effects, as there is strong evidence that their pH and Gran ANC concentrations have not declined: Sensitive lakes LAK006, LAK022, LAK042; and Less Sensitive lakes LAK016, LAK024. The evidence is insufficient to reject the hypothesis of declines in Gran ANC for sensitive lakes LAK012 and LAK028 (46% and 34% belief in an ANC decline, Table 7.73 in Aquatic Appendix F), so they move on to the next part of the decision tree.

- At the third blue decision box, we find that lakes LAK012 and LAK028 have not exceeded the thresholds for either pH or Gran ANC (low % belief, see Table 7-9). These lakes should be closely monitored over time. In the ranking of lakes within the EEM Plan (Appendix D in ESSA et al. 2014), both these lakes were considered to be of low importance.
- In response to requests from reviewers of the draft comprehensive review report, we have completed a sensitivity analysis to assess the effects of using 2012-2014 as an alternative baseline to 2012 (Aquatic Appendix I). While use of a 2012-2014 baseline does change some of the results of the statistical analyses, it does not change any of the overall conclusions regarding effects of the smelter on EEM lakes (see Table 3-4 and Figure 6 in Aquatic Appendix I).

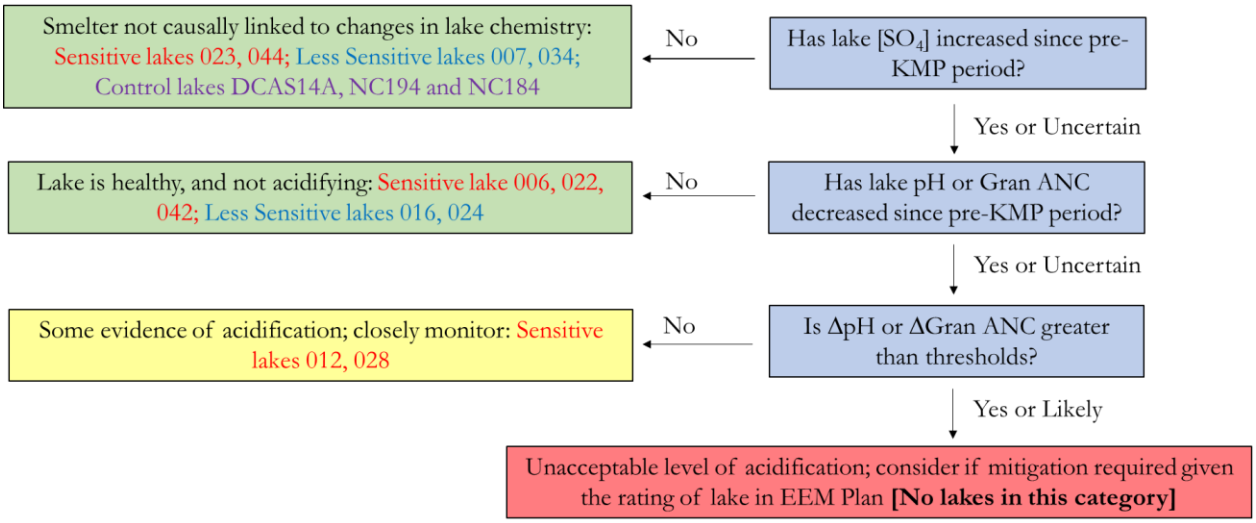


Figure 7-10. Classification of EEM lakes according to the simplified evidentiary framework in Figure 7-3.

Table 7-12. Application of EEM Evidentiary Framework (Table 17 in the 2014 SO_2 EEM Plan, ESSA et al. 2014a) for evaluating if acidification has occurred and whether it is or is not related to KMP. SPR = Source-Pathway-Receptor conceptual model for the EEM Program (see Section 1.1). The last three columns show answers to the question in column 2. Highlighted cells are the answer to the question (pink for evidence consistent with smelter effects, orange for evidence inconsistent with smelter effects, purple for uncertain outcomes).

Links in SPR model	Question	Methods Used to Answer Question *Answers to question* [References with examples of these analyses]	Implications of Answers		
			Evidence consistent with KMP as primary cause of observed change	Evidence against KMP as primary cause of observed change	Can't answer question with available data
3	Have SO_2 emissions from KMP increased significantly beyond levels in the pre-KMP period, potentially causing increased acidic deposition?	Compare mean daily emissions in pre-KMP period vs. KMP ramp-up period vs. post-KMP steady state period; assess trends. *Emissions of SO_2 increased from an average of 12.5 tpd in 2012-2015 (pre-KMP plus transition period) up to an average of 29.3 tpd over 2016-2018 (post-KMP period); see Section 1.* ***Therefore, emissions increased by about 135% between the 2012-2015 period and the 2016-2018 period.***[50]	**Yes**	No	Uncertain
3	Has SO_4^{2-} deposition at Kitimat and Lakelse monitoring stations increased since pre-KMP period in a manner proportional to SO_2 emissions? Has N deposition shown negligible changes? Is deposition of base cations too low to neutralize SO_4^{2-} deposition?	Compare monthly and annual SO_4^{2-} deposition in pre-KMP period vs. KMP ramp-up period vs. post-KMP steady state, and assess trends, for each deposition site. *Wet deposition increased by 37% at Haul Road (2016-2018 vs. 2012-2015) and by 62% at Lakelse Lake (2016-2018 vs. 2013-2015); Section 3.2. Dry deposition increased by 73% at Haul Road between 2015 and 2016-2018 (Section 3.2).* ***Therefore, wet and dry deposition have increased, but by a smaller percentage than the increase in SO_2 emissions.*** *The most likely explanation for this pattern is that only a small fraction of the emitted SO_2 is deposited within the study area (8.1%, see Section 3.2).*	**Yes**, but not proportional to change in emissions	No	Uncertain

[50] We are using the periods 2012-2015 and 2016-2018 to allow comparisons with the record of deposition monitoring. We used only 2012 as a pre-KMP period for pH and Gran ANC, as discussed in Section 7.3.2.2.

Links in SPR model	Question	Methods Used to Answer Question *Answers to question* [References with examples of these analyses]	Implications of Answers		
			Evidence consistent with KMP as primary cause of observed change	Evidence against KMP as primary cause of observed change	Can't answer question with available data
2, 3	Has background SO_4^{2-} deposition (long range sources outside the study area) increased much less than the estimated increase in KMP-related SO_4^{2-} deposition, since the pre-KMP period?	Examine trends in SO_4^{2-} deposition and [SO_4] in wet deposition from Alaska and other monitoring stations, as reported in the literature. Compare observed change to modelled effect of KMP deposition. *Whereas wet deposition of SO_4^{2-} increased by 37% and 62% at Haul Road and Lakelse Lake (respectively) between pre-KMP and post-KMP periods, wet deposition at three NADP monitoring sites outside of the study area (Port Edward, B.C.; Marblemount, WA; Juneau, AK) showed decreases of 23%, 26%, and 25% between the pre and post-KMP periods (see Section 3.2).* ***Therefore, background wet deposition has decreased during the period that wet deposition increased within the study area.***	**Yes**	No	Uncertain
3, 8, 9	Has lake [SO_4] increased post-KMP in a manner consistent with predicted increases in deposition of SO_4, and deposition levels inferred from monitoring observations?	Examine distribution of changes in lake [SO_4] across multiple lakes and time trends within individual lakes. Compare trends in [SO_4] to predicted changes in SO_4^{2-} deposition with KMP in the STAR, as well as observed SO_4^{2-} deposition from Kitimat and Lakelse monitoring stations. *There is strong support for SO_4^{2-} increases in six of the 14 EEM lakes (LAK006, LAK012, LAK022, LAK016, LAK024 and LAK028), intermediate support in three lakes (LAK042, DCAS14A, NC184), and very low support in five lakes (LAK044, LAK034, LAK023, LAK007, NC194). In LAK028 and LAK024 (Lakelse Lake) the change in lake SO_4^{2-} was greater than expected (Section 7.1.3.1.2 of Aquatic Appendix A), but it was less than expected in the other 9 EEM lakes included in the analysis (all but the control lakes). The trends in lake [SO_4^{2-}] are not correlated with changes in emissions of SO_2 (Aquatic Appendix F).* ***Despite evidence of increased wet deposition of SO_4, there is strong support for increased lake [SO_4^{2-}] in only 6 of 14 lakes.***	**Yes** ***for 6 lakes***	**No** ***for 5 lakes***	**Uncertain** ***for 3 lakes***

Links in SPR model	Question	Methods Used to Answer Question *Answers to question* [References with examples of these analyses]	Implications of Answers		
			Evidence consistent with KMP as primary cause of observed change	Evidence against KMP as primary cause of observed change	Can't answer question with available data
7,9	Do the observed spatial and temporal changes in climate, pH, ANC, DOC and sulphate suggest drought-caused oxidation of sulphate stored in wetlands, related to KMP rather than due to climate fluctuations affecting wetland storage of historical S deposition?	Examine trends in annual precipitation from meteorological stations, and assess if periods of drought followed by wetter years were correlated with increases in [SO_4] and decreases in ANC. *This question is most relevant for two lakes (LAK012, LAK028) where there have been increases in SO_4, and decreases in pH or ANC (though less than the thresholds). However, there is no wetland upstream of LAK028, and there is no evidence of changes in DOC, which would be expected if there were releases of SO_4^{2-} from wetlands. There was a drought in the summer of 2018, so 2019 data will be important to determine if the drought and subsequent wash-out of watershed ions had any temporary effects on water chemistry in the following year. It may not be possible to confidently answer this question, as wash-out of watershed ions could occur at times of the year outside of the sampling window.* ***Uncertain.***	Yes	No	**Uncertain**
8	Has lake ANC decreased post-KMP in a manner consistent with increases in lake [SO_4] and watershed neutralizing abilities (F-factor)?	Examine distribution of changes in lake ANC across multiple lakes and ANC time trends within individual lakes. Compare ANC and SO_4^{2-} time trends. *Changes in mean ANC between 2012 and 2016-2018 have been positive in all 7 sensitive lakes, opposite from what was predicted given the estimated change in SO_4^{2-} deposition (Section 7.1.3.1.2 of Aquatic Appendix A). This question is most relevant for just two of the seven sensitive lakes (LAK012, LAK028) where there is strong support for increases in SO_4^{2-}, moderate support for decreases in ANC (46% and 34%, respectively), but very low support for ANC changes beyond the KPI thresholds (1% and 2% respectively). Changes in mean ANC have been opposite to what was expected given the increase in SO_4^{2-} concentrations, and the F-factors for these lakes (i.e., mean ANC increased rather than decreased).* ***Therefore, ANC has not decreased post-KMP in a manner consistent with increases in lake [SO_4^{2-}] and watershed neutralizing abilities.***	Yes	**No**	

Links in SPR model	Question	Methods Used to Answer Question *Answers to question* [References with examples of these analyses]	Implications of Answers		
			Evidence consistent with KMP as primary cause of observed change	Evidence against KMP as primary cause of observed change	Can't answer question with available data
8	Has lake pH decreased post-KMP in a manner consistent with SO_4^{2-} increases, ANC decreases, and lake-specific titration curves?	Examine distribution of changes in lake pH across multiple lakes and time trends within individual lakes. Use lake-specific titration curves to assess if SO_4, ANC and pH changes are all consistent with hypothesis of SO_4-driven acidification. *Changes in mean pH between 2012 and 2016-2018 have been positive in all 7 sensitive lakes, opposite from what was predicted given the estimated change in SO_4^{2-} deposition (Aquatic Appendix G). This question is only relevant for just two of the seven sensitive lakes (LAK012, LAK028) where there is strong support for increases in SO_4. Based on the fall sampling (four samples/year), there is 0% support for decreases in mean lab pH in LAK012, and 1% support for decreases greater than the KPI threshold. LAK028 shows intermediate support for decreases in pH (46% belief; Aquatic Appendix F), but low support that these decreases exceeded the KPI threshold of 0.3 pH units (18%; Aquatic Appendix F).* ***Therefore, lake pH has not decreased post-KMP in a manner consistent with SO_4^{2-} increases.***	Yes	**No**	
8	Have lake pH and ANC values decreased beyond identified thresholds?	Assess pH changes across all 7 EEM lakes, and the percent of comparisons showing decreases of more than 0.3 pH units. Examine time trends in pH and ANC using regression analyses for lakes with more intensive monitoring that provide better estimates of natural variation in pH and ANC. *This question is only relevant for two of the seven sensitive lakes (LAK012, LAK028) where there is strong support for increases in SO_4, and low to intermediate support for changes in either pH or ANC. There are only very low levels of support for changes in pH and ANC beyond the thresholds (pH: 1%, 18%; ANC: 1%, 2% respectively for LAK012, LAK028). Two of the three intensively monitored lakes (LAK006, LAK012) showed both increased SO_4^{2-} and declining trends in pH since late 2014, but these trends reflect changes from an elevated baseline after emissions declined, were not statistically*	Yes	**No**	

Links in SPR model	Question	Methods Used to Answer Question *Answers to question* [References with examples of these analyses]	Implications of Answers		
			Evidence consistent with KMP as primary cause of observed change	Evidence against KMP as primary cause of observed change	Can't answer question with available data
		significant and did not exceed the 0.3 threshold. ***None of the lake pH and ANC values have decreased beyond identified thresholds.***			
2, 3, 7, 8, 9	Are observed changes in Cl^-, NO_3^- and DOC consistent with causes of acidification other than KMP (i.e., sea salt driven episodes, N emissions, organic acidification)?	Examine the percent anion composition of each lake and how it has changed over time. *This question is only relevant for just two of the seven sensitive lakes (LAK012, LAK028) where there is strong support for increases in SO_4, and low to intermediate support for changes in either pH or ANC. Based on visual inspection of graphed data, there are no apparent changes in nitrate, Cl^- or DOC, though we have not conducted statistical analyses of these parameters.* ***There is no apparent evidence for acidification driven by sea salt, N emissions or organic acidification.***	No	Yes	

7.3.5 Conclusions

7.3.5.1 *Does the Weight of Evidence indicate that KMP has contributed to the acidification of aquatic ecosystems?*

Of the 14 lakes in the EEM program (seven acid-sensitive lakes, four less sensitive lakes, three control lakes), 12 lakes show no evidence of sulphur-induced acidification causally related to the Kitimat smelter. The sensitive lakes have shown considerably less response to increased emissions than was predicted in the STAR. LAK028, a 1 ha fishless lake close to the Kitimat smelter, shows some evidence of sulphur-induced acidification causally related to the smelter, a continuation of pre-KMP conditions, but the EEM thresholds for ΔpH and ΔANC have not been exceeded. LAK012 (Little End Lake), a 2.3 ha lake to the southwest of Lakelse Lake, has shown increased concentrations of sulphate and some evidence of a decline in ANC, but no evidence of sulphur-induced acidification causally related to the smelter that exceeds the ANC or pH thresholds established in the EEM Plan to protect aquatic biota.

7.3.5.2 *Summary of answers to questions in the STAR and EEM*

Table 7-13 summarizes the answers to the key questions identified in the STAR, as described in Section 7.1. Table 7-14 summarizes the answers to the other questions that emerged during or since the development of the EEM Plan, as described in Section 7.1.3.

Table 7-13. Summary of answers to questions in the STAR.

Questions from the STAR	Answers
W1. How do assumptions in deposition and surface water models affect the predicted extent and magnitude of critical load exceedance post- KMP?	The main report describes the expected level of exceedance of critical loads, and future changes in pH and Gran ANC under the most likely assumptions. Aquatic Appendix G contains sensitivity analyses for many model inputs and parameters. In general, the model results are robust to wide variation in assumptions.
W2. How many of the seven to ten potentially vulnerable lakes actually acidify under KMP, and to what extent?	Of the 14 lakes in the EEM program (seven acid-sensitive lakes, four less sensitive lakes, three control lakes), 12 lakes show no evidence of sulphur-induced acidification causally related to the Kitimat smelter. LAK028, a 1 ha fishless lake close to the Kitimat smelter, shows some evidence of sulphur-induced acidification causally related to the smelter. LAK012 (Little End Lake), a 2.3 ha lake to the SW of Lakelse Lake, has shown increased concentrations of sulphate, but no consistent evidence of sulphur-induced acidification causally related to the smelter.
[**W2a**.] Have any of the sensitive lakes exceeded their KPI thresholds?	As illustrated in the simplified evidentiary framework, this question is only relevant for lakes which have shown an increase in sulphate concentrations, and a potential decline in either pH or ANC (i.e., any level of decline, irrespective of the thresholds). Only two lakes meet these criteria: LAK028 and LAK012. However, LAK028 shows a low % belief that thresholds for either ΔpH and ΔANC have been exceeded (18% belief and 2% belief respectively) and LAK012 shows no support for exceedance of the thresholds for either ΔpH or ΔANC (1% belief for both thresholds).
[**W2b**.] Does the weight of evidence suggest that any of the lakes have actually acidified and that such acidification is due to KMP (examining changes in all relevant water chemistry parameters)?	LAK028 showed evidence of smelter influence prior to KMP (described in the STAR), and still shows evidence of smelter influence. Its pH and Gran ANC levels have not decreased beyond the EEM thresholds.
[**W2c**.] What is the water chemistry of the four less sensitive lakes? Do any of them show any evidence of acidification and/or impact from KMP?	The data from two of the less sensitive lakes (LAK016 and LAK024 – Lakelse Lake) show strong evidence of increases in SO_4^{2-} (97% belief and 96% belief, respectively), but no support for decreases in pH or ANC beyond the EEM thresholds (0% belief and 1% belief respectively for pH; 1% belief and 1% belief for ANC). The other two less sensitive lakes (LAK007 and LAK034) show strong support for a decline in lake SO_4.
[**W2d**.] How many lakes have actually acidified due to KMP and exceeded their KPI thresholds?	None.
[**W2e.**] Are additional sites suggested by ENV (i.e., lakes MOE-3 and MOE-6, Cecil Creek, and Goose Creek) at risk of acidification under KMP?	No. All of these sites were found to have high critical loads and to be insensitive to acidification (see Section 7.4.1 and Aquatic Appendix A).

Questions from the STAR	Answers
W3. What is the current status of the fish community in the potentially vulnerable lakes that can be safely accessed for fish sampling?	Four of the seven sensitive lakes were sampled for fish using gill nets in 2013 (West Lake (LAK023), End Lake (LAK006), Little End Lake (LAK012), Finlay Lake (LAK044)), and a fifth sensitive lake was sampled in 2017 (LAK028). No fish were caught in Finlay Lake (which has no inlets or outlets) or in LAK028 (which has no inlet and a blocked outlet). Threespine stickleback and coho salmon were present in West Lake, End Lake and Little End Lake, though in West Lake the coho were confirmed to remain in freshwater for their entire life cycle, rather than going to sea. End Lake and Little End Lake also had coastal cutthroat trout and dolly varden char. Three of the less sensitive lakes were sampled in 2015: Clearwater Lake (LAK007), LAK016 and LAK034. They generally had similar fish assemblages and numbers of fish species to the sensitive lakes with fish. Coastal cutthroat trout was common in all three lakes. Other species found included coho salmon and dolly varden char (in LAK007 and LAK016), threespine stickleback (in LAK007 and LAK034), and (in LAK007 only) rainbow trout and Chinook salmon. Altogether, six species were found in LAK007, three in LAK016, and two in LAK034. Further details on age classes and size of fish are available in the Limnotek annual technical reports from each of the years of sampling.
W4. If some of the potentially vulnerable lakes that can be safely accessed for fish sampling show an acidifying trend, then do these lakes also show changes in their fish communities?	None of the lakes have shown an acidifying trend beyond the EEM thresholds requiring them to be resampled.

Table 7-14. Summary of answers to questions that emerged after the STAR, especially during the development and implementation of the EEM Program.

Questions that emerged after the STAR	Answers
How do the observed changes in SO_4, Gran ANC and pH compare to the steady-state predictions from the STAR?	The observed changes in SO_4, Gran ANC and pH have generally been much less than the steady-state predictions from the STAR (as adjusted to reflect actual emissions rather than maximum emissions). The only exceptions have been: 1) LAK024 increased in sulphate more than predicted (but showed very low support for a ΔGran ANC and ΔpH beyond the thresholds – 1% belief and 1% belief respectively, consistent with the STAR predictions of no change in either parameter) ; 2) LAK028 increased in sulphate much more than predicted; 3) LAK007 decreased in Gran ANC despite a prediction of no change (but LAK007 has an extremely high Gran ANC, and shows strong evidence (100% belief) of a small *decrease* in sulphate, indicating that the change in Gran ANC was unrelated to emissions from the smelter); and 4) LAK034 decreased in pH despite a prediction of

Questions that emerged after the STAR	Answers
	no change (but this is not associated with smelter emissions because sulphate decreased to essentially zero).
Can we estimate F-factors from the empirical sampling results?	Only for LAK028, where there was a sufficient change in lake sulphate to permit an estimate of the F-factor. The revised estimates of the F-factor are in the range from 0.65 to 0.85, compared to an initial estimate of 0.44 in the STAR, indicating that over the period of the EEM program approximately 65% to 85% of the deposited acidity associated with sulphur deposition was neutralized by exchanges for base cations in the watershed of LAK028. Some additional neutralization of acidity occurs through bacterial reduction of sulphate in the deeper waters (anoxic hypolimnion) of LAK028. The only way to determine the long-term ability of LAK028's watershed and in-lake processes to neutralize acidity is through continued monitoring of its lake chemistry.
Do we see any evidence of regional acidification if we analyze the lakes as a group rather than individuals?	No. There is a spatial pattern to changes in lake sulphate, with lakes closer to the smelter being more likely to show an increase in sulphate, but none of the lakes have acidified beyond the established thresholds for pH and Gran ANC (Figure 7-5).
Is there a benefit to adding appropriate control lakes to the EEM?	Yes. The control lakes provide insights and statistical inferences on natural variability in water chemistry unrelated to the smelter (e.g., year-to-year variation in regional weather patterns and longer term changes in climate), and can be used in statistical analyses to detect changes in the sensitive lakes that differ from the control lakes. The power analysis completed in 2016 demonstrated that inclusion of control lakes increases statistical power.
Is there a benefit to more intensive water sampling?	Yes. Intensive water sampling provides a better estimate of within-year variability in water chemistry, allows for a more precise estimate of lake chemistry for the fall period, and provides an additional data set for examining long-term trends in pH. As discussed below (Section 7.4), it is sufficient to have data from just one intensively monitored lake rather than three.
Is there a benefit to collecting other data on the EEM lakes?	Yes – the bathymetric analyses have provided a much more accurate estimate of lake volume and therefore improved our initial estimates of water residence time so we can better understand the temporal lag (or lack thereof) in lake chemistry responses to changes in deposition levels. Yes – the lake level data have provided information by which to examine the extent to which intra-annual changes in lake chemistry may be associated with hydrologic events. The lake level data provide information specific to the watershed rather than general regional patterns that are represented by weather stations or flow data from major rivers.
Will increased emissions result in immediate (i.e., same year) changes to lake chemistry or will there be a lag?	Changes in lake chemistry have not shown a consistent response to the increase in sulphur emissions after 2015. Additionally, estimates of water residence time shown in Appendix A (including revised estimates from those in the EEM Plan and more precise estimates for four lakes with bathymetry data) suggest that all seven sensitive lakes should respond within a year or two to changes in watershed inputs.

Questions that emerged after the STAR	Answers
How important will it be to consider multiple metrics in our evaluations of the data?	As discussed above in Section 7.1.3, the approach that we've used in this report, and will continue to use in future comprehensive review reports, uses multiple metrics, in a logical evidentiary framework. The simplified evidentiary framework (Figure 7-3) organizes multiple metrics into a logical decision tree.

7.3.5.3 *Assessment of acceptable or unacceptable impacts on aquatic receptor*

Based on the KPIs and thresholds in the EEM Plan (for pH), as well as those added for Gran ANC, there have been no exceedances of these thresholds, and therefore no unacceptable impacts on aquatic receptors

7.3.5.4 *What outstanding questions still require further or ongoing investigation?*

We only have three years of post-KMP data so far, and more years of data will improve our ability to detect how much change in water chemistry has occurred.

7.3.5.5 *What new questions have emerged?*

By the 2050s, global warming is likely to result in warmer summers (possibly drier or wetter) and warmer, wetter winters, with less snowpack[51]. Continued monitoring of both the sensitive lakes and control lakes will help to elucidate the independent and combined effects of the smelter and climate change.

LNG Canada will be developing a liquified natural gas facility in the Kitimat area, which will add emissions of both SO_2 and N oxides. Modelling will be required to disentangle the relative impacts of the Rio Tinto smelter and the LNG Canada facility.

7.4 What Do We Recommend for the EEM Program Going Forward?

7.4.1 Monitoring program for aquatic ecosystems

Going forward, we have the following recommendations for the monitoring program for aquatic ecosystems:

Recommendation 1 – Monitoring of sensitive lakes: The seven sensitive lakes should continue to be the core of the EEM Program. Continue with four samples of full chemistry each October from the six sensitive lakes that are accessible (LAK006, LAK012, LAK023, LAK028, LAK042, LAK044) to provide reliable measures of year-to-year changes in lake chemistry. Continue annual sampling (once per year) of sensitive LAK022, which is only accessible by helicopter.

Recommendation 2 – Monitoring of less sensitive lakes: Continue annual sampling of the full chemistry of less sensitive LAK016, which has an intermediate level of sensitivity (Gran ANC of 70 to 90 µeq/l). Discontinue the annual sampling of LAK007 (Clearwater Lake), LAK024 (Lakelse Lake) and LAK034, as the EEM program has shown these lakes to be insensitive under both *current* and *maximum future* levels of sulphur emissions. Under the initial EEM design, the less sensitive lakes were added to the sampling program to serve as reference points against which the changes in the sensitive lakes (i.e., the lakes of concern) could be compared. However, these

[51] Climate projections are available for the Kitimat-Stikine region from the Pacific Climate Impacts Consortium (PCIC) here: https://www.pacificclimate.org/analysis-tools/plan2adapt

lakes were not appropriate as controls since they are subject to the same exposure as the sensitive lakes (i.e., located within the plume) but not expected to change in response to increased emissions. Within the first couple years of the EEM Program, we decided that it would be most beneficial to add some true control lakes that would add information that would be more directly valuable to the program than the less sensitive lakes – i.e., lakes of comparable sensitivity to the EEM sensitive lakes that are located outside of the smelter plume and thus able to provide information about regional patterns independent of smelter emissions. Three such control lakes were added in 2015 (with baseline data from 2013), which provide a superior reference point for the lake chemistry patterns observed in the EEM sensitive lakes, and therefore the EEM less sensitive lakes no longer serve an essential purpose within the program. The box below provides some additional technical context on the relative sensitivity of the less sensitive lakes, especially the three being recommended to discontinue.

How sensitive are the "less sensitive" lakes

- **LAK024** (Lakelse Lake) was added to the EEM due its public importance. Analyses show that it has a high critical load (CL) (370 meq/m^2/yr based on the STAR 2012 data; 552 meq/m2/yr based on 2012-2018 data) but would receive only 11.8 meq/m2/yr of sulphur deposition under a 42 tpd emission scenario (Table 2-3 in Aquatic Appendix H). Therefore, S deposition would need to increase 31x to 47x above the permitted emission level of 42 tpd before LAK024 would exceed its CL (ratio of CL to deposition level under 42 tpd).
- For **LAK007** (Clearwater Lake, chosen due to its ease of access), S deposition would need to increase 63 X above the permitted level before its CL would be exceeded.
- For **LAK034**, in the north of the study area with a projected S deposition of only 4.7 meq/m2/yr under emissions of 42 tpd, deposition would need to increase 27x to 29x above the permitted level before its CL would be exceeded.

None of these three lakes showed any evidence of S-driven acidification (Table 7-12). With such a huge safety margin between maximum potential deposition and CLs, and no evidence of S-driven acidification, there is no need to continue to monitor these lakes within the EEM Program.

By comparison, the CL safety margin for **LAK016** (recommended for continued inclusion in the next phase of the EEM) is 9x. Although this is considerably smaller than for the other three EEM less sensitive lakes described above; however, it still means that S deposition would need to be almost an order of magnitude greater than the deposition modeled under the maximum permitted emissions level in order to exceed its estimated critical load.

Recommendation 3 – Monitoring control lakes: Continue annual sampling of the full chemistry of the three control lakes (NC184, NC194, DCAS14A) to provide reliable measures of year-to-year changes in lake chemistry, an assessment of regional factors such as changing weather patterns, and critical data for statistical analyses of changes in sensitive lakes relative to control lakes. Include one year with multiple sampling visits of the three control lakes during October, so as to estimate the within-year variability in lake chemistry, and thereby improve statistical inferences (added to the 2019 October lake sampling).

Recommendation 4 – Re-evaluation of EEM lakes monitoring program: We recommend that the EEM lakes be re-evaluated in the 2021 Annual Report with respect to their inclusion in the EEM Program going forward. Some of the EEM lakes (which were all identified in the STAR as being potentially sensitive to increased acidic deposition) are now not predicted to acidify under updated modelling based on additional years of data. There are multiple lakes that are not predicted to exceed their critical loads, not predicted to decrease in pH below their 2012 baseline

values, and do not show any evidence in their empirical observations of lake chemistry of patterns that are consistent with smelter-driven acidification. However, the power analyses conducted in 2014-2015 recommended that the EEM Program should not make any strong conclusions about the changes in lake chemistry that have occurred until there have been at least five years of post-KMP data collected. Therefore, we are recommending collecting an additional three years of post-KMP data for all of the originally identified sensitive lakes, for a total of six years of post-KMP data, before making any conclusions about the need for the continued inclusion of each of the lakes.

Recommendation 5 – Additional lakes: We do not recommend adding any additional lakes to the EEM Program. We examined the critical loads and exceedances in the context of the updated CALPUFF deposition modeling for all the original STAR lakes, KAEEA lakes located within the study area, and additional lakes sampled early in the EEM Program. These analyses did not provide evidence that any of the lakes excluded from EEM Program should be re-considered for inclusion in the program.

Recommendation 6 – Intensively monitored lakes: Continue intensive sampling (Rio Tinto voluntary initiative) of LAK006 (End Lake) with the new Onset pH monitor – install the monitor for the ice-free period of the year, measure pH every half hour, with calibration visits every two weeks (including a chemistry sample analyzed for pH and ANC), and changes in the pH sensor every 3 months, so as to provide long term measures of variability in pH and ANC. Continue measurements of lake levels so as to assess pH changes associated with storm events. Discontinue continuous monitoring of LAK012 (Little End Lake) and LAK023 (West Lake), as these lakes have shown very similar patterns to End Lake, and provide no incremental value beyond the intensive monitoring of End Lake. Furthermore, West Lake has not shown any increase in lake SO_4^{2-} since the pre-KMP period. In both the intensively monitored lakes and the other EEM lakes, it is essential to allow sufficient time for pH measurements to stabilize (see Limnotek's recommendations in Section 7.1.3.2.7 of Appendix A).

Recommendation 7 – Intensively monitored streams: Thoroughly review the report prepared by Paul Weidman (once it is released) to determine potential next steps in stream monitoring. Discontinue the monitoring of Anderson Creek, which has not provided useful information to the EEM Program.

Recommendation 8 – Fish sampling: If additional fish sampling is required (i.e., additional sampling is triggered by specific conditions in the EEM design), then explore the use of eDNA sampling to estimate any changes in the presence of fish species, and avoid the potential population impacts of gill-net sampling.

Recommendation 9 – Other "non-EEM" sites sampled during EEM Program: In addition to the lakes sampled annually within the EEM Program, multiple other "non-EEM" lake and stream sites (i.e., outside the core program) were identified for exploratory water chemistry sampling in particular years over the course of the EEM Program. None of these sites were found to be sensitive to the predicted increases in acidic deposition and therefore none of them were recommended to be added to the EEM Program for further monitoring. See Aquatic Appendix A for more details.

7.4.2 Changes to the KPIs or informative indicators and thresholds

KPIs should fulfill the following criteria:

1. be responsive to changes in deposition;
2. provide an early warning of potential impacts to biota;
3. have scientifically defensible thresholds of change that can act as triggers for more intensive monitoring or mitigation;
4. are capable of being monitored, analyzed and modelled with an acceptable level of reliability; and
5. have an appropriate balance of Type I and Type II errors.

There are some strengths and weaknesses to the existing KPI that focuses on pH. We have used a pH of 6.0 as the threshold for determining critical loads. This threshold is well supported by existing literature on biological effects, as described in the STAR, and deposition scenarios can be evaluated against this threshold through well-established models. There is abundant literature showing how aquatic biota respond to pH levels, as reviewed in the STAR and EEM Plan. The existing KPI threshold of a 0.3 unit change in pH fulfills most of the above criteria well, but scores only a fair grade on criterion 4 due to the high levels of variability in pH on various time scales (year-to-year, seasonal, daily). This weakness was evident in the power analysis completed in 2016 and described in Section 7.3.2.2 – ΔpH had lower statistical power than ΔGran ANC. In addition, the logarithmic nature of pH means that the actual pH level needs to be considered jointly with the ΔpH (e.g., a change from pH 5.0 to 4.7 is biologically significant, whereas a change from pH 7.0 to 6.7 is not). ANC scores well on all of the five criteria for a KPI, and in particular does better than pH on criterion 4.

Recommendation 10 – ANC KPI: We recommend that ANC become the primary KPI for the EEM Program, with pH as an informative indicator, since ANC better fulfills the criteria for a KPI.

Recommendation 11 – Alternative ANC metrics: We recommend that further analyses be completed to determine which of three possible metrics should be utilized as the KPI for the EEM Program: Gran ANC, BCS or ANC_{OAA}. Each of these metrics have various advantages and disadvantages: Gran ANC has been used throughout the EEM Program to date, but is difficult to analyze in commercial labs; BCS has been used in the northeastern U.S. and is easily computed from data analyzed in commercial labs; ANC_{OAA} is used in Europe and is also easily computed from data analyzed in commercial labs. A criterion level to protect aquatic biota of 25 µeq/L would be consistent for both BCS (Baldigo et al. 2009) and ANC_{OAA} (Hesthagen et al. 2016), as described in the literature review of ANC (Aquatic Appendix B). These analyses can be conducted with existing data in support of the development of the next phase of the EEM Program. There will then be an additional year of data available (i.e., 2019) but that is not a critical pre-requisite.

Recommendation 12 – Two threshold KPI structure: We recommend that the KPI(s) include two components: a *level of protection* to prevent acidification of lakes that are currently not at risk of aquatic impacts (i.e., an absolute threshold); and a *change limit* which prevents further acidification (for lakes already below the level of protection due to natural organic acids or past acidic deposition) (i.e., a relative threshold). A *level of protection* of 25 µeq/L would be consistent for both BCS (Baldigo et al. 2009) and ANC_{OAA} (Hesthagen et al. 2016), as described in the literature review of ANC (Aquatic Appendix B). Re-analysis of the functional relationship between pH and Gran ANC, using all the EEM data, has determined that a pH of 6.0 corresponds to a Gran ANC of 31 µeq/L, which would form the *level of protection* for Gran ANC. The other component of

the threshold would be the allowable ΔANC, which was derived from the lab titrations for each lake – the Δ Gran ANC equivalent to a 0.3 unit change in pH. Determining lake-specific *change limits* (ΔANC) for alternative ANC metrics equivalent to those developed for Gran ANC will require further evaluation.

Recommendation 13 – Implementation of KPI: We recommend that KPI should be defined such that a lake must exceed ***both*** the *level of protection* and *change limit* in order to be considered as an exceedance of the indicator. This concept is summarized in Table 7-15, using potential values for each of the thresholds.

Table 7-15. Proposed structure for ANC and pH indicators.

	Indicators	
Water chemistry component	**ANC**	**pH**
Level of Protection *(i.e., absolute threshold)*	Decrease† below BCS or ANC_{oaa} of 25 ueq/L , or Gran ANC of 31 µeq/L	Decrease† below pH=6.0
Change Limit *(i.e., relative threshold)*	Decrease† of greater than lake-specific thresholds (from titration analyses)	Decrease† of > 0.3 pH units
KPI Exceedance	**BOTH** thresholds exceeded in more than two lakes of medium to high importance*	**BOTH** thresholds exceeded in more than two lakes of medium to high importance*

† To be considered as a contribution toward exceedance of the indicator, exceedance of either threshold must be causally related to the smelter (i.e., increase in SO_4^{2-} sufficient to explain ANC or pH decrease).
*Lake importance evaluated in Table 22 of Aquatic Appendix D of the 2014 SO_2 EEM Plan (ESSA et al. 2014a).

This two-threshold structure will provide protection of aquatic ecosystems (by using thresholds supported from the literature) while avoiding the following types of false positives:

- A lake demonstrates a decrease in the indicator that is greater than the *change limit* but remains sufficiently above the *level of protection* that a change of that magnitude is not a concern for aquatic biota (e.g., decreasing in pH from 7.1 to 6.7 or in BCS from 60 to 45 µeq/L).
- A lake is already below the *level of protection* but always has been (e.g., a naturally acidic lake that is not expected to change much).
- A lake just above the *level of protection* demonstrates a minor decrease that drops it below that level.

In practice this approach essentially means that: 1) lakes that are currently above the *level of protection* must be kept above that level, and 2) lakes that were historically below or close to the *level of protection* must be kept to small changes.

Recommendation 14 – Potential use of biological indicators (e.g., zooplankton): Continue to use indicators of biologically relevant water chemistry, which provides the best early warnings of changes in lake chemistry that could be damaging to aquatic biota *in advance* of potential damage to aquatic biota and is therefore a *proactive* indicator. Do not use indicators of biological change which provide an indication that damage to aquatic ecosystems *has already occurred* and is therefore a *reactive* indicator. Biologically relevant water chemistry provides the best early warnings of changes in lake chemistry that could be damaging to aquatic biota, *in advance* of potential damage to aquatic biota, and is therefore a *proactive* indicator. Biological change provides an indication that damage to aquatic ecosystems *has already occurred* and is therefore a *reactive* indicator. Changes in ANC and pH are detectable prior to changes in lake biota such as zooplankton or benthic species richness, or fish densities. Early detection of biological change requires extensive knowledge of the relative sensitivity of different species to pH change (e.g., Marmorek and Korman 1993), information which is not available for the lakes in the Kitimat Valley and would be very difficult to acquire. Without such detailed information on each species' sensitivity to acidification, one must rely on such measures as total species richness, which only declines with major changes in lake pH, due to species replacements at the early stages of the acidification process (Marmorek and Korman 1993). Changes in sulphate, Gran ANC and pH are the most reliable early warning indicators of changes that could cause an impact on aquatic biota.

7.4.3 Critical loads and exceedances modelling

Recommendation 15 – Critical loads modelling: The critical loads modelling does not need to be done again in the future, except in a case where a lake has shown strong evidence of acidification (not the case for any of the EEM lakes). The critical load of a particular lake is an inherent property of the lake based on the geochemical characteristics of its watershed and is not expected to change over time. With seven years of water chemistry data, we now have greatly improved estimates of the critical loads of the EEM lakes. We have also greatly improved upon the modelling of critical loads that was done in the STAR by conducting extensive sensitivity analyses.

Recommendation 16 – Prediction of critical load exceedances: The prediction of exceedances does not need to be updated again in the future unless actual or predicted cumulative emissions from all sources are in excess of 42 tpd SO_2 or if the emissions modelling framework is significantly modified. Predicted exceedances of the estimated critical loads was based on deposition under the *maximum* future emissions allowable under the permit (i.e., 42 tpd SO_2), whereas actual future emissions are anticipated and/or planned to remain well under that ceiling (e.g., 35 tpd SO_2).

Recommendation 17 – Critical loads and/or exceedances as indicators: As described in the previous two recommendations, the critical loads of the EEM lakes do not need to be modelled again in the future and there is no need to estimate exceedances again until there are significant changes in emissions of sulphur or N in the Kitimat Valley beyond the currently permitted level. For these reasons, neither critical loads nor predicted exceedances would be appropriate metrics upon which to build an indicator for the EEM Program. These two metrics will not be responsive to potential changes in deposition due to smelter operations over the next phase of monitoring and therefore do not satisfy a critical criterion for a good indicator (see list of five criteria for indicators at start of Section 7.4.2).

7.4.4 Analyses and annual reporting

Recommendation 18 – Statistical methods for detection of change in water chemistry: The statistical methods provided in Aquatic Appendix F provide a sound basis for evaluating future changes in water chemistry in the seven sensitive lakes, less sensitive lake LAK016, and the three control lakes, as well as examining changes on a finer scale in the intensively monitored LAK006 (End Lake). These statistical methods will be re-run on an annual basis to assess status and detect any anomalous patterns.

Recommendation 19 – Annual Report: We recommend that the Annual Report be significantly streamlined where possible. The Annual Report should focus on reporting the new data from the monitoring program and updating critical analyses. The Annual Report should not attempt to make interpretations or inferences with respect to year-to-year changes in water chemistry, but should update statistical evaluations of long term changes between pre-KMP and post-KMP periods (see Recommendation 17). However, the scope of the future annual reports will be determined as part of the discussion and development of the next phase of the EEM Program.

7.4.5 Additional Topics

Effects of acidic deposition on wetlands. This is discussed in Section 6 on terrestrial ecosystems.

Potential inclusion of inorganic monomeric Al**.** Inorganic monomeric aluminium has been added to the lake sampling program for 2019 and could be included going forward. Additional years of data (beyond only 2013) would provide better understanding of patterns and relationships with other water chemistry properties. However, it can be very difficult to find commercial laboratories that can measure inorganic monomeric Al. The lakes of concern (e.g., LAK028) are already flagged by other analyses and accurately identified by values of BCS < 0. Therefore, we propose continuing to calculate BCS and use it as an indicator of Al toxicity concerns.

Hypolimnion of LAK028. SO_4^{2-} concentrations in LAK028 may be affected by episodic mixing of hypolimnetic waters (i.e., hypolimnetic SO_4^{2-} that is converted to hydrogen sulfide by sulphate-reducing bacteria, and could be re-oxidized back to SO_4^{2-} as it rises through shallower waters). Sulphate-reducing bacteria have been identified in the deeper waters of LAK028 below the thermocline. A temperature mooring placed in LAK028 in 2019 will help to describe the mixing characteristics in LAK028 that may help in either ruling out a contribution of hypolimnetic sulphur to surface chemistry or show that it is occasionally a confounding factor.

8 Holistic Understanding of KMP Effects on the Environment and Human Health across all Lines of Evidence

The SO_2 EEM Program was designed to monitor effects of the modernized smelter along the lines of evidence assessed in the STAR. Results of the SO_2 EEM Program for 2013 to 2018 along these lines of evidence are discussed in Sections 3, 4, 5, 6 and 7. In this holistic section, we describe what we have learned about the links between SO_2, human health and ecosystems when we examine results from the SO_2 EEM Program *across* those lines of evidence.

It is helpful to understand the linkages between the lines of evidence, as this informed how we approached the holistic analysis. One of the linkages is through shared exposure pathways among some receptors. Human health and vegetation share the atmospheric SO_2 exposure pathway, and vegetation, terrestrial ecosystems and aquatic ecosystems share the atmospheric S deposition exposure pathway. There are also ecological linkages among vegetation, terrestrial ecosystems and aquatic ecosystems; and both terrestrial and aquatic ecosystems use critical loads as an indicator. This is illustrated in Figure 8-1 which shows the SPR conceptual model first presented in Section 1, with symbols added to show where SO_2 EEM monitoring and modelling fits in. Another linkage is co-location. Some of the pathway and receptor monitoring occurs in the same geographic locations, or very near to each other. This is illustrated in Figure 8-2 which shows a map of all SO_2 EEM monitoring sites in the Kitimat Valley. Some of these linkages also result in the informational linkages among the pathways and receptors shown in the looking-outward matrix in Table 8-1.

This synthesis examines evidence through several lenses: (1) KPI results compared to thresholds for all receptors, (2) results for receptors sharing the SO_2 exposure pathway, (3) results for receptors sharing the S deposition exposure pathway, (4) knowledge we have gained over the past six years about pathways and effects in the SPR model, and (5) the ability of KPIs and informative indicators to detect trends towards unacceptable impacts. This section concludes with a summary of what we have learned from the first six years of the SO_2 EEM Program about the links between SO_2, human health and ecosystems, and what the results mean overall for the health of the valley.

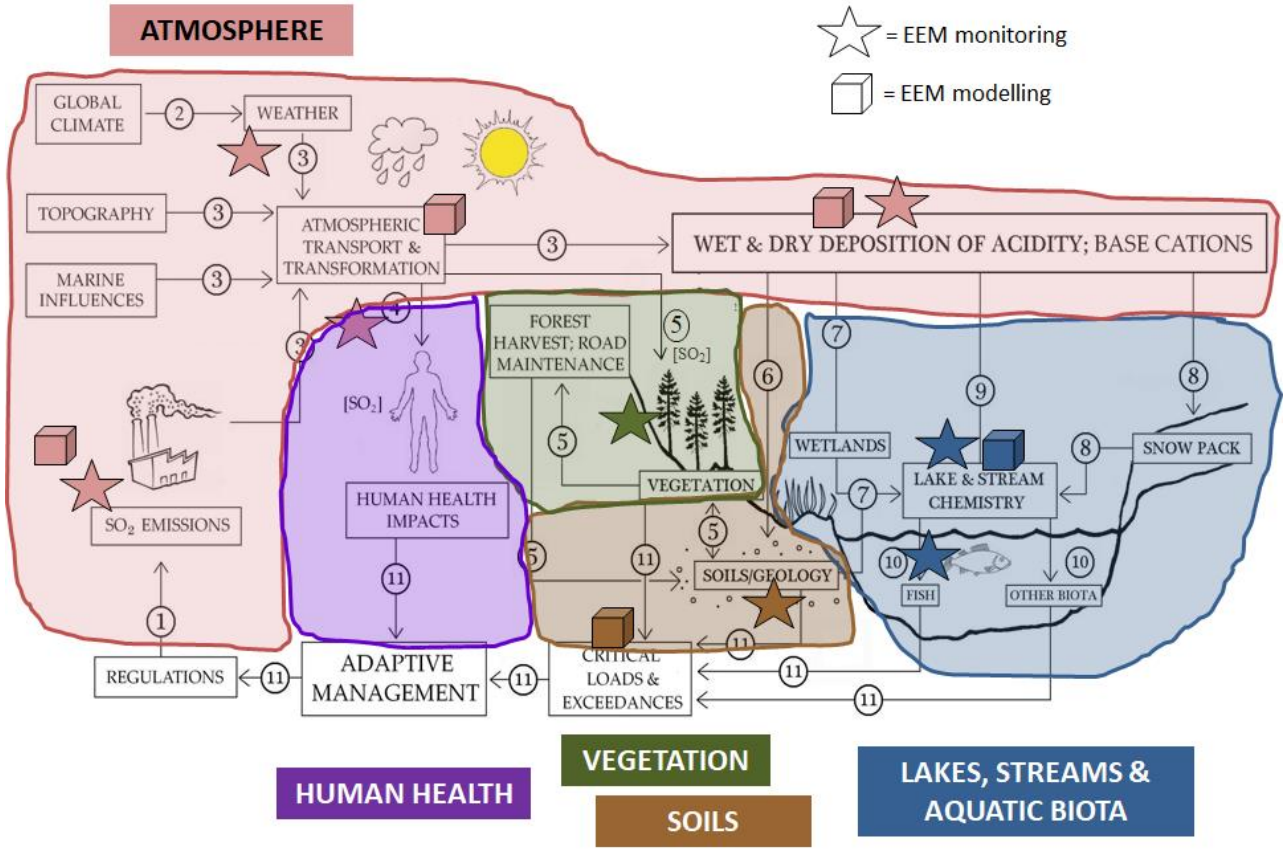


Figure 8-1. SO_2 Source-Pathway-Receptor (SPR) conceptual model for the SO_2 EEM Program, showing where SO_2 EEM monitoring and modelling occurs.

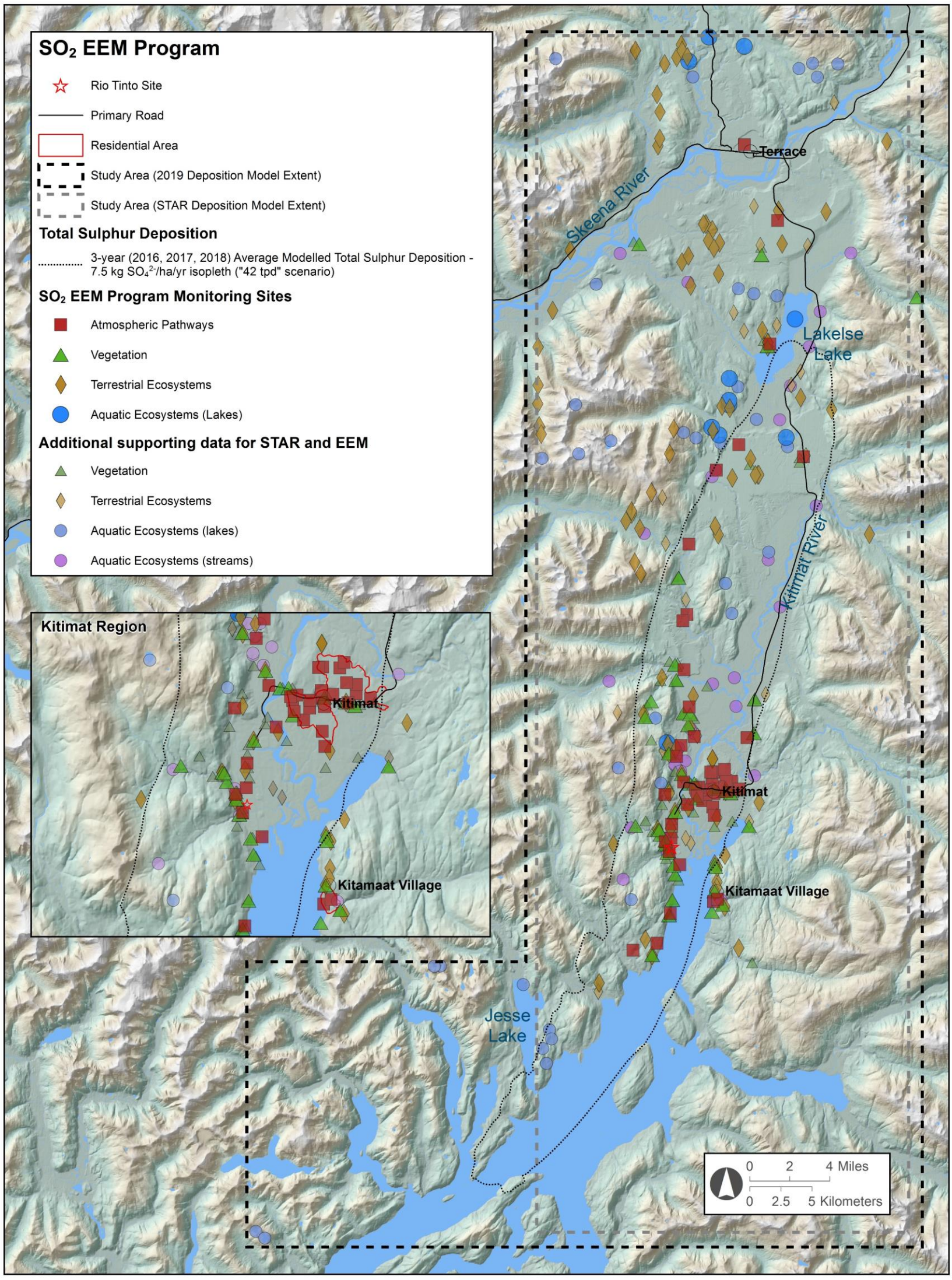


Figure 8-2. Map of monitoring locations across all lines of evidence. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleth.

Table 8-1. Looking Outward Matrix showing information linkages among SO_2 EEM pathways and receptors. Each cell describes information that is provided *from* the line of evidence for that row *to* the line of evidence for that column.

To → **From ↓**	Atmosphere	Human Health	Vegetation	Terrestrial Ecosystems (Soils)	Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)
Atmosphere		SO_2 concentrations vs. the KPI threshold	SO_2 concentrations and SO_4^{2-} deposition versus vegetation thresholds, including passive monitoring sites	Deposition vs CL, and versus soil base saturation	Deposition vs CL, and versus acidic episodes Use SO_4^{2-} deposition predictions for 2016-18 to estimate lake $[SO_4^{2-}]$, under varying assumptions of runoff
Human Health	NA		NA	NA	NA
Vegetation	SO_2 concentrations in needles versus observed / predicted SO_2 concentrations in air	NA		Observations of acidification effects on vegetation	Observations of vegetation effects in a given watershed
Terrestrial Ecosystems (Soils)	NA	NA	Soil CL exceedance versus vegetation observations		Soil CL exceedance versus lake CL exceedance; compare soil weathering rates with SSWC estimates
Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)	NA	Water quality in Kitimat River near water treatment plant	Locations where there is some evidence of lake acidification	BC weathering rate from [BC] and runoff versus soil estimates	

8.1 Synthesis Lens 1: KPI Results Compared to Thresholds – Early Warning of Adverse Effects

All receptors in the SO_2 EEM program have KPIs, and KPI thresholds that provide early warning of harm. The KPI for human health is based on the CAAQS which are based on the response of the most susceptible population. The KPI for vegetation is based on ambient SO_2 exposures that are known to cause visible injury to plant species, and inspections that document and assess plant health and provide early warning of impacts on vegetation. One of the two KPIs for terrestrial ecosystems is a precautionary and early-warning prediction-based indicator, with a second observation-based indicator for further precaution. The KPI for aquatic ecosystems is based on water chemistry which is a broad indicator of aquatic ecosystem health. Using biologically-relevant water chemistry as a KPI provides earlier warning of aquatic ecosystem effects than using biota as a KPI.

Thus far in the SO_2 EEM Program, none of the KPI thresholds have been reached for any of the receptors. Table 8-2 summarizes the KPIs, their thresholds, and results from 2012 to 2018.

Table 8-2. Summary of KPIs, thresholds and performance 2012-2018.

	KPI	Threshold for **increased monitoring**	Threshold for **receptor-based mitigation**	Threshold for **facility-based mitigation**	Summary of Results
Human Health	B.C. Air Quality Objective measured at residential air monitoring stations	NA – there is no threshold for increased monitoring for this KPI	NA – there is no threshold for receptor-based mitigation for this KPI	3-yr average of 97th percentile of the D1HM for 2015-2017; 97.5th percentile for 2016-18; 98th percentile for 2017-2019. There is an allowance of a one-time exceedance of the 75 ppb threshold to a maximum concentration of 85 ppb over 2017-2019.	The KPI threshold was not exceeded
Vegetation	Visible vegetation injury caused by SO_2	More than occasional symptoms of SO_2 injury outside of Rio Tinto Alcan Kitimat properties, causally related to KMP	NA – there are no reasonable receptor-based mitigations	Severe & repeated symptoms of SO_2 injury outside Rio Tinto properties causally related to KMP, including species of economic or social/ traditional importance, or symptoms of SO_2 injury causally related to KMP at long-distance (>15km) monitoring locations	Neither of the two thresholds were exceeded
Terrestrial Ecosystems (Soils)	Atmospheric S deposition and critical load exceedance risk	S deposition causally related to KMP emissions exceeding CL in > 1% (~20 km^2) of semi-natural upland forest soils in the study area	S deposition causally related to KMP exceeding CL in >5% (~100 km^2) of semi-natural upland forest soils in the study area within 200 yrs	S deposition causally related to KMP emissions exceeding CL in >5% (~100 km^2) of semi-natural upland forest soils in the study area within 100 years (based on projected change in base cations)	None of the thresholds were exceeded

	KPI	Threshold for **increased monitoring**	Threshold for **receptor-based mitigation**	Threshold for **facility-based mitigation**	Summary of Results
	Long term soil acidification attributable to S deposition	For one plot: a 40% decrease in 5 yrs or a 20% decrease in 10 yrs in exchangeable cation pools for at least one element, and decrease is causally related to KMP emissions	For one or more plots: a 40% decrease in 5 yrs or a 20% decrease in 10 yrs in exchangeable cation pools for at least 1 element and in >1% (~20 km^2) of the area of semi-natural upland forest soils	Decrease in the magnitude of exchangeable cation pool of >20% in 10 years, and in > 5% (~100 km^2) of the area of semi-natural upland forest soils, based on modelling, and decrease is causally related to KMP	None of the thresholds were exceeded
Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)	Water chemistry - acidification	Observed decrease in pH ≥0.30 pH units below mean baseline pH level measured pre-KMP in one or more of the 7 acid-sensitive lakes, and other evidence	More intensive sampling confirms a decrease causally related to KMP of> 0.30 pH units below mean baseline pH level pre-KMP and liming is feasible	More than 2 lakes rated Medium or High (based on relative lake rating; Appendix D of the 2012-2018 SO_2 EEM Plan) with decrease causally related to KMP of > 0.30 pH units below measured baseline pre-KMP (prior to liming)	None of the thresholds were exceeded

Why have no KPI thresholds been reached?

The KPIs in the SO_2 EEM Program were chosen to provide early warning of potential impacts on the receptors. The KPI thresholds were also set at levels that the receptors can tolerate, so that if needed, action could be taken to avoid impacts. Air concentrations of SO_2 at residential monitoring stations are well below the B.C. IAQO. The concentrations are also below the CAAQS which will become the B.C. Air Quality Objectives starting in 2020. Air concentrations of SO_2 in the valley are well below concentrations that would cause visible injury to vegetation. The only areas of predicted exceedance of soil critical loads under the 42 tpd scenario were close to the smelter, and less than 1% of semi-natural upland forest soils in the study area. There was no statistical decrease in soil chemistry between 2015 and 2018 in the top 0–30 cm of mineral soil, and the only soil variable that consistently showed a statistical decrease at lower cumulative depths was exchangeable acidity, suggesting that there was a decrease in acidity between 2015 and 2018, despite the increase in acidic deposition. Even after adjusting for the fact that deposition of SO_4^{2-} has been less than predicted in the STAR, most lakes (12 out of 14) have shown a smaller increase in SO_4^{2-} than expected (after adjusting for the fact that emissions have been lower than the modelled 42 tpd), and all sensitive lakes have shown a smaller change in pH and ANC than expected. These results reflect the conservative assumptions built into both atmospheric and aquatic models, which tend to over-predict effects of the smelter.

Atmospheric dispersion of emissions led to actual SO_2 air concentrations and S deposition that were different from what was predicted in the STAR. We took a conservative approach to the CALPUFF modelling in the STAR by making assumptions that would over-predict SO_2 concentration and S deposition. We therefore expected that actual SO_2 concentrations and S deposition would be lower than modelled. Indeed, the STAR predictions were generally conservative, particularly in residential areas. Actual measured SO_2 concentrations were substantially lower than model predictions of post-KMP SO_2 concentrations from the STAR at most locations and were near model predictions at Haul Road.

Even though smelter emissions have not reached the 42 tpd maximum allowed under the permit, we based predictive modeling of critical loads for soils and lakes on the permit limit of 42 tpd. Observational KPIs were calculated using actual emissions.

8.2 Synthesis Lens 2: Results for Receptors along the SO_2 Concentration Exposure Pathway

Both plants and humans have metabolic pathways that require sulphur because it is an essential element necessary for certain amino acids (Laurence 2012; Nimni et al. 2007). Plants can use sulphur that is taken up through soil or air, while humans use sulphur taken up through ingestion.

Both humans and plants are also affected by the concentration of SO_2 in the air. Some humans and plants are more sensitive to concentration of SO_2 in the air, and some are less sensitive. A great majority of plants and a great majority of humans do not respond to SO_2 until exposed to concentrations at a much higher level than the levels occurring in and around Kitimat.

For plants and lichens, there are specific species that are known to be more sensitive to SO_2 such as cyanolichens; however, given the SO_2 concentrations monitored, cyanolichens would respond to changes in deposition rather than air concentrations and would not provide effective early (within a single growing season) warning. Plants in the genus *Rubus*, such as salmonberry and thimbleberry, may be among the more sensitive higher plants, and would respond more quickly and in a more identifiable manner (e.g. visible injury to leaves) than lichens if SO_2 concentrations reached a threshold. Visible symptoms of SO_2 injury have not been observed on either salmonberry or thimbleberry. For humans, specific properties of the upper airways of asthmatics cause this population to have a much higher level of sensitivity to short-term peaks of SO_2 concentration. For these reasons, the design of the 2014 SO_2 EEM Plan and the KPIs for vegetation and human health have focused on thresholds or phenomena *acutely* affecting the most sensitive species or sub-populations.

SO_2 thresholds set for the most sensitive populations of humans and plants are in a similar range. Acute effects of SO_2 on plants may occur at 500 ppb in three hours and causes leaf damage but is not typically fatal to plants. There are also one-hour thresholds that are higher, reaching 1,000

ppb or more. Effects of acute exposure of SO_2 on humans have been observed in asthmatic humans at levels of 200 to 400 ppb. The CAAQS is set at 70 ppb to protect the most susceptible asthmatics.

The KPI for neither vegetation nor human health were exceeded. Air concentrations of SO_2 are well below the B.C. Air Quality Objective at residential monitoring stations, and well below concentrations that would cause visible injury to vegetation.

What do these results tell us?

Two of the four SO_2 EEM receptors – people and plants – respond directly to atmospheric SO_2 concentrations. To date, monitored and modelled SO_2 concentrations have not exceeded the levels established as protective and accepted by regulatory agencies. The concentrations are low enough with respect to the known sensitivity of plants that we can refocus our program to monitor long-term, more subtle effects thus integrating vegetation more strongly with terrestrial ecosystems.

8.3 Synthesis Lens 3: Results for Receptors along the S Deposition Exposure Pathway

The soils and aquatic analyses have used observational data: long term soil plots and long-term monitoring of lake chemistry. Neither of these two data sets have shown evidence of sulphur-induced acidification that exceeds the protective thresholds established in the EEM Plan, with the exception of one small lake (LAK028) near the smelter that has low support for a decline below the pH threshold and no support for a decline beyond its ANC threshold.

The map of soil critical loads (left panel in Figure 8-3) shows exceedance near the smelter and one grid cell very close to LAK028. Deposition at LAK028 was close to exceeding its aquatic critical load (0 to -10 meq/m^2/yr).

Average weathering rates estimated for soils (78 meq/m^2/yr) are less than average weathering rates estimated for all the STAR lakes (352.8 meq/m^2/yr). This is to be expected because the soils analysis only computes weathering rates for the top soil layers, whereas the lake analysis considers all the parts of the watershed contributing base cations to the lake.

Weathering rates from the soil analysis are generally homogenous in the area to the SW of Lakelse Lake, and lakes in this zone also show a similar level of non-exceedance (right panel in Figure 8-3). In the north central part of the study area, there are three very small lakes with divergent CL levels (top of right panel in Figure 8-3), whereas the soils analysis shows similar weathering rates; this reflects the small scale heterogeneity in watershed soil and hydrologic attributes that can influence lake chemistry. In the northwestern part of the study area, there is an area with relatively low soil CLs. The only sampled lake in this area (LAK041) had a CL in the STAR of 54 meq/m^2/yr, but no exceedance in either the STAR or CL, as CALPUFF deposition was 5 meq/m^2/yr in the STAR, and 1.2 meq/m^2/yr in this report (with a background deposition of 7.5 meq/m^2/yr).

We compared the soil weathering rates by watershed with weathering rates for each of these watersheds computed in the aquatic analysis (estimated from the SSWC model for each of the

STAR lakes, plus additional lakes within the study area that were sampled in the Kitimat Airshed Assessment). As expected from the average weathering rates noted above, the weathering rates from the SSWC model were consistently higher than the soil weathering rates (in 42 of the 51 watersheds analyzed), and there was no consistent relationship between these two metrics. This is not surprising given that the soil weathering rates are estimated at a coarse grid scale (0.5 km x 0.5 km = 0.25 km^2), whereas the weathering rates from the SSWC model are based on the water chemistry of lakes which often have very small watershed areas (32 of the 51 watersheds are less than 1 km^2 in area). Though the soil mapping cannot capture the fine-scale heterogeneity that appears in the lake chemistry, the two measures together provide complimentary and valuable lines of evidence.

Wetlands are least well-known due to a lack of information on sensitivity as well as distribution of wetlands. (We considered using data from the KAEEA, but that landcover map did not cover the full study area.) Only 5 of the 51 lakes have more than 0.5% of their catchments characterized as wetland land classes from landcover data. This implies that effects of wetlands on lake chemistry are likely to be minor.

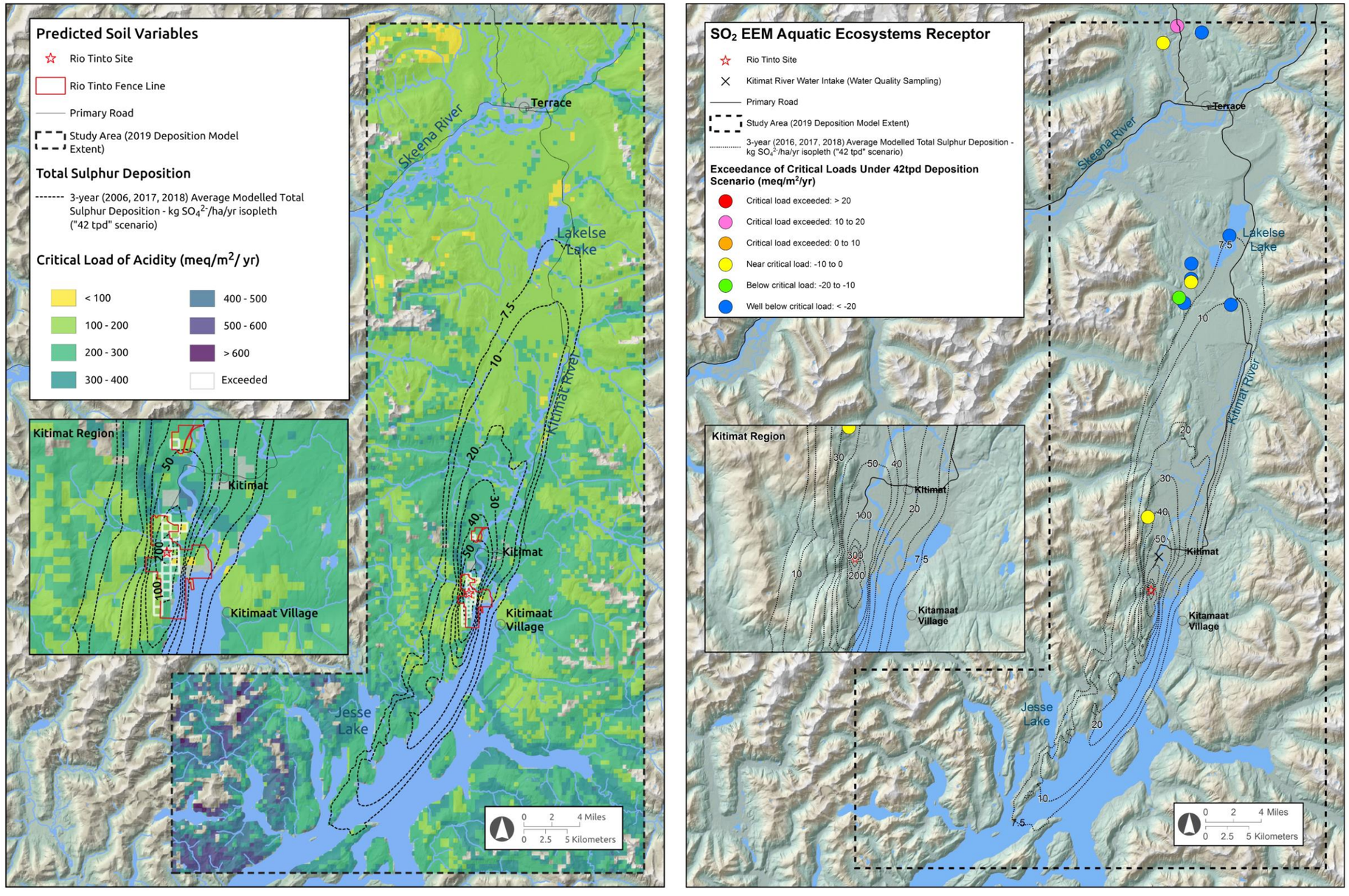


Figure 8-3. Maps showing areas of predicted critical loads and predicted critical load exceedances in soils (left) and predicted critical load exceedances in aquatic ecosystems (right), both under the 42 tpd scenario. Background deposition of 3.6 kg SO_4^{2-}/ha/yr is not included in the isopleths.

Do vegetation results appear to relate to soil and aquatic critical load results?

We did not observe signs or symptoms related to plant health, including symptoms of SO_2 exposure or soil acidification associated with the predicted areas of exceedance (under the 42 tpd scenario) of soil or aquatic critical loads. Eleven sampling and/or inspection sites are located in or near the area of predicted soil critical load exceedance and provide coverage to detect effects of acidification, had any been apparent. No symptoms were observed from a recent aerial survey of the predicted area of soil critical load exceedance. In the case of the aquatic line of evidence, no vegetation sampling and/or inspection sites are located adjacent to EEM lakes. An aerial survey conducted as part of the vegetation program included flying over some of the EEM lakes and we did not observe anything out of the ordinary.

While the areas of predicted soil critical load exceedance have been exposed to considerable deposition in the past, it is possible that it will take some time for soil critical loads to manifest with regard to vegetation in the areas of predicted exceedance. If and when it does, it will most likely be through changes in plant communities or a decline in the health of acid-sensitive species.

What do these results tell us?

The exceedance of the soil critical loads very close to LAK028 shows a consistency between the soil and aquatic critical load analyses in that part of the study area. This contrasts with the very northern part of the study area where there is a lot of variability in the aquatic critical load results for three lakes, whereas there is strong consistency in the soil critical load results (all mapped as having critical loads in the range of 100-200 meq/m^2). This is probably because there is fine-scale variability in the geology, soils and hydrology which is not reflected in the coarser-scale interpolations from geology and soils data.

8.4 Synthesis Lens 4: What We have Learned under the SPR Conceptual Model

What have we learned about the SPR conceptual model, and what new questions have arisen?

Table 8-3 summarizes what we have learned, uncertainties we have reduced in our understanding of the SPR model for SO_2 effects in the Kitimat Valley, and remaining knowledge gaps to include in the SO_2 EEM Program going forward. Table 8-3 demonstrates linkages across the different components of the EEM Program, from emissions through atmospheric SO_2 concentrations and deposition, to responses of the human health, vegetation, soils and aquatic receptors.

Table 8-3. Summary of what we have learned under the SPR conceptual model, and remaining knowledge gaps.

Link #	Link Name	What We Have Learned Since 2013	Remaining Knowledge Gaps
1	Regulation of SO_2 emissions	• Emissions have increased by 135% between the 2012-2015 period (12.5 tpd) to the 2016-2018 period (29.4 tpd) although they are still well below the maximum permitted level of 42 tpd. • Emissions may be over-estimated, since it is assumed that all S in raw materials is emitted.	• None
2	Global Climate	• Projected trends in climate for the region include wetter, warmer winters and drier, warmer summers which could be either drier or wetter[52]. • Drought in 2018 (approximately a 30% decrease in precipitation) affected both patterns of deposition (more dry deposition, less wet deposition), water chemistry (increased pH in many lakes), and vegetation health (leaves aged and dropped prematurely in dry areas). • We need more years of monitoring to determine the longer-term effects of the 2018 drought on lake chemistry.	• We don't know the interactive effects of climate change and SO_2 emissions on vegetation or lake ecology • If runoff and temperature changes, then soil weathering rates could change • Changes in snowpack could make roots more vulnerable to freezing
3	Atmospheric transport and transformation/ sea salt episodes and acidic deposition	• Due to a large amount of dispersion of emissions, only a small fraction of the emitted SO_2 (~8.1%, see Section 3.2) is deposited within the study area, a similar result to what was found in the STAR. • Deposition patterns are sensitive to variations in weather, with lower levels of deposition in dry years such as 2018 (Section 3.1)	• Understanding east-west extent and position of the plume (e.g., location of 7.5 kg SO_4^{2-}/ha/yr isopleth) to north and the extent and position of the plume to the south
4	Human Health impacts	• The highest SO_2 concentrations are well below the health KPI. • Average annual SO_2 concentrations during 2016-2018 were very low (<1 ppb in all three monitoring areas), and compare well with other communities.	• No knowledge gaps need to be included in the SO_2 EEM Plan moving forward
5	Vegetation impacts/forest interactions	• Direct effects of SO_2 on vegetation, including visible injury, have not been observed despite surveys, and under emissions of 42 tpd, are only expected rarely in a few locations. • Work during the 1970s and 1980s, as well as recent surveys by ENV, show a similar area of reduced lichen species richness that corresponds to the plume path for at least the last 50 years. • S concentrations in hemlock does not correlate well with modelled SO_2 emissions or concentrations, or S deposition.	• Deposition modelling and new science tells us that we have areas where there are likely effects on sensitive lichen species. Impacts on lichens have been documented since the 1970s and were likely the result of exposure to both SO_2 and HF. HF

[52] Projections are available for the Kitimat-Stikine region from the Pacific Climate Impacts Consortium (PCIC) at: https://www.pacificclimate.org/analysis-tools/plan2adapt.

Link #	Link Name	What We Have Learned Since 2013	Remaining Knowledge Gaps
		• Under current emissions (~29.4 tpd) and potential emissions (42 tpd), only 0.36% and 0.58% (respectively) of the valley's forest soils are projected to receive deposition at levels that could indirectly affect vegetation through changes to soils. • Soil acidification has not been observed in long term monitoring plots.	emissions have dropped substantially. Will improvement in lichens be observed in the future? • No vegetation observations exactly in the area of soil CL exceedance off of the Rio Tinto property • Developing vegetation informational indicators to support the terrestrial ecosystem line of evidence
6	Watershed acid neutralization/ geology	• Virtually all of the area's forest soils have a very high ability to neutralize acidic deposition and would not be affected under an emissions scenario of 42 tpd. • In general, the region's soils and lakes are not sensitive to acidic deposition, based on high neutralizing capacity of the regions' soils, and the weathering of minerals.	• Understanding sensitivity of wetlands to acidification • Understanding Al solubility in upland soils
7	Wetlands and organic acids	• Many of the lakes in the Kitimat Valley are brown water lakes with organic acids, and have been naturally acidified (STAR, Figure 9.4-9). • Organic acids have been considered in the analyses of changes in water chemistry. • Over 2012-2018, there have been only minor changes in the concentrations of DOC (Aquatic Appendix E), which appear to be insufficient to markedly shift the ANC or pH of lakes. • Only 5 of the 51 sampled lakes have more than 0.5% of their watershed area as wetlands, so changes to wetlands from acidic deposition are unlikely to affect lake chemistry.	• Statistical analyses of changes over time in DOC and organic anion concentrations
8	Acidic episodes, snowmelt and fall rains	• The SO_2 EEM program has focused on lakes, which have more stable water chemistry than streams. • Lake pH levels tend to decrease after heavy storm events, but these changes are not statistically significant (Section 7.6.4.3.6 of Aquatic Appendix F on Statistical Analysis of Water Chemistry)	• Awaiting report from Paul Weidman
9	Lake and stream chemistry	• Of the 14 lakes in the SO_2 EEM program (7 acid-sensitive lakes, 4 less sensitive lakes, 3 control lakes), 12 lakes show no evidence of sulphur-induced acidification causally related to the Kitimat smelter. LAK028, a 1 ha fishless lake	• Need more years of data to obtain higher statistical power • Need better understanding of within-

Link #	Link Name	What We Have Learned Since 2013	Remaining Knowledge Gaps
		close to the Kitimat smelter, shows some evidence of sulphur-induced acidification causally related to the smelter. LAK012 (Little End Lake), a 2.3 ha lake to the SW of Lakelse Lake, has shown increased concentrations of sulphate, but no consistent evidence of sulphur-induced acidification causally related to the smelter. • Going forward, only LAK028 is expected to show declines in pH greater than 0.1 pH units (0.2).	year variability of control lakes' chemistry
10	Acidification effects on biota	• Modelling of critical loads has used pH 6.0 to ensure protection of the region's lakes. • Water chemistry monitoring indicates that the conditions for aquatic biota have not changed since 2012. • Fish sampling revealed a total of six species across 6 lakes (sensitive lakes LAK006, 012 and 023; less sensitive lakes LAK007, 016, 034). No fish were caught in LAK042 (which has no inlets or outlets) or in LAK028 (which has no inlet and a blocked outlet). • Since no lakes have shown evidence of declines in pH and ANC below the thresholds, there has been no need to resample fish in these lakes.	• None at this time
11	Adaptive management/ critical loads	• The SO_2 EEM Plan provides for adaptive changes to emissions if required. • As none of the KPI thresholds have been exceeded, no adaptive changes to emissions are required at this time.	• None at this time

8.5 Synthesis Lens 5: How the EEM Program Will Detect Trends Towards Unacceptable Impacts

The EEM Program has been designed both to detect the exceedance of KPI thresholds, as well as trends towards unacceptable impacts, as described in Table 8-4.

Table 8-4. Ability of KPIs and informative indicators to detect trends towards unacceptable impacts.

	KPI	Ability to Detect Trends Towards Unacceptable Impacts
Human Health	B.C. Air Quality Objective measured at residential air monitoring stations	Hourly air quality monitoring of SO_2 at three residential sites provides the inputs used to calculate the KPI. Short term declines in air quality lead to advisories based on the Air Quality Health Index. Trends in both the inputs to the KPI, as well as trends in the KPI itself provide an early warning of trajectories towards unacceptable impacts. Since rare meteorological events can have a strong impact on the KPI, it is important to determine if observed trajectories in the KPI are driven primarily by trends in emissions or by rare meteorological events. Going forward, the health KPI will shift toward alignment with the CAAQS for SO_2.
Vegetation	Visible vegetation injury caused by SO_2	Future KPI and informative indicators are under development. Triennial monitoring of plant biodiversity along deposition gradients in areas potentially susceptible to changes in soil chemistry or critical load could provide a long-term trend in vegetation response (Section 5.4). Any future KPI and associated thresholds will be determined through collaborative work by Rio Tinto, ENV and QPs in 2020 and 2021.
Terrestrial Ecosystems (Soils)	Atmospheric S deposition and critical load exceedance risk	Modelling of the exceedance of terrestrial critical loads of acidity has indicated areas where there is a risk to plant health, which together with the KPI for long term soil acidification (described below) provide an early warning of trajectories towards unacceptable impacts in soils. In addition, exceedance of critical loads has helped to define sensitive areas for monitoring of plant biodiversity (described above). Critical loads and exceedances may be re-estimated if new data become available or there are significant increases in S or N deposition beyond the scenarios that have been modelled (Section 6.4).
	Long term soil acidification attributable to S deposition	The objective of the three long-term soil plots is to monitor changes in soil chemistry (exchangeable base cations) attributable to S deposition over time, through repeated sampling and analysis (every five years). The monitoring plots provide a framework for replicate random sampling of soils, allowing for the statistical assessment of changes between sampling campaigns, which can provide an indication of trajectories towards unacceptable impacts at these sites. Monitoring at the soil plots can detect a change of 40% in exchangeable cations over a 5-year period with high statistical power (Section 6.4). Smaller changes in exchangeable cations may be observed, but will have lower statistical power for drawing conclusions

	KPI	Ability to Detect Trends Towards Unacceptable Impacts
Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)	Water chemistry - acidification	Lake chemistry has been sampled annually for eight years, gradually increasing the sampling intensity. The future EEM program will continue annual sampling in seven sensitive lakes, one less sensitive lake, and three control lakes, as well as intensive monitoring of pH in one sensitive lake (End Lake). The rigorous statistical methods described in Aquatic Appendix F provide the means of detecting trajectories in SO_4, ANC and pH, and will be applied annually. Trends in the percent belief of KPI exceedance and trends in pH in End Lake can provide an indication of possible trajectories towards unacceptable impacts, though the EEM Program has been designed to detect exceedances of the EEM thresholds, not smaller changes. Going forward, ANC will be the KPI, and pH will be an informative indicator (Section 7.4). Power analyses showed that ANC is less variable than pH, and therefore provides for earlier detection of biologically significant thresholds with higher statistical power.

8.6 Holistic Summary

What have we learned about the links between SO_2, human health and ecosystems?

Humans and plants are both affected by the concentration of SO_2 in the air, and they both have populations that are more sensitive to SO_2 and populations that are less sensitive to SO_2. In plants this includes variation in sensitivity both within and between species. Thresholds for SO_2 in the air are set for the most sensitive populations of humans and plants are in a similar range. Acute effects of SO_2 on plants occurs at 500 ppb in three hours and causes leaf damage but are not typically fatal to plants. Effects of acute exposure of SO_2 on humans have been observed in asthmatic humans at levels of 200 to 400 ppb. To date, monitored and modelled SO_2 concentrations have not exceeded the levels for either humans or direct effects on plants established as protective and accepted by regulatory agencies.

The soils and aquatic analyses both used observational data: long-term soil plots and long-term monitoring of lake chemistry. These data have shown no evidence of sulphur-induced acidification that exceeds the protective thresholds established in the EEM Plan, except for one small lake (LAK028) near the smelter that has low support for a decline below the pH threshold and no support for a decline beyond its ANC threshold. The soils and aquatic analyses also both used predictive critical load modelling under the 42 tpd scenario. Critical loads of acidity for forest soils and wetlands are predicted to be exceeded near to the smelter, and near LAK28 which is close to exceeding its aquatic critical load. Though two other lakes further north are also predicted to be close exceeding their critical loads, and the northern-most lake in the study area is predicted to exceed its critical load, none of these three lakes is predicted to show a decrease in pH of more than 0.1 pH units under an emissions scenario of 42 tpd. Continued sampling of the water chemistry of sensitive lakes will be valuable to provide at least five years of post-KMP data, which will improve the statistical power to detect changes.

There is a lack of information on the distribution and sensitivity of wetlands. Effects of wetlands on lake chemistry are likely to be minor, as only 5 of the 51 lakes have more than 0.5% of their catchments characterized as wetland land classes from landcover data.

Overall, what do the results mean for the health of the valley?

The KPIs in the SO_2 EEM Program were chosen to provide early warning of potential impacts on the receptors, and thus far we see no early warnings. None of the KPI thresholds have been reached, not even the thresholds for increased monitoring. No prediction-based KPI threshold exceedances are projected even under the 42 tpd scenario. Air concentrations of SO_2 at residential monitoring stations are well below the B.C. Air Quality Objective. Air concentrations of SO_2 in the valley are well below concentrations that would cause visible injury to vegetation. No soil plots show evidence of acidification. Only one small lake near the smelter shows some evidence of sulphur-induced acidification that exceeds the protective thresholds established in the EEM Plan (low support for a decline below the pH threshold and no support for a decline beyond its ANC threshold); the other lakes do not show any evidence of such a change. Prediction-based KPIs for soils and lakes are not expected to reach mitigation thresholds even under SO_2 emissions at 42 tpd. Looking across these lines of evidence we do not see signs of harm in the valley, under present or predicted future conditions. Through all of the analyses, discussions, and results of the comprehensive review we are confident in these conclusions and recommend going forward with a more consolidated, efficient program.

9 Overall Recommendations

This section provides a summary compilation of all of the recommendations conveyed in the previous sections for all pathways and receptors. Further details on these recommendations are provided in the pathway and receptor sections. The section ends with a recommendation for the next review.

Recommendations for Atmospheric Pathways

1) Continue SO_2 continuous monitoring at all or most of the current sites.
2) Consider establishing a temporary or fixed continuous SO_2 monitoring station within the Service Centre commercial area to provide information on model performance in this area.
3) Continue the passive sampling network in the Kitimat Valley and review the number of sites and frequency of monitoring.
   a) Add passive sampling sites to the east and west of current sites located to the north of the smelter, where possible.
4) Consider reducing the current north to south network if needed to accommodate the proposed east to west expansion.
   a) Evaluate whether additional passive sampling sites can be established in locations south of the smelter.
   b) Assess the passive sampling site locations for whether some sites could be moved to align with the proposed biodiversity plots (or vice versa).
5) For the deposition monitoring program, we recommend continuing the Lakelse Lake monitor and considering discontinuing the Haul Road wet deposition monitor. The monitoring of wet deposition at Haul Road provides no ecological value (i.e., for the assessment of impacts) owing to its fence line location, and it provides limited value for model (CALPUFF) evaluation.

Recommendations for Human Health

The KPI for the EEM Program going forward will shift toward alignment with the CAAQS for SO_2. As such, there is no basis for a recommendation for changes to the quantitative basis for the existing KPI since it is in the process of changing according to the adoption and further adjustment of the CAAQS.

Recommendations for Vegetation

Acute effects on plants are unlikely and we recommend shifting SO_2 EEM monitoring to long-term, more subtle effects that integrate vegetation more strongly with terrestrial ecosystems.

1) Establish a terrestrial ecosystem line of evidence with the soil KPI of critical loads and informative indicators of plant biodiversity and plant health.
   a) Discontinue the current KPI for vegetation.
   b) Conduct a plant biodiversity pilot project to develop appropriate thresholds and related measures of variability to assure success.
2) Establish informative indicators of changes in plant biodiversity and changes in plant health due to emissions from B.C. Works to support the Soil Critical Load KPI.

3) Change the focus of the vegetation sampling and inspection program to detecting mid to long-term effects on terrestrial ecosystems by:
   a) Implementing a set of biodiversity plots to detect changes in plant communities related to B.C. Works,
   b) Revisiting ENV-established lichen plots at appropriate intervals (e.g. every 5 years) to document changes in lichen communities,
   c) Conducting a triennial inspection to document changes in plant and ecosystem health, and
   d) Discontinuing sampling and chemical analysis of western hemlock foliage in favor of maintaining a valley passive sampler network and monitoring vegetation health.

Recommendations for Terrestrial Ecosystems (Soils)

1) Revise critical loads of acidity for terrestrial ecosystems only if new data become available; however, estimate exceedances for any updated S (and N) deposition scenarios.
2) To address several uncertainties in the regional assessment of impacts to terrestrial receptors:
   a) Survey wetland geochemistry and sulphur storage capacity; wetlands make up almost 25% of the exceeded area, yet there is no chemical information on wetlands in the Kitimat valley. This information will provide support for the critical limit for wetlands.
   b) Assess Al solubility in mineral soils; Al solubility is a key parameter in the determination of critical loads, associated with the critical limit and $ANC_{leaching}$. This information will help to confirm the current estimates on ANC leaching.
   c) If feasible, establish at least one of the (newly) proposed plant biodiversity plots within the critical load exceeded areas south of the smelter. Further, as noted in the vegetation section, a terrestrial ecosystem line of evidence should be established to integrate the vegetation and soil line of evidence.
3) Revise the assessment of changes in exchangeable base cation at the long-term soil plots to:
   a) Use a change (decrease) in base saturation (%) to calculate KPI (rather than a change in exchangeable base cation pools),
   b) Use soil concentrations in the top 0–30 cm (rather than 0–5cm or 0–15 cm) of mineral soil rather than pools to assess changes in soil chemistry,
   c) Further analyse the minimum detectable difference to evaluate the potential of an early warning change in soil base saturation using a lower level of significance and / or lower power, and
   d) Carry out the next sampling of long-term plots during 2025 (to return to a five-year period) and measure trees (DBH) at time of soil sampling. If the KPI is triggered, measure tree chemistry to assess Bcu by trees.

Recommendations for Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)

Recommendations for the aquatic monitoring program:

1) The seven sensitive lakes should continue to be the core of the EEM Program. Continue with four samples of full chemistry each October from the six sensitive lakes that are accessible, to provide reliable measures of year-to-year changes in lake chemistry. Continue annual sampling (once per year) of sensitive LAK022, which is only accessible by helicopter.

2) Continue annual sampling of the full chemistry of less sensitive LAK016, which has an intermediate level of sensitivity. Discontinue the annual sampling of LAK007 (Clearwater Lake), LAK024 (Lakelse Lake) and LAK034, as the SO_2 EEM Program has shown these lakes to be insensitive under both *current* and *maximum future* levels of sulphur emissions.

3) Continue annual sampling of the full chemistry of the three control lakes to provide reliable measures of year-to-year changes in lake chemistry, an assessment of regional factors such as changing weather patterns, and critical data for statistical analyses of changes in sensitive lakes relative to control lakes. Include one year with multiple sampling visits of the three control lakes during October, to estimate the within-year variability in lake chemistry, and improve statistical inferences.

4) Re-evaluate the EEM lakes in the 2021 Annual Report with respect to their inclusion in the SO_2 EEM Program going forward. This will allow us to collect an additional three years of post-KMP data for all of the originally-identified sensitive lakes, for a total of six years of post-KMP data, before deciding on the need for the continued inclusion of each of the lakes.

5) We do not recommend adding any additional lakes to the EEM Program. We examined the critical loads and exceedances in the context of the updated CALPUFF deposition modeling for all the original STAR lakes, KAEEA lakes located within the study area, and additional lakes sampled early in the EEM Program. These analyses did not provide evidence that any of the lakes excluded from EEM Program should be re-considered for inclusion in the program.

6) Continue intensive sampling of LAK006 (End Lake) with the new Onset pH monitor. Continue measurements of lake levels to assess pH changes associated with storm events. Cease continuous monitoring of LAK012 (Little End Lake) and LAK023 (West Lake), as these lakes have shown very similar patterns to End Lake, and provide no incremental value beyond the intensive monitoring of End Lake. Furthermore, West Lake has not shown any increase in lake SO_4^{2-} since the pre-KMP period.

7) Conduct a thorough review of the report prepared by Paul Weidman (once released) to determine potential next steps in stream monitoring. Discontinue the monitoring of Anderson Creek, which has not provided useful information to the SO_2 EEM Program.

8) If additional fish sampling is required, explore the use of eDNA sampling to estimate any changes in the presence of fish species, and avoid the potential population impacts of gill-net sampling.

9) In addition to the lakes sampled annually within the SO_2 EEM Program, multiple other "non-EEM" lake and stream sites were identified for exploratory water chemistry sampling in particular years over the course of the EEM Program. None of these sites were found to be sensitive to the predicted increases in acidic deposition and therefore none of them were recommended to be added to the EEM Program for further monitoring.

Recommendations for aquatic KPIs, thresholds, and informative indicators:

10) Use ANC as the primary KPI for the program, with pH as an informative indicator.

11) Undertake further analyses to determine which of three possible metrics should be utilized as the KPI for the EEM Program: Gran ANC, BCS or ANC_{OAA}.

12) Include two components in the KPI(s): a *level of protection* to prevent acidification of lakes that are currently not at risk of aquatic impacts (i.e., an absolute threshold); and a *change limit*

which prevents further acidification (for lakes already below the level of protection due to natural organic acids or past acidic deposition) (i.e., a relative threshold).

13) Define the KPI such that a lake must exceed *both* the *level of protection* and *change limit* in order to be considered as an exceedance of the indicator.

14) Continue to use indicators of biologically relevant water chemistry, which provides the best early warnings of changes in lake chemistry that could be damaging to aquatic biota *in advance* of potential damage to aquatic biota and is therefore a *proactive* indicator. Do not use indicators of biological change which provide an indication that damage to aquatic ecosystems *has already occurred* and is therefore a *reactive* indicator.

Recommendations for aquatic critical loads and exceedance modelling:

15) Do not conduct critical loads modelling again in the future, except in a case where a lake has shown strong evidence of acidification (not the case for any of the EEM lakes).

16) Do not update the prediction of exceedances again in the future unless actual or predicted cumulative emissions from all sources are in excess of 42 tpd SO_2 or if the emissions modelling framework is significantly modified.

17) As described in the previous two recommendations, the critical loads of the EEM lakes do not need to be modelled again in the future and there is no need to estimate exceedances again until there are significant changes in emissions of sulphur or nitrogen in the Kitimat Valley beyond the currently permitted level. For these reasons, neither critical loads nor predicted exceedances would be appropriate metrics upon which to build an indicator for the EEM Program.

Recommendations for aquatic analyses and annual reporting:

18) Use the statistical methods provided in Aquatic Appendix F for evaluating future changes in water chemistry in the seven sensitive lakes, less sensitive lake LAK016, and the three control lakes, as well as examining changes on a finer scale in the intensively monitored LAK006 (End Lake). These statistical methods can be re-run on an annual basis to assess status and detect any anomalous patterns.

19) We recommend that the Annual Report be significantly streamlined where possible. The Annual Report should focus on reporting the new data from the monitoring program and updating critical analyses. The Annual Report should not attempt to make interpretations or inferences with respect to year-to-year changes in water chemistry, but should update statistical evaluations of long term changes between pre-KMP and post-KMP periods (see aquatic recommendation #17). However, the scope of the future annual reports will be determined as part of the discussion and development of the next phase of the EEM Program.

<u>Recommendations for the next Review</u>

As the 2019 comprehensive review will conclude in 2020, we recommend that the next review be done in 2026. We recommend that it be more focused than this 2019 review, because of the considerable learning that has occurred in the first six years of the SO_2 EEM Program.

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