Sulphur Dioxide Environmental Effects Monitoring for the Kitimat Modernization Project

Detailed Terms of Reference for the 2019 Comprehensive Review

Apr 5, 2019

Prepared for:

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

Prepared by:

ESSA Technologies Ltd.
Suite 600 – 2695 Granville St.
Vancouver, BC, Canada V6H 3H4

Authored by:
Dr. Julian Aherne, Trent University, Peterborough ON
Ms. Hui Cheng, Trinity Consultants, Kent WA
Mr. Alexander Hall, ESSA Technologies Ltd., Vancouver BC
Ms. Anna Henolson, Trinity Consultants, Kent WA
Dr. John Laurence, Portland OR
Mr. David Marmorek, ESSA Technologies Ltd., Vancouver BC
Ms. Carol Murray, ESSA Technologies Ltd., Vancouver BC
Dr. Shaun Watmough, Trent University, Peterborough ON

The Terms of Reference (TOR) consist of three items:

1. **Section 9.2 of the EEM Program Plan for 2013-2018**
2. **Draft outline for the Comprehensive Review Report**
3. **Draft schedule for Comprehensive Review tasks**

TOR Item 1: EEM Program Plan for 2013-2019, Section 9.2

RioTintoAlcan KMP SO_2 ENVIRONMENTAL EFFECTS MONITORING (EEM) PROGRAM

9.0 Annual Reporting, and Comprehensive Review in 2019

9.1 ANNUAL REPORTING AND CONSULTATION

SO_2 EEM reporting will occur on an annual basis. These annual reports will contain a concise summary of activities and results from the year, and plans for the subsequent field program based on the results from the previous field season. Information on aluminum production and SO_2 for the past year will also be included, to provide context for results interpretation. The annual reports will be written for a non-technical audience and intended for public distribution. Annual report preparation will begin early in the next calendar year, with the intention of publication by March 31st. Details of the results from each year will be documented in technical memoranda, allowing access to the technical details for the ECC, KPAC, and anyone else who is interested. The Haisla First Nation will be invited to participate in detailed annual program reviews, study designs and evolutions of the EEM program.

Each year of the EEM program, a meeting will be called to review the annual EEM program report and during the course of the meeting develop an interpretation of the EEM data integrated across the four lines of evidence (surface waters, vegetation, soils, and human health).

Annual Kitimat Public Advisory Committee (KPAC) meetings will be held in each spring to review EEM results and report out on the findings from the previous year, and discuss actions planned for that year.

9.2 COMPREHENSIVE REVIEW IN 2019

A comprehensive review will be conducted in 2019, examining what has occurred under the SO_2 EEM Plan from 2013 to 2018. A report synthesizing the results of this review will be prepared by October 31, 2019, which will:

- Summarize what has been learned, and what question have been answered,
- Describe which if any of the 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 SO2 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.

PROGRAM PLAN FOR 2013 TO 2018 48

TOR Item 2: Outline for the Comprehensive Review Report

Executive Summary and KPI Report Cards

Table of Contents

List of Figures

List of Tables

Glossary

Abbreviations

ANC	Acid neutralizing capacity
BACI	Before-after-control-impact
BCS	Base cation surplus
CBANC	charge balance ANC
CCME	Canadian Council of the Ministers of the Environment
CL	Critical load
CR	SO_2 EEM 2019 Comprehensive Review
DFO	Canadian Department of Fisheries and Oceans
DOC	Dissolved organic carbon
ECCC	Environment and Climate Change Canada
ENV	BC Ministry of Environment and Climate Change Strategy
KAEEA	Kitimat Airshed Emissions Effects Assessment
KMP	Kitimat Modernization Project
KPI	Key performance indicator
MDD	Minimum detectable difference
NADP	National Atmospheric Deposition Program
PCA	Principle components analysis
QA/QC	Quality assurance / quality control
QPs	Qualified professionals (for the SO_2 EEM Program)
$RCOO^-_s$	Strongly acidic organic anions
SO_2 EEM	Rio Tinto BC Works' SO_2 Environmental Effects Monitoring Program
SSMB	Steady State Mass Balance (model)
STAR	SO_2 Technical Assessment Report
TOR	terms of reference for the SO_2 EEM 2019 Comprehensive Review

1 Introduction

1.1 Background

List the objectives of the report (from EEM Plan, Section 9.2):

- Summarize what has been learned, and what question have been answered
- Describe which if any of the 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
- Recommend a date for the next comprehensive review

1.2 Facility Production and Emissions from 2013 to 2018

1.3 Organization of this Report

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

To be written after Section 3 is completed.

- Summarize results and learning across pathways and receptors:
    - Results and recommendations (example template shown in Table 1 below)
    - What has been learned and what questions have been answered (example template shown in Table 2 below)

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

	Atmospheric Pathways	Human Health	Vegetation	Terrestrial Ecosystems (Soils)	Lakes, Streams & Aquatic Ecosystems
Were any KPI thresholds reached? If so, what was the response?					
Were any KPIs modified? Are any modifications					

	Atmospheric Pathways	Human Health	Vegetation	Terrestrial Ecosystems (Soils)	Lakes, Streams & Aquatic Ecosystems
recommended to either KPIs or informative indicators that support KPIs?					
Were there any modifications to methods used for KPIs and informative indicators? Are any modifications recommended to methods of monitoring or modelling KPIs or informative indicators?					

Table 2. Summary of what questions have been answered thus far under the EEM Program, and whether any questions remain to be answered or new questions have emerged.

	Atmospheric Pathways	Human Health	Vegetation	Terrestrial Ecosystems (Soils)	Lakes, Streams & Aquatic Ecosystems
EEM Questions that have been answered					
Questions still to be answered					
New questions that emerged					

- This will be a summary table showing which questions from Table 19 of the EEM Plan have been answered, and which are still in process. The questions will be stated here, but not the hypotheses.
- A table of questions and hypotheses will be in the back of this report. The wording of those from the original STAR/EEM Program questions/hypotheses may appear slightly modified in this report, as needed based on how things evolved during the EEM Program development, and subsequently during the first 6 years. If the wording of the questions and hypothesis in this report is not an exact match to those in the STAR we will explain why.

3 Review Results for Atmospheric Pathways

3.1 Atmospheric Concentrations

3.1.1 What did we set out to learn?

- Explain that we set out to learn if any KPI thresholds were reached.
- Briefly explain the questions and hypotheses from the STAR.
    - A1. Does CALPUFF accurately represent post-KMP SO_2 air concentrations?
    - D1. Does the CALPUFF model accurately predict post-KMP total sulphur deposition?
    - D2. What are the base cation deposition values in the study region?

3.1.1.1 EEM Informative Indicators

- Informative Indicator: Atmospheric SO_2 concentrations
- Informative Indicator: Atmospheric S deposition
- Informative Indicator: Atmospheric base cation deposition
- NEW: contribution of particulate sulphate to dry S deposition
- NEW: contribution of dry deposition to total deposition

3.1.2 What methods did we use?

- Describe all of the inputs and methods used in the analyses for this review.
- Provide an overview and put details in an appendix.

3.1.2.1 Data we collected: modeling

- Describe the collection of data inputs for CALPUFF.

3.1.2.2 Planned analyses: modeling

- Model actual SO_2 emissions for 2016-2018 post-KMP using CALPUFF (including CALMET data for 2016- 2018), actual emissions, and SO_2 Technical Assessment Report (STAR) methods. Compare with monitored SO_2 data for the same period. Refine CALPUFF methods if there is insufficient alignment between modeled and monitored SO_2 concentrations (method described in EEM Program Plan, page 7). This subtask includes evaluating hourly SO_2 concentrations at the Haul Road, Riverlodge, Whitesail and Kitamaat Village continuous monitoring station locations, for 2013-2018. [This subtask must be done early in the Review process as the results are required inputs for some of the receptor analyses.] We will also model 35 and 42 tpd.[1]
- Compare monitoring with modelling:
    a) Compare continuous analyzer monitoring results to CALPUFF model output from the STAR and to output from the 2018 CALPUFF for 2016-2018.
    b) Compare the spatial gradient of SO_2 concentrations from the passive monitoring program to output from the 2018 CALPUFF application to 2016-2018.

[1] We considered running a separate 30 tpd scenario, but 2016-2018 actuals will serve as the ~30 tpd future steady state case because the average of the 2016-2018 emissions is 29.3 tpd (27.8 tpd, 29.5 tpd, and 30.6 tpd in 2016, 2017, and 2018 respectively).

c) Compare wet deposition monitoring results (S) for 2016-2018 to CALPUFF model output from the STAR and to output from the 2018 CALPUFF for 2016-2018.
d) Compare dry and total deposition of S to estimates (using the Big Leaf model and observations) for 2016-2018 to CALPUFF model output from both STAR and output from the 2018 CALPUFF for 2016-2018.

3.1.2.3 Data we collected: monitoring

- Describe the continuous monitoring network; site locations and sampling frequency.
- Describe the SO_2 passive sampler network; site locations and sampling frequency.
- Describe additional monitoring under the multi-seasonal study.
    - Include statistical analysis that accounts for wind direction.
- Describe the monitoring of particulates using filter packs.

3.1.2.4 Planned analyses: monitoring

- Report on progress of multi-seasonal study on seasonality aspects of Kitimat's air quality to determine the seasonal and spatial variability of SO_2 concentrations in the residential areas of Kitimat; Terms of Reference to be finalized with ENV.
- Report on the optimization of the air quality monitoring network and summarize optimization effort and associated conclusions to-date.
    - Discuss why zoning maps were used instead of census data.
    - Comment on whether commercial areas are sufficiently represented.
    - Identify what planning documents were used as information sources.
    - Summarize the 2016 Air Quality Workshop, results, and public feedback.
- Evaluate sulphur dioxide (SO_2) passive sampler results for 2015–2018.
    a) Calibrate passive samplers against active (continuous) stations (compare average monthly SO_2 concentrations estimated from passive monitors with estimates from 4 continuous monitors during the period from 2015 to 2018; note: during 2015 data are only available for passive sampler trial). The calibration / evaluation will be carried out station-by-station.
    b) Assess if a peak-to-mean ratio can be established for the SO_2 passive samplers.
    c) Evaluate temporal variation in SO_2 passive samplers in the Kitimat Valley (2016 to 2018).
    d) Evaluate spatial variation in SO_2 passive samplers in the Kitimat Valley (spatio-temporal plots).
    e) Develop framework for synthesizing SO_2 results from 2016-2018; the objective will be to develop an approach for spatial and temporal scaling.
- Evaluate particulate sulphate (pSO_4^{2-}) filter pack results for 2017–2018.
    a) Evaluate performance of filter packs, i.e., comparison of filter pack SO_2 to continuous station SO_2 (for all co-exposures).
    b) Evaluate the SO_2 to pSO_4^{2-} ratio, and its relationship to SO_2 concentration.
    c) Develop a framework for synthesizing pSO_4^{2-} results; the objective will be to develop an approach for spatial and temporal scaling.

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

- Provide an overview of the results, referencing past Tech Memos, and put details in an appendix.
- Summarize what has been learned overall from these results thus far under the first 6 years of the EEM Program.
- Describe adjustments that have been made to modelling and monitoring methods based on what was learned.
- Explain whether question A1 from the EEM Plan has been answered, and whether new material questions have emerged.
- Are the spatial SO_2 dispersion patterns predicted in STAR within residential areas of Kitimat in agreement with post-KMP measurements (from continuous analyzers and possibly passive samplers)?
- Are changes needed to the SO_2 monitoring network?
- Identify incomplete actions from sections 2.2.1, 2.2.2, 2.2.3 and 2.3.3 of the EEM Plan.
- Explain what changes if any have been already made to this informative indicator.

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

- Recommended changes to monitoring methods, frequency or extent
  - Evaluate whether available data to the south of the smelter are sufficient for receptor impact analysis needs.
- Recommended changes to modelling methods
- Recommended changes to the informative indicators

3.2 Atmospheric Deposition

3.2.1 What did we set out to learn?

- Briefly explain the questions and hypotheses from the STAR.

3.2.2 What methods did we use?

- Describe all of the inputs and methods used in the analyses for this review.
- Provide an overview and put details in an appendix.

3.2.2.1 Data we collected

- Describe the collection of rainfall chemistry by the NADP stations.

3.2.2.2 Analyses we conducted with these data

- Evaluate wet deposition results for Haul Road (2012–2018) and Lakelse Lake (2013–2018).
  a) Examine ion balance (quality control) of precipitation chemistry; other QA/QC procedures will be applied to evaluate the quality of the data (in general the methods will follow accepted approaches used under the Convention on Long-Range Transboundary Air Pollution).
  b) Evaluate rainfall amount (compared with ECCC meteorological stations).
  c) Evaluate seasonality in precipitation chemistry and deposition.
  d) Evaluate temporal change in precipitation chemistry and deposition.
  e) Evaluate relationship between station chemistry.

   f) Compare Haul Road and Lakelse Lake to the NADP station at Prince Rupert (and potentially further afield).
   g) Produce temporal maps of sulphate deposition (month by week plots) for Haul Road and Lakelse Lake.
   h) Assess base cation precipitation chemistry (inputs to revision of regional critical loads).
- Evaluate the Big Leaf dry deposition model.
   a) Describe data requirements for the Big Leaf model.
   b) Describe data sources (2015 to 2018; 4 years) for application of the model to Kitimat and Terrace Airport.
   c) Evaluate model sensitivity to cloud cover and approach for the estimation of solar irradiance.
   d) Evaluate the use of temperature and wind speed from Haul Road versus Whitesail on deposition velocity for SO_2 in Kitimat.
   e) Compare dry deposition velocity for SO_2 and pSO_4^{2-} in Kitimat and Terrace (may use temporal maps [day by hour] to visual changes in dry deposition velocity).
- Evaluate dry deposition of SO_2 (passive samplers) and pSO_4^{2-} (filter pack).
   a) Summarise hourly deposition velocity for SO_2 (and p SO_4^{2-}) into monthly exposure periods, i.e., summaries that correspond to the exposure periods for passive samplers.
   b) Estimate dry deposition for monitoring periods and assess relative importance of particulate deposition. Note: particulate concentration at each passive sampling location will be estimated from the filter pack relationship.
   c) Evaluate total S deposition at Haul Road and Lakelse Lake for passive sampler monitoring periods, i.e., wet SO_4^{2-}, dry SO_2 and dry pSO_4^{2-}.
   d) Extrapolate seasonal total deposition to annual estimates.

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

- Provide an overview of the results, referencing past EEM reports and Technical Memos, and put details in an appendix.
- Summarize what has been learned overall from these results under the first 6 years of the EEM Program.
- Identify incomplete actions from sections 2.2.1, 2.2.2 and 2.2.3 of the EEM.
- Explain whether questions D1 and D2 from the EEM Plan have been answered, and whether new questions have emerged.
- Explain what changes if any have been already made to the informative indicators.

3.2.3.1 Knowledge gained

- Reliability of passive samplers
- Spatial and temporal variation of SO_2
- Relative importance of particulate sulphate
- Spatial and temporal variation of total sulphur deposition
- Contribution of dry to total deposition
- Evaluation of modelled and observed atmospheric sulphur data

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

- Recommended changes to monitoring methods, frequency or extent
  - Passive sampler network: Valley and Kitimat
  - Continuous network (station locations)
- Recommended changes to modelling methods
- Recommended changes to the informative indicators

4 Review Results for Human Health

4.1 What Did We Set Out to Learn?

- Explain that we set out to learn if any KPI thresholds were reached or exceeded.
- Briefly explain the questions and hypotheses from the STAR.
- Review the rightmost column of Table 10.3-1 in Volume 2 of the STAR.

4.2 What Methods Did We Use?

- Describe all of the inputs and methods used in the analyses for this review.
- Provide an overview and put details in an appendix.

4.2.1.1 Planned analyses:

- Evaluate KPI results for 2017-2018. Describe evolution of this KPI over time (past and future, BC IAAQO and CCME values).
  - Conduct assessment of acceptable or unacceptable impacts to the receptor (was the threshold for facility-based mitigation exceeded?).

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

- Provide an overview of the results, referencing past EEM reports and Technical Memos, and put details in an appendix.
- Summarize what has been learned overall from these results re human health thus far under the first 6 years of the EEM Program.
- Explain whether questions HH1 and HH2 have been answered, and whether new questions have emerged.
- Explain whether a KPI threshold been reached, and if so, what actions were taken, or need to be taken.
- Explain what changes if any have been already made to the health KPI (the KPI itself, methods, or thresholds).
  - Convey that the threshold will become 65 ppb after 2025.
- Discuss the shift away from the informative indicator in the EEM Plan, and why.

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

- Recommended changes to monitoring methods, frequency or extent
- Recommended changes to the KPI
- Recommended responses to exceedances of thresholds

5 Review Results for Vegetation

5.1 What Did We Set Out to Learn?

- Explain that we set out to learn the answers to the vegetation questions in Table 19 of the EEM Program Plan, and their underlying hypotheses.
  - V1. Validation of the dispersion model – are we looking in the right place?
  - V2. How healthy is vegetation in sites with predicted exceedance of critical loads of soil and/or lakes and streams south of Lakelse Lake?
  - V3. Are plants of public importance showing symptoms in areas with highest exceedances of soil critical loads?
  - 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?

5.1.1 EEM Key Performance Indicator

- Was the Key Performance Indicator exceeded?
- Is the Key Performance Indicator appropriate? Evaluate within the context of the answers to questions V1-V4 (see Section 5.1)

5.1.2 EEM Informative Indicator

- Was the Informative Indicator exceeded?
- Is the Informative Indicator appropriate? Evaluate within the context of the answers to questions V1-V4 (see Section 5.1).

5.1.3 Other questions that have emerged since the development of the EEM

- Are there more sensitive indicators of potential impacts on vegetation?
- Is the sampling array appropriate given current emissions and predictions of deposition?
- Is the sampling array representative of ecotypes in the area, including ecosystems at risk and plant species at risk in the area?

5.2 What Methods Did We Use?

5.2.1 Data we collected

- CALPUFF simulations for actual deposition and emission scenarios of interest
- Updated scientific literature on the response of vegetation to SO_2
- Observations of vegetation condition, health, and visible injury
- Concentrations of sulphur in western hemlock foliage

5.2.2 Analyses we conducted with these data

- Evaluate the post-KMP CALPUFF results (for actual emissions and additional scenarios) both to answer question V1 in the STAR, but also to assess the extent of potential S deposition that might affect sensitive vegetative receptors. Revisit the STAR dose-response and threshold analysis to determine if it has changed based on the updated CALPUFF modeling results or recent results published in peer-reviewed scientific literature since STAR.

- Evaluate the results of visible injury inspections post-KMP and compared them to those in the pre-KMP SO_2-Vegetation baseline of 1998-2011.
- Evaluate visual vegetation inspection results for 2014-2018.

5.2.2.1 Planned analyses:

- Analyze the extent of any insect infestations or disease epidemics to observation results.
- Evaluate the results of chemical analysis of western hemlock foliage post KMP and compared S (and F to provide context) to pre-KMP baselines.
  - Conduct assessment of acceptable or unacceptable impacts to the receptor (was the threshold for facility-based mitigation exceeded?)
  - If needed, apply the weight-of-evidence approach for assessing causality (described in Section 7 of the EEM Program Plan).
- Evaluate S content (and F content to provide context) in Hemlock needle results for 2014-2018.
- Conduct a spatial analysis to relate results to updated CALPUFF modeling (actual and scenarios); include a map overlaying CALPUFF model results for Vegetation.
- Using historical data and post KMP S and F concentrations in western hemlock foliage, assess the value of each vegetation sampling site with regard to understanding deposition.
- Integrate the results of vegetation monitoring—inspection and sampling—with results of soils monitoring to assure coverage of sensitive soils or critical load exceedances.
- Compare presence in 2014-2015 with presence in 2016-2018 of species reported to be sensitive to SO_2 selected by ENV.
- Evaluate the suitability of the KPI and Informative Indicator to assess impacts to vegetation and ecosystems. Incorporate published peer-reviewed scientific literature since STAR in the analysis.
  - Explore alternative KPIs as suggested by peer-reviewed scientific literature.

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

5.3.1 Knowledge gained

- An updated synthesis of scientific literature on the effects of SO_2 and soil/air acidification on vegetation
- Updated thresholds of concern for vegetation
- Relationship of S (and F for context) concentrations in western hemlock to measured and modeled deposition of S
- Comparison of pre- and post-KMP S (and F for context) concentrations in western hemlock needles, including measures of variability
- A synthesis of results of vegetation inspections (including any biotic stressors) pre- and post-KMP
- An analysis of whether the location of sampling and inspection sites is appropriate given changes in monitored and modeled deposition patterns post-KMP

5.3.2 Modifications to the EEM Program

- Identify potential changes to the KPI and Informative Indicator depending on the results of the analyses.
- Make recommendations for other potential KPIs or Informative Indicators that are more integrative of air monitoring, soil measures, critical loads, and vegetation results.
- Describe potential development of measures to support the inspection and sampling program-for instance, periodic measurement and assessment of permanent forest plots including Canadian Forest Service CFI plots.

5.3.3 Comprehensive synthesis ('pulling the pieces together')

- Relate vegetation results-observations of plant health and results of chemical analyses-to soils, aquatics, and critical load results.
  - Provide spatial overlays of vegetation sites with sensitive soils, and SO_2 isopleths to visually show the relationships
- Use CALPUFF results and results from soil, aquatics, and critical load analyses to adjust the location of vegetation inspection and sampling sites if necessary.

5.3.4 Conclusions

- Are the current KPI and Informative Indicator sensitive and useful for assessment of the risk to vegetation from KMP emissions? If not, are changes in the levels necessary, or are there more appropriate indicators.
  - Discuss uncertainties in the ability of the KPI and Informative Indicator to detect an early effect / worsening condition signal on vegetation.
- What changes have occurred post-KMP with regard to risk to vegetation and ecosystem health?
- How does the vegetation inspection and sampling program integrate with and support other components of the EEM?

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

- Recommendations regarding the Key Performance Indicator
- Recommendations regarding the Informative Indicator
- Recommendations for the inspection and sampling program

6 Review Results for Terrestrial Ecosystems (Soils)

6.1 What Did We Set Out to Learn?

- Explain that we set out to learn if any KPI thresholds were reached.
- Briefly explain the questions and hypotheses from the STAR.
- Review the rightmost column of Table 10.3-1 in Volume 2 of the STAR.
  - S1. Are estimates of average weathering rates by bedrock type valid for vulnerable areas (e.g., where lakes have low base cations)?
  - S2. What is the current buffering capacity (base cation pool) of the soils in exceeded areas?

- S3. What is the rate of soil acidification measured as loss of base cations (or increase in protons) owing to acidic deposition?
- NEW. What is the minimum detectable change in soil base cation pools?
- NEW. What is the time-to-depletion for base cation pools in the long-term soil plots under current (modelled) deposition of sulphur?

6.1.1 EEM Key Performance Indicators

- KPI: Atmospheric S deposition and critical load (CL) exceedance risk
- KPI: Long-term soil acidification (rate of change of base cation pool) attributable to S deposition

6.1.2 EEM Informative Indicators

- Informative Indicator: Soil base cation weathering rates
- Informative Indicator: Magnitude of exchangeable cation pools (Ca, Mg, K, Na)
- Informative Indicator: Time to depletion of exchangeable cation pools (Ca, Mg, K, Na)

6.2 What Methods Did We Use?

- Describe all of the inputs and methods used in the analyses for this review.
- Provide an overview and put details in an appendix.

6.2.1 Data we collected

- Regional soil samples (sampling and analysis)
- Establishment of long-term soil plots
- Sampling and analysis of long-term soil plots (2015 and 2018)
  - Explain the protocol/rationale for not sampling the Kemano plot (and secondary plots).
  - Explore the idea of sampling plots more frequently at first and less frequently later and convey the conclusion/recommendation.

6.2.2 Analyses we conducted: critical loads

- Re-calculate critical loads across the study domain using the SSMB model with updated methodology and additional soil and updated deposition data. See Technical Memo S01 (March 2015) for overview:
  a) Physico-chemical properties in the Kitimat Valley: Describe results from STAR soils and EEM soil sampling (oxide content, organic matter, coarse fragment, particle size, etc.); describe data distributions, descriptive statistics, relationships between parameters, change in soil properties with depth
  b) Application of the A2M solver to estimate soil mineralogy; A2M requires soil oxide content
  c) Modelling of soil base cation weathering rate using the PROFILE model. The model requires mineralogy (estimated using A2M and soil observations from the regional soil samples)
  d) Collation of continuous data layers (maps) for the Study domain; climate, soils, geology, land cover, etc.
  e) Application of regression-kriging to map soil properties (such as organic matter, texture, bulk density, etc.) across the Kitimat Valley

f) Spatial mapping of soil weathering rate across the Kitimat Valley using regression kriging and spatial maps of soil properties (approach removes dependency on bedrock geology)
g) Evaluation of appropriate critical chemical indicators, i.e., selection of Bc:Al ratio by vegetation type (requires that vegetation types can be identified from existing spatial databases)
h) Regional mapping of base cation deposition (using observations from the NADP stations)
i) Re-calculate CL using SSMB with updated soil weathering maps, base cation deposition, background sulphur deposition (domain boundary inputs are not included in CALPUFF), and revised Bc:Al [Note: the assessment will include wetlands as applied under the Prince Rupert Airshed Study]
j) Estimate exceedance of the study area using CALPUFF results from Atmospheric Pathways (the current deposition (2016–2018), 35 and 42[2] tonnes per day CALPUFF predictions)
k) Sensitivity analysis: determination of exceedance of critical load under multiple chemical criteria to assess the influence of the chosen criterion on predicted exceedance (following approach used under the KAEEA)
l) Exceedance will be evaluated for the entire study area and effects domain (the area under the 7.5 kg $SO_4^{2-}ha^{-1}yr^{-1}$ deposition plume from 42 tonnes per day CALPUFF predictions).
m) If exceedance is expected in some areas, analyze sampled soils for exchangeable base cations to estimate time to effects (based on estimated depletion of the base cation pool).

6.2.3 Analyses we conducted: long-term soil plots

- Evaluate results of the long-term plots during from 2015 and 2018.
  a) Define conceptual basis for long-term soil monitoring plot.
  b) Discuss long-term soil monitoring plot design, location and sampling (Coho Flats, Lakelse and Kemano).
  c) Describe biomass (tree species only) and evaluate spatial (horizontal and vertical) variability in soil properties at Coho Flats, Lakelse Lake and Kemano (pH, organic matter and bulk density). Evaluate the use of geostatistical approaches to describe (quantify and visualise) variability.
  d) Evaluate spatial variability of soil exchangeable cations including calcium (horizontal and vertical) at Coho Flats and Lakelse Lake. Evaluate the use of geostatistical approaches to describe variability.
  e) Evaluate relationship between soil variables.
  f) Determine exchangeable pools (including calcium) and base saturation; evaluate spatial variability at Coho Flats and Lakelse Lake. Evaluate the use of geostatistical approaches to describe variability.

[2] We considered running a separate 30 tpd scenario, but 2016-2018 actuals will serve as the ~30 tpd future steady state case because the average of the 2016-2018 emissions is 29.3 tpd (27.8 tpd, 29.5 tpd, and 30.6 tpd in 2016, 2017, and 2018 respectively).

g) Determine time to effects, to depletion of base cation pools under 2016 to 2018 deposition (and scenarios based on 35 and 42 tonnes per day CALPUFF predictions).
h) Evaluate temporal variability in soil exchangeable pools (including calcium), base saturation, pH and organic matter at Coho Flats and Lakelse Lake (2015 and 2018).
i) Evaluate statistical power for detecting change in exchangeable base cation pools (using minimum detectable distance or power analysis).

- Evaluate results of the long-term plots during from 2015 and 2018, and the schedule of future sampling (e.g., assessment of resample period).

6.2.4 Assessment of acceptable or unacceptable impacts to terrestrial receptor

- The assessment of the impacts to the terrestrial ecosystems as "acceptable" or "unacceptable" is directly linked to the KPI (exceedance of critical loads, and change in exchangeable base cation pools). The weight of evidence approach for assessing whether the critical load exceedance is casually related to KMP will be summarised. .
    - If the KPI thresholds associated with facility-based mitigation in the EEM is exceeded, this will be identified as an "unacceptable" impact to the terrestrial receptor.
    - Impacts to terrestrial ecosystems that do not exceed the KPI threshold associated with facility-mitigation in the EEM will be identified as "acceptable"
    - NOTE: all impacts, regardless of classification will be explored, analyzed, interpreted and documented in detail.
- If needed, apply the weight-of-evidence approach for assessing causality (described in Section 7 of the EEM Program Plan).

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

- Provide rationale for the KPI's and the Informative indicators.
- Provide an overview of the results, referencing past EEM reports and Tech Memos, and put details in an appendix.
- Discuss what has been learned overall regarding KMP effects on soils thus far under the first 6 years of the EEM Program.
- Explain whether questions S1, S2 and S3 have been answered, and whether any new questions have emerged.
- Explain whether a KPI threshold been reached, and if so, what actions were taken, or need to be taken.
- Explain what changes if any have been already made to the soils KPIs (the KPI itself, methods, or thresholds) or the informative indicators.

6.3.1 Knowledge gained

- Spatial information (mapping) of soil properties
- Critical loads and exceedances for terrestrial ecosystems
- Spatial patterns in soil chemistry
- Ability to detect changes in soil chemistry
- Identification of major knowledge gaps that add uncertainty in results

6.3.2 Comprehensive synthesis ('pulling all the pieces together')

- Summary of observed changes in soil chemistry
- Exceedances of critical loads
- Link changes in base saturation, base cation pools, exceedance of critical loads in the context of potential effects to sensitive receptors, lakes, and vegetation.

6.3.3 Conclusions

- Has KMP contributed to the Acidification of terrestrial ecosystems?
- Summary of uncertainties from the STAR and EEM
- Assessment of acceptable or unacceptable impacts on Terrestrial receptor

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

- Recommended changes to monitoring methods, frequency or extent
- Recommended changes to the KPIs or informative indicators
- Recommended changes to thresholds
- Recommended responses to exceedances of thresholds

7 Review Results for Aquatic Ecosystems (Lakes, Streams and Aquatic Biota)

7.1 What Did We Set Out to Learn?

- Briefly explain the questions and hypotheses from the STAR, noting that the questions and hypotheses are further refined later in this outline.
- Review the rightmost column of Table 10.3-1 in Volume 2 of the STAR.
- QUESTIONS from STAR & EEM:
  - W1. How do assumptions 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 under KMP, and to what extent?
    - [W2a.] Have any of the sensitive lakes exceeded their KPI 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)?
    - [W2c.] What is the water chemistry of the 4 less sensitive lakes? Do any of them show any evidence of acidification and/or impact from KMP?
    - [W2d.] How many lakes have actually acidified due to KMP and exceeded their KPI thresholds?
    - [W2e.] Are additional sites suggested by MOE (i.e., lakes MOE-3 and MOE-6, Cecil Creek, and Goose Creek) at risk of acidification under KMP?
  - W3. What species, age classes, and size of fish are present 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 accessed for fish sampling show an acidifying trend, then do these lakes also show changes in their fish communities?
- OTHER questions elsewhere within the STAR / EEM Plan
    - Do we see any evidence of regional acidification when we analyze the lakes as a group?
    - "Estimate expected time to steady state for SO_4 based on observed trends in [SO_4] and approximate estimates of water residence time".
    - Examine changes in ANC, SO_4 and pH relative to steady-state predictions.
    - Estimate F-factor from empirical sampling.

7.1.1 EEM Key Performance Indicators

- KPI: Observed pH decrease ≥0.30 pH units below mean baseline pH level measured pre-KMP, and is causally related to KMP emissions (where the mean pH during 2012 was measured in August, and the mean pH during 2013-2018 was measured during the fall index period – month of October)

7.1.2 EEM Informative Indicators

- *Informative Indicator:* Atmospheric S deposition and CL exceedance risk
- *Informative Indicator:* Predicted steady state pH versus current pH
- *Informative Indicator:* Estimates of natural variability in pH and other indicators
    - For intensively monitored lakes we're interested in all of these time scales for the ice free period (daily, weekly, monthly, seasonally, storm effects). For other lakes, we're interested in variability within the index period (e.g., SE of the mean of 4 measurements), and also year to year variability.
    - Other important lake chemistry indicators = ANC, SO_4, DOC, base cations, Cl
- *Informative Indicator:* Evidence that pH is causally related to KMP SO_2 emissions
    - This includes analyses of the changes in ANC, SO_4, DOC, base cations, Cl, in combination with application of the evidentiary framework.
    - NOTE: Particular attention and rigor will be given to the analyses of ANC
        - The importance of ANC as a potentially stronger indicator of changes in lake chemistry and a candidate for a future KPI has received increasingly focused attention since the development of the EEM.
        - Changes in ANC will be analysed *as if* it were a KPI (i.e., "dry run" for potential future implementation), including sensitivity analyses on different formulations of ANC thresholds (both variability in ΔANC corresponding to a ΔpH of 0.3 (from lab titrations), and a scientifically defensible range for the ANC threshold in the CL analysis (e.g., 20, 26 and 40 μeq/l)).
        - The role of organic acids needs to be carefully considered throughout the analysis, both retrospectively and prospectively, as some lakes have a high organic acid component.
- *Informative Indicator:* Aquatic biota: fish presence/absence per species in sensitive lakes
- *Informative Indicator:* Lake ratings
- *Informative Indicator:* Episodic pH change

- *Informative Indicator:* Amphibians

7.1.3 Other questions that have emerged since the development of the EEM

- New questions that have emerged
  - Is there a benefit to adding appropriate control lakes to the EEM?
  - Is there a benefit to additional intra-annual data (e.g., intensive/continuous)?
  - Is there a benefit to collecting other data on the EEM lakes?
    - Water residence time analysis
    - Lake level monitoring
  - Will increased emissions result in immediate (i.e., same year) changes to lake chemistry or will there be a lag?
  - How sensitive will the analyses be to alternative assumptions about the baseline?
  - How important will it be to consider multiple metrics in our evaluations of the data?

7.1.4 Complexity and causality of changes in lake chemistry

- Contextual discussion on the complexity of lake chemistry dynamics within these lakes.
  - There are various changes occurring simultaneously (e.g., changes in ANC, pH, organic acids, Cl, SO_4), which add complexity to analyses and interpretations of changes in lake chemistry.
  - Importance of understanding both natural and anthropogenic change
  - Brief discussion of limitations and concerns with pH KPI
  - Summarize how the EEM evidentiary framework (section 7) assesses causality associated with observed changes in lake chemistry.
  - Explain the rationale for developing a multi-metric framework for assessing causality (i.e., understand mechanisms driving observed changes to better understand system; understand whether or not observed changes are attributable to changes in emissions from the smelter).

7.2 What Methods Did We Use?

- Describe all of the inputs and methods used in the analyses for this review.
- Provide an overview and put details in an appendix, including improved methods based on comments from Tim Sullivan (e.g., revising charge density assumptions to improve charge balance).

7.2.1 Data we collected

- Annual Monitoring Samples (full chemistry, collected during October, the fall index period)
- Intensive Monitoring of Lakes (pH, measured every half hour during the ice-free season – generally April through to the end of October)
- Summarize (with reference to the STAR and Kitimat Airshed Assessment) how all lakes were selected, (including the control lakes, and their similarities in various attributes to the sensitive EEM lakes).

7.2.2 Analyses we conducted with these data

- NOTE ON ANC VALUES:
  - Gran ANC has been the primary measure of ANC for all the analyses in the STAR and EEM. It is the capacity of a solution to neutralize strong acids, and is determined by titration to the inflection point of the pH-alkalinity titration curve. Gran ANC includes the buffering effect of organic anions.
  - Based on recommendations from other QPs, ENV, and external experts at the workshop held December 10-11th, 2018, and a subsequent conference call on Jan 10, 2018, we will explore using charge balance ANC (CBANC), and Base Cation Surplus (BCS, Lawrence et al. 2007, 2013) as alternative measures of ANC.
  - CBANC is also the capacity of a solution to neutralize acidity, and is generally calculated as the equivalent sum of base cations (Ca, Mg, Na, K) minus the equivalent sum of strong acid anions (SO_4, NO_3, Cl).
    - CBANC has the benefits that it has been used in many studies of long term trends (e.g., Stoddard et al. 1998, 2003), and it can be analyzed in commercial labs without specialized equipment for Gran ANC titrations. However, the usual formulation of CBANC has the detriments that it doesn't take into account buffering by organic anions (which are very important in some of the EEM lakes) and that it's calculated from the sum of seven different measurements and therefore can potentially accumulate measurement errors (Evans et al. 2001). Estimating charge balance and charge density also involves summing up multiple measurements.
  - The Gran ANC and CBANC are related by the following equation:
    - CBANC = Gran ANC + a * DOC, [1]
    - where a is an estimate of charge density, generally in the range of 4-6 μeq per mg DOC, but can be from 2-10 μeq per mg DOC (Hemond 1990, Marmorek et al. 1996).
    - Based on the recommendations ENV's external expert, we propose to calculate a lake-specific charge density (a) to achieve the best possible charge balance, and then apply that value to equation [1] to compare CBANC vs Gran ANC within each lake, for the purposes of understanding the relationship between these two indicators.
    - We will explore the feasibility of using only CBANC and BCS in future years, due to the difficulties of finding commercial labs that can reliably conduct Gran ANC titrations (which have to date been performed at Trent University).
  - BCS is equal to CBANC minus strongly acidic organic anions (called $RCOO^-_s$), which (Lawrence et al. 2007, 2013) estimate from a linear regression of anion deficits vs. DOC for samples with a pH between pH 4 and 4.5 (33 stream samples in their 2007 paper, 200 lake samples in their 2013 paper). $RCOO^-_s$ is set equal to the anion deficit from this linear regression, for all water samples (i.e., both those with pH $\leq$ 4.5, and those with pH > 4.5), since the strong acid fraction of DOC is not likely to change with pH. The advantage of BCS as a measure of lake condition is that inorganic aluminum (which is associated with acidification and

is toxic to fish and other organisms) consistently increases as BCS declines below zero (i.e., BCS < 0 is a concern).

- In the EEM data set we do not have any samples with a pH < 4.5, so we would need to either: a) directly apply the regression lines from Lawrence et al. 2013 (derived from lakes in Adirondacks NY); b) derive similar linear regressions using EEM and other regional data for lakes within a pH range from 4.5 to 5.1; or c) fitting a triprotic model for organic acids, applied to all of the STAR and KAA lake chemistry samples as per Lydersen et al. 2004, Hruska et al. 2001, or Driscoll et al. 1994.
- Method a) has the advantage of using data in a pH range where it can be assumed that the anion deficit is entirely due to strong organic acids (weaker organic anions will be protonated), but has the weakness that organic anions in the Adirondacks may be of different character than those found in EEM lakes.
- Method b) has the advantage of using local data, but we would need to derive regressions from data with a higher pH range than that recommended by Lawrence et al. (2007, 2013). For method b), we have ~14 lake samples with pH values in the range from 4.5 to 5.1 based on the STAR and EEM sampling (LAK028, LAK042, LAK054, LAK056). Most of these samples (11 of 14) come from LAK028. None of the additional 40 lakes sampled in the Kitimat Airshed Study had a pH below 5.1. Two lakes sampled by Environment Canada for the Prince Rupert Airshed Study had high DOC and pH values below 5.1 (NC313 - pH 4.84; DOC 16 mg/l; NC360 - pH 4.91, DOC 12 mg/l), so we could get up to n=16, which is about half the sample size of Lawrence et al. (2007). The DOC in these 16 samples varies from 4.5 to 16 mg/L, so there might be enough contrast to get a weak regression line between anion deficit and DOC, from which we could estimate strong organic anions and apply the BCS approach.
- Method c) involves fitting a triprotic model (3 pK values for organic anions) to all of the data, and then estimating the strong organic acid component.
- We propose to compare methods a), b) and c). Methods a) and c) are more defensible.
- Inorganic Al was measured in 2013; total Al and dissolved Al has been measured every year. Analyses of the 2013 data could be used to determine how inorganic Al is related to dissolved Al, pH and DOC in EEM lakes.

- In the Comprehensive Review, we'll assess the variability, strengths and weaknesses of these three measures (i.e., Gran ANC, CBANC, and BCS) and compare them. If appropriate, analyses of ΔANC over time will be conducted with all three measures, using a weight of evidence approach.

7.2.2.1 Critical loads, exceedances and predicted changes in pH

- Re-run the SSWC model (critical loads & exceedances) and ESSA-DFO model (predicted pH at steady-state) based on water chemistry data for all lakes sampled from 2012-

2018 (original 40 STAR lakes, plus any lakes from the Kitimat Airshed Assessment, sampled in 2013, that fit within the Rio Tinto CALPUFF modelling domain).

  - Re-run SSWC model with 2012 Critical Loads (CLs), 2012 water chemistry and updated CALPUFF predictions of deposition under 2016-2018 emissions, as well as 35 and 42[3] tpd; get revised estimates of exceedances.
    - Run sensitivity analyses of CLs (e.g., run model with 2016-2018 water chemistry - post-KMP conditions for EEM lakes only).
    - Examine effects of using CB-ANC rather than Gran ANC.
    - Sensitivity analysis of runoff assumptions (using WRF model)
  - Re-run ESSA-DFO model based on current 2012 water chemistry and updated CALPUFF predictions of deposition under 2016-2018 emissions, as well as 35 and 42 tpd.
    - Run sensitivity analyses (e.g., run model with 2016-2018 water chemistry; post-KMP conditions for EEM lakes only).
    - Sensitivity analysis of runoff assumptions (using WRF model)
    - Examine effects of using CBANC rather than Gran ANC.
    - Empirical estimate of F-factor, original SO_4 for LAK028.
- Compare different scenarios with new inputs with original STAR results.
- Estimate F-factor in those lakes where there has been sufficient chemical change to do so, and compare to the assumed F-factor. [Quite close for LAK028, see 2016 EEM tech report].
- Compare soil CL results with aquatic CL results [may get moved to section on holistic synthesis].

7.2.2.2 *Temporal patterns in water chemistry*

- **General Patterns of Variability and Change**
  - Scatter plots to look at relationships among emissions, precipitation and water chemistry variables of interest (i.e., SO_4, ANC, pH, DOC, BC, Cl, Al)
  - Simple graphs of changes over time in mean values of each variable of interest for each lake (as included in previous EEM reports)
  - Overview of statistical power analyses from 2015 EEM tech memo and implications (with only 3 years of post-KMP observations, statistical power will generally be low for pH, but somewhat better for ANC)
- **Statistical Analyses of Trends and Temporal Patterns, and comparison to EEM thresholds**
  - **EEM Thresholds:** 0.3 units for ΔpH; lake-specific thresholds for ΔANC that correspond to 0.3 units of ΔpH in each lake; analysis will consider a range of ANC thresholds, derived from multiple ANC titrations performed at Trent University
  - **Focal Questions:** *Within each of the seven sensitive EEM lakes, use a weight of evidence approach to determine how much change has occurred in each chemical indicator of interest (Y in examples below) between the pre-KMP period and the*

[3] We considered running a separate 30 tpd scenario, but 2016-2018 actuals will serve as the ~30 tpd future steady state case because the average of the 2016-2018 emissions is 29.3 tpd (27.8 tpd, 29.5 tpd, and 30.6 tpd in 2016, 2017, and 2018 respectively).

post-KMP period? How likely is it that the change in pH and ANC exceeds the EEM thresholds?

- **Methods for annually sampled lakes.**
  - We plan to use the simplest methods first (in which all sources of variation are present in the data), and then explicitly account for individual sources of variation to improve our understanding of the sources of variation.
  - We propose 8 analyses, which build incrementally, and are applied using both frequentist and Bayesian approaches.
  - If the frequentist approach shows a clear result for a lake (e.g., 95% confidence intervals for ΔANC do not overlap that lake's threshold for ΔANC) then there's no need to proceed with the Bayesian analysis for that parameter in that lake.
  - To simplify the presentation in the Comprehensive Report, and minimize confusion, we'll present the most scientifically defensible approach (likely the later analyses in the sequence presented below). We'll only include additional sensitivity analyses in the appendices if they're helpful in clarifying the results and add incremental value and understanding. This is similar to the preparation of a journal paper, where only the most scientifically defensible analytical method is included, with sensitivity analyses as required.

Frequentist approach (use alpha=0.01 to account for multiple tests):

1. Two-sample Before-After t-tests of 2012 chemistry vs. 2016-2018 for each individual lake, just using mean values for each year
   - This is the simplest analysis, providing (for each lake) an estimate of the change in the mean value of each chemical component between the pre-KMP period (2012) and the post-KMP period (2016-2018). This analysis does not account for various sources of variation (e.g., natural variability unrelated to the smelter, variability within the October sampling period).
   - It will be very difficult to show a statistically significant change given only 1 pre-KMP observation and 3 post-KMP observations. Calculate Minimum Detectable Difference (MDD) to demonstrate what level of change would be statistically significant.
   - Apply methods of Kilgour et al. 1998.
   - *Form of test:* $Y_t \sim BA$; where *Y* is the overall mean across both before and after categories of years, and BA is the effect of Pre-KMP (Before) vs Post-KMP (After)
   - *Assumptions:*
     - The chemistry of component Y in a given lake is a function only of the time period (before vs after).
     - The mean value of component Y represents the state of component Y in a given year.

        - Use process error from 2016-18 to provide estimated variability for 2012 measurement.

2. Two-sample Before-After test of 2012 chemistry vs. 2016-2018 for each individual lake, using 4 measurements from each year.
    - This method provides greater insight than method 1, as it accounts for unequal sampling in various years and lakes (e.g., 1 sample in some lakes in some years, 4 samples in most lakes and years). The estimated before-after change between the pre-KMP and post-KMP periods removes the effect of natural variability within the sampling period.
    - *Form of test:* $Y_t \sim BA + YRE$, where YRE = Year Random Effect due to multiple samples taken in the October sampling period;
    - *Assumptions:*
        - Same as analysis 1, plus:
        - The chemistry of component Y in a given lake is a function of the time period (before vs after), as well as the variability within the October sampling window
        - All of measured values of component Y during the October sampling window represent the state of component Y in a given year

3. BACI (Before-After-Control-Impact) approach: Data from one sensitive lake vs. group of 3 control lakes.
    - Focal questions for this analysis are slightly different: *how much change has occurred in chemical indicator Y between the pre-KMP period and the post-KMP period, relative to the changes observed in the control lakes? Is the direction and magnitude of change in the sensitive lake different from what was observed in the control lakes?*
    - We will describe in section 7.2.1 how the control lakes were selected, and their similarities in various attributes to the sensitive EEM lakes.
    - This method explicitly accounts for natural variation in lake chemistry due to factors other than the smelter (e.g., year to year changes in precipitation and temperature) which affect both the EEM lakes and the control lakes.
    - The effect of the smelter on a given lake is expressed in terms of how the chemical changes over time (between the pre-KMP and post-KMP periods) differ from the changes observed in the control lakes (taken as a group), taking into account before-after changes that have affected all lakes.
    - *Form of test:* $Y_t \sim BA + ICE + BACI\ Interaction + LRE + YRE$, where
        - ICE = Impact/Control Effect;

- BACI Interaction = Treatment * Time Interaction (difference in how impact and control lakes changed over time; key variable in the analysis);
- LRE = Lake Random Effect due to consistent differences between lakes (e.g., the sensitive lake always has a lower pH than two of the control lakes);
- BA and YRE as in analysis 2

- *Assumptions:*
  - Same as analysis 2, plus:
  - Observed value from 2013 serves as a pre-KMP value for the control lakes (control lakes were not sampled in 2012); implicitly assume that 2012 and 2013 were similar
  - Variability in the control lakes over 2013, 2015-2018 used to help estimate variability in the sensitive lake in 2012

4. BACI approach with individual measurements rather than just using mean values. Same model as analysis #3 + lake*year interaction random effect. The differences between analyses 4 and 3 are analogous to the differences between analyses 2 and 1. The form of output is the same as in method #3, but now takes into account the variability observed during the sampling period.

5. Method 4 + assumption of no change in control lakes. If we assume that there's no B/A change in control lakes (forcing ΔY in control lakes to be zero), the B/A change in the sensitive lake becomes the absolute change in component Y. This would involve removing some of the terms in the model 4. Note that the range of fluctuation in pH in the control lakes over 2013 and 2015-2018 is generally close to the range of pH measurement error of ± 0.2 pH units. The form of output is the same as in method #4.

6. Adding other measurements (e.g., ALS pH in addition to Trent University pH), or covariates (such as emissions or precipitation) to explain year to year variation. If these covariates help to explain variability in chemistry, then we could use 2013-2015 data, in addition to 2012 and 2016-2018. In terms of the form of the test, we would add covariates into the linear model to ascribe some of the observed changes in chemical components to these covariates (e.g., increase in $[SO_4]$ with emissions of SO_2 in the year prior to October sampling; decreases in component concentrations with precipitation in the week prior to sampling). The overall form of the results would be similar to method 4, but would potentially separate out variation due to changes in emissions, or due to fluctuations in precipitation (if these covariates are shown to be correlated with the measured chemistry).

7. We could also explore using Principle Components Analysis (PCA) on each lake's measurements, and then use the PC in the BACI analysis, and compare the results. The PCA approach would describe (for each lake) the combination of chemical constituents which explains the greatest amount of variability in the 2012-2018 dataset. The overall form of the results would be similar to method 4, but would show the changes in the first principle component, over time and relative to the control lakes.

8. Building on analysis #6, conduct an analysis with 3 time periods: Before (2012); Transition (2013-2015); and After (2016-2018), using covariates established in analysis #6. Advantage is that having more years gives a better estimate of process error. The overall form of the results would be similar to method 4, but with three time periods (before, transition, after) rather than just two (before, after).

9. Examination of the temporal trends in lake chemistry within groups of lakes (e.g., those closest to the smelter, those at an intermediate distance, and those furthest away). Grouping lakes will provide higher levels of statistical power, and is the approach used by Stoddard et al. (1996, 1998, 2003) for assessing trends in the northeastern U.S. Due to the paucity of baseline data, analyses of covariance may be helpful in elucidating trends (e.g., Wiens and Parker 1995).

Bayesian approach: As noted above, we would only apply a Bayesian approach in situations where the frequentist approach is unable to clearly reject the hypothesis of a smelter effect. For the Bayesian approach, we would use the BEST approach (Kruschke 2013), applied to methods 1-8. Results are expressed in terms of the posterior belief that a lake's change in pH or ANC has exceeded an EEM threshold. For other chemical parameters, results are expressed in terms of the credible range of changes from pre-KMP to post-KMP periods. Sensitivity analyses would include an analysis of the effects of assumed priors.

- **Methods to be used for intensively monitored lakes:**
  - Assess variability in pH on various time scales (i.e., daily, weekly, monthly, seasonally, storm effects).
  - Assess various covariates to explain variability in pH (time of day, season, lake elevation change, hourly CALPUFF predictions of S deposition during 2016-2018).
  - Could apply methods 1-6 using the mean pH values for the October index period, accounting for serial correlation in the data.
  - Use "process control plots" to identify potential anomalies in continuously monitored pH (e.g., storm events), or could do analysis to determine effects of storm events first.

7.2.2.3 Assessing changes in water chemistry with respect to STAR and EEM

- Empirical Changes in Water Chemistry Relative to Steady-state Predictions
  - Examine actual change in SO_4, ANC and pH vs. predicted ANC and pH change at steady state from the ESSA/DFO model, and expected lake [SO_4] from CALPUFF post-KMP predictions vs. observed [SO_4].
  - Redo ESSA/DFO and SSWC model predictions using specific CALPUFF runs for current emissions (2016-2018; average of 29.3 tpd emissions), 35 tpd and 42 tpd.
  - Assess changes relative to both pre-KMP and pre-industrial conditions (estimated in the STAR; ESSA-DFO model predicts pre-industrial ANC and pH; SSWC model predicts pre-industrial base cations).
  - Assess influence of runoff assumptions.

7.2.3 Weight-of-Evidence approach for assessing causality

- Evidentiary framework for identifying patterns consistent with smelter-driven acidification
- Summarize how we have applied EEM evidentiary framework to assess evidence that observed changes in chemistry are causally related to KMP (based on empirically observed changes – Table 17, pg. 43 in EEM Plan).
- What are the most likely causes of the observed chemical changes in each of the seven sensitive lakes? (e.g., STAR table 9.4-4)

7.2.4 Episodic acidification studies

- See section 7.2.2.2
- Analyze continuous pH data (3 lakes + Anderson Creek) with respect to episodic acidification.
  - Look at Lakelse wet deposition data and lake level data to assess if correlated with observed pH episodes.
  - Summarize analyses of factors causing variation in water chemistry during the October index period (only period with full chemistry analyses).
- Research Project by Dr. Paul Weidman (pending availability of results)

7.2.5 Kitimat River water quality

- Monitoring and analyses methods

7.2.6 Other data and/or analyses previously reported

- BRIEFLY mention other pieces and cite past reports for details:
  - Fish sampling – methods and extent of fish sampling under the EEM
  - Amphibians work under the EEM
  - Flow data
  - Lake level monitoring
  - Water residence time – report on estimated residence time of water for lakes with detailed bathymetry

7.2.7 Assessment of acceptable or unacceptable impacts to aquatic receptor

- The assessment of the impacts to the aquatic receptor as "acceptable" or "unacceptable"[4] is directly linked to the KPI
  - If the KPI threshold associated with facility-based mitigation in the EEM is exceeded, this will be 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 will be identified as "acceptable".
  - NOTE: all impacts, regardless of classification will be explored, analyzed, interpreted and documented in detail.

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

- Provide an overview of the results, referencing past EEM reports and Tech Memos, and put details in an appendix.
- Discuss what has been learned overall regarding KMP effects on aquatic ecosystems thus far under the first 6 years of the EEM Program.
- Explain whether questions W1, W2, W3 and W4 have been answered, and whether any new questions have emerged.
- Explain whether a KPI threshold been reached, and if so, what actions were taken, or need to be taken.
- Explain what changes if any have been already made to the KPI (the KPI itself, methods, or thresholds) or the informative indicators.

7.3.1 Knowledge gained

7.3.1.1 Ability to detect changes in water chemistry

- This IS reported elsewhere, but the results are so fundamental to much of our interpretation and modifications (especially relevant to interpretation of rest of the results).
  - What has been learned from the statistical power analysis and the analyses in this report about the ability to detect changes in water chemistry?

7.3.1.2 Spatial and temporal patterns in water chemistry

- Observed Changes and Variability
- Statistical Analyses of Trends and Temporal Patterns
- Observed Changes Relative to Steady-state Predictions
- Application of multiple lines of evidence
- Observed Changes Relative to KPI Thresholds
- Statistical Evaluation of Observed Changes Relative to KPI Thresholds
- Results of Sensitivity Analyses

---

[4] 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 SO2 daily discharge limit shall revert back to 27 Mg/d, unless the Director amends the discharge limit."

7.3.1.3 Critical loads, exceedances and predicted changes in pH

- Results of scenarios with new inputs, compared to STAR results (by lake)
  - Are the results substantially different?
  - Were the original results over/underestimates?
  - What are the implications of this – lakes are more likely less/more sensitive?
  - How to results from aquatic CL models compare with soil CL models?
- F-factor – new empirically based estimates vs. STAR assumptions

7.3.1.4 Episodic acidification studies

- Results from analyses of continuous pH monitoring data
- Results from research project by Dr. Paul Weidman (pending availability of results)

7.3.1.5 Kitimat River water quality

- Summary of results of water quality monitoring

7.3.1.6 Results from previously reported analyses

- BRIEFLY mention other pieces and cite past reports for details:
  - Results of Kitimat Airshed Assessment
  - Fish sampling
  - Amphibians
  - Flow data
  - Lake level monitoring
  - Water residence time for lakes
  - Non-EEM sites

7.3.2 Modifications to the EEM Program

7.3.2.1 Adjustments to sampling program

7.3.2.2 Modification of methods

7.3.2.3 Refining how we interpret the results

- Variability in pH and Issues with Low Power
- Need to Examine Other Metrics (particularly ANC)

7.3.3 Comprehensive synthesis ('pulling all the pieces together')

7.3.3.1 Changes to and/or confirmation of STAR results and assumptions

- i.e., Emissions/deposition, F-factor, Critical Loads and Exceedances, Predicted pH

7.3.3.2 Summary of observed changes in lake chemistry, 2012-2018

7.3.3.3 Exceedances of EEM indicators

- i.e., KPI and informative indicators

7.3.3.4 Application of the Evidentiary Framework

- For each lake, does the evidence suggest that acidification has occurred and is causally related to KMP (application of evidentiary framework in Table 17 of EEM Plan)?

7.3.4 Conclusions

7.3.4.1 Does the Weight of Evidence indicate that KMP has contributed to the acidification of aquatic ecosystems?

7.3.4.2 Summary of answers to questions in the STAR and EEM

7.3.4.3 Assessment of acceptable or unacceptable impacts on aquatic receptor

7.3.4.4 What outstanding questions still require further or ongoing investigation?

7.3.4.5 What new questions have emerged?

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

7.4.1 Recommendations regarding EEM lakes

NOTE: The following outlines the categories under which recommendations could potentially be made. Additional notes describe some of the topics that we currently anticipate will warrant discussion. However, the actual recommendations will be an outcome of the comprehensive review process and design work in 2020 – the notes in this section are not intended to suggest or reject any particular recommendation.

- Recommended changes to monitoring methods, frequency or extent, to be ranked in terms of their importance to the EEM program
  - Continue monitoring EEM lakes?
  - All EEM lakes?
  - Annual and/or within-season?
  - Full lake chemistry sampling?
  - Continuous pH monitoring?
  - Control lakes?
- Recommended changes to the KPIs or informative indicators and thresholds
  - Identification and discussion of criteria for choosing effective KPIs
    - e.g., timeliness of response to changes in deposition, relationship to biological change, ability to measure/model with acceptable of reliability, appropriate balance of Type I and Type II errors
  - Discussion of benefits and limitations of current KPI
  - Potential changes to KPI of $\Delta pH = 0.3$
    - Higher variability / lower statistical power for pH than for ANC
    - Logarithmic nature of pH means that actual pH level is also important, not just ΔpH (e.g., change from pH 5.0 to 4.7 is 100 times greater change in [H+], and biologically very significant, whereas change from pH 7.0 to 6.7 is not biologically significant)
  - Discussion of other proposed alternatives for KPIs and/or thresholds, including:
    - Tim Sullivan's proposal for pH and ANC:

1. [ΔpH of ≥ -0.3] AND [pH < lake-specific pH threshold to protect biota] OR
2. [lake-specific ΔANC equivalent to ΔpH of 0.3] AND [lake-specific ANC threshold equivalent to lake specific pH threshold]
3. Biological rationale for thresholds (e.g., Baldigo et al. (in review), Lydersen et al. 2004, Holt et al. (2003), Lien et al. 1997, Baker et al. 1990)
4. Application of evidentiary framework (Table 17 in section 7 of EEM Plan), including analysis of patterns in marine salt loading (Cl), organics (DOC) and climate (yr-to-yr and within year variation)
5. Review of the literature to determine lake-specific levels of pH and ANC to use as appropriate thresholds

- Potential for adding exceedances of CL as a KPI (Frazer's proposal)

- Recommended changes to EEM analyses going forward
  - Discuss relative benefits and limitations of Gran ANC vs. CBANC vs. BCS.
  - Discussion of relative benefits and limitations of frequentist vs. Bayesian statistical approaches.
  - Effects of wetlands on lake chemistry (effects of deposition on wetlands will be discussed in section 6 on terrestrial ecosystems).
  - Potential use of biological indicators (e.g., zooplankton; fish species tolerance; eDNA)
  - Potential inclusion of inorganic monomeric Al
  - Potential use of critical loads and exceedances as indicators

7.4.2 Recommendations regarding non-EEM lakes

- Reiterate the recommendations from the relevant annual reports
- Additional recommendations as appropriate

8 Holistic Understanding of KMP Effects on the Environment and Human Health across all Lines of Evidence

- Provide a map showing all sampling/monitoring locations across pathways and receptors.
- Look across all lines of evidence and receptors, integrate information across disciplines, and provide a clear summary of what we've learned about the links between SO_2, human health and ecosystems.
  - Consider including a Looking Outward Matrix to organize this (example template shown in Table 3 below).
  - Summary of KPI, thresholds and results over 2012-2018 (example template in Table 4 below)
  - Synthesis of deposition-driven S results across vegetation, terrestrial ecosystems and aquatic ecosystems
  - Synthesis of SO_2 concentration-driven results across human health and vegetation

- Summarize what we've learned in terms of the STAR source-pathway-receptor diagram, and identify gaps in data or knowledge.

Table 3. Looking Outward Matrix showing information links among pathways and receptors (example for illustration of the matrix format).

To → / From ↓	Atmosphere	Human Health	Vegetation	Soils	Surface Waters
Atmosphere		[SO_2] vs. KPI & respiratory responses	[SO_2] vs. vegetation thresholds	Deposition vs CL, and vs. soil base saturation	Deposition vs CL, and vs. acidic episodes
Human Health					
Vegetation	[S] in needles vs. observed / predicted [SO_2] in air				
Soils			Soil CL exceedance vs. Vegetation observations		Soil CL exceedance vs. Lake CL exceedance
Surface Waters	Use Δ lake [SO_4] to inform CALPUFF	Water quality in Kitimat River near water treatment plant		BC weathering rate from [BC] and runoff vs. soil estimates	

Table 4. Summary of KPIs, thresholds and performance 2012-2018.

	KPIs	Threshold for increased monitoring	Threshold for receptor-based mitigation	Threshold for facility-based mitigation	Results over 2012-2018
Human Health					
Vegetation					
Soils					
Surface Waters					

9 Cited References and Reports

These will include the following references cited in Section 7 of this outline:

Baker, J.P., D.P. Bernard, S.W. Christensen, M.J. Sale, J. Freda, K. Heltcher, D. Marmorek, L. Rowe, P. Scanlon, G. Suter, W. Warren-Hicks, and P. Welbourn. 1990. Biological Effects of Changes in Surface Water Acid-Base Chemistry. NAPAP Report 13. In: National Acid Precipitation Assessment Program, Acidic Deposition: State of Science and Technology. Volume II, 1990.

Driscoll, C.T., M.D. Kehtinen and T.J. Sullivan. 1994. Modeling the acid-base chemistry of organic solutes in Adirondack, New York, lakes. Water Res. Research. 30 (2): 297-306.

Evans, C.D., R. Harriman, D.T. Monteith and A. Jenkins. 2001. Assessing the suitability of acid neutralizing capacity as a measure of long-term trends in acidic waters based on two parallel datasets. Water, Air and Soil Pollution 130: 1541-1546.

Hemond, H.F. 1990. Acid neutralizing capacity, alkalinity, and acid-base status of natural waters containing organic acids. Environmental Science and Technology 24: 1486-1489.

Henriksen A., P.J. Dillon, and J. Aherne. 2002. Critical loads of acidity for surface waters in south-central Ontario, Canada: regional application of the steady-state water chemistry (SSWC) model. Canadian Journal of Fisheries and Aquatic Sciences 59: 1287-1295.

Holt, C.A., N.D. Yan, and K.M. Somers. 2003. pH 6 as the threshold to use in critical load modeling for zooplankton community change with acidification in lakes of south-central Ontario: accounting for morphometry and geography. Can. J. Fish. Aquat. Sci. 60:151-158

Hruska, J., H. Laudon, C.E. Johnson, S. Kohler and K. Bishop. 2001. Acid/base character of organic acids in a boreal stream during snowmelt. Water Res. Research 37 (4): 1043-1056.

Kilgour, B.W., K.M. Sommers, D.E. Matthews. 1998. Using the normal range as a criterion for ecological significance in environmental monitoring and assessment. Ecoscience 5(4): 542-550.

Kruschke 2013. BEST - Bayesian Estimation Supersedes T-Test , J Exp Psychol Gen. 142(2): 573-603

Lawrence, G. B.; Sutherland, J. W.; Boylen, C. W.; Nierzwicki-Bauer, S. A.; Momen, B.; Baldigo, B. P.; Simonin, H. A. Acid rain effects on aluminum mobilization clarified by inclusion of strong organic acids. Environ. Sci. Technol. 2007, 41 (1), 93−98.

Lawrence, G.B., J. E. Dukett, N. Houck, P. Snyder, and S. Capone. 2013. Increases in dissolved organic carbon accelerate loss of toxic Al in Adirondack lakes recovering from acidification. Environ. Sci. Technol. 2013, 47, 7095−7100. dx.doi.org/10.1021/es4004763

Lien, L., G.G. Raddum, A. Fjellheim, A. Henriksen. 1996. A critical limit for acid neutralizing capacity in Norwegian surface waters, based on new analyses of fish and invertebrate responses. Science of the Total Environment 177: 173-193.

Lydersen, E., T. Larssen, E. Fjeld. 2004. The influence of total organic carbon (TOC) on the relationship between acid neutralizing capacity (ANC) and fish status in Norwegian lakes. Science of the Total Environment 326 (2004) 63–69. doi:10.1016/j.scitotenv.2003.12.005

Marmorek, D.R., R.M. MacQueen, C.H.R. Wedeles, J. Korman, P.J. Blancher, and D.K. McNicol. 1996. Improving pH and alkalinity estimates for regional-scale acidification models: incorporation of dissolved organic carbon. Canadian Journal of Fisheries and Aquatic Sciences 53: 1602-1608.

Stoddard, J. L., A. D. Newell, N. S. Urquhart, and D. Kugler. 1996. The TIME project design: II. Detection of regional acidification trends. Water Resources Research 32:2529-2538.

Stoddard, J.L., C.T. Driscoll, J.S. Kahl, and J.H. Kellogg. 1998. A regional analysis of lake acidification trends for the northeastern U.S. 1982-1994.

Stoddard, J.L., J.S. Kahl, F.A. Deviney, D.R. DeWalle, C.T. Driscoll, A.T. Herlihy, J.H. Kellogg, P.S. Murdoch, J.R. Webb, and K.E. Webster. 2003. Response of Surface Water Chemistry to the Clean Air Act Amendments of 1990. EPA 620/R-03/001. US Environmental Protection Agency, Office of Research and Development. National Health and Environmental Effects Research Laboratory, Research Triangle Park, NC 27711. 92 pp.

Wiens, J.A. and K.R. Parker. 1995. Analyzing the Effects of Accidental Environmental Impacts: Approaches and Assumptions. Ecol. Applications 5 (4): 1069-1083. https://doi.org/10.2307/2269355

10 Cited EEM Technical Memos

Appendices

- Appendices will be prepared for Comprehensive Review details not appropriate for the main CR Report

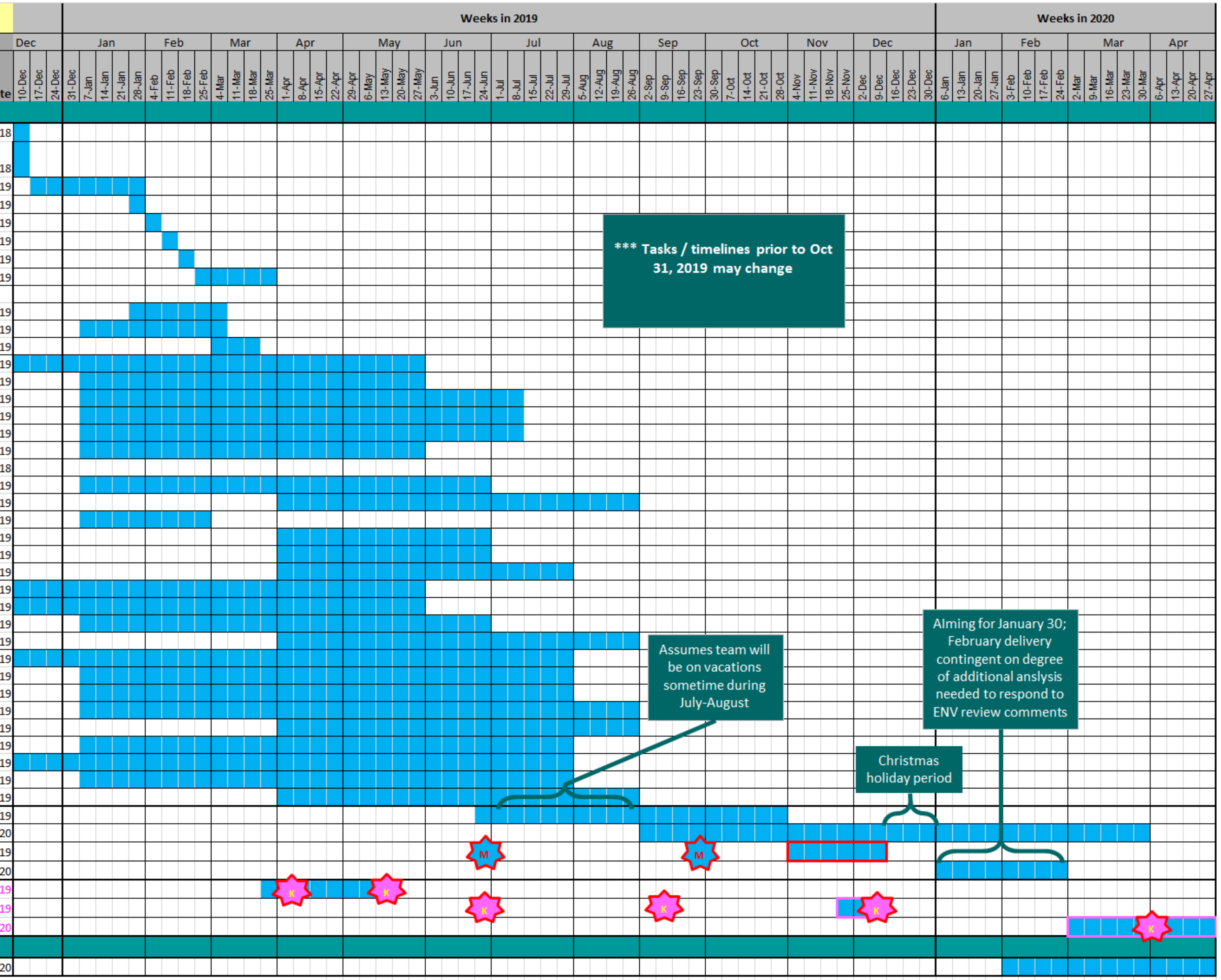
TOR Item 3: Schedule of Comprehensive Review Tasks

Schedule for EEM 2019 Comprehensive Review ***

READ ME

Bars autogenerate from:

Task	Sub-task	Start Date	End Date
EEM 2019 Comprehensive Review and Report ***			
1.1. Workshop to discuss TOR for EEM 2019 Comprehensive Review		10-Dec-18	14-Dec-18
Terms of Reference	Updated TOR comments tracking table to QPs	10-Dec-18	14-Dec-18
	QP writing TOR sections	14-Dec-18	1-Feb-19
	Merging QP sections & consistancy editing	28-Jan-19	1-Feb-19
	QP cross-over review	4-Feb-19	8-Feb-19
	RT Review	11-Feb-19	15-Feb-19
	ENV review	18-Feb-19	22-Feb-19
	Detailed TOR Production	25-Feb-19	31-Mar-19
	a) Model SO2 emissions for 2016-2018 post KMP		
	AQ monitoring station and data audits	28-Jan-19	4-Mar-19
	SO2 Dispersion Model Plan writing	7-Jan-19	4-Mar-19
	ENV approvel of model plan	4-Mar-19	18-Mar-19
1.2. **Pathways analyses**	SO2 Dispersion modeling	3-Sep-18	30-May-19
	b) Compare to monitoring data	7-Jan-19	30-May-19
	c) Report on progress of 2-year seasonality study	7-Jan-19	12-Jul-19
	d) Compare wet dep. monitoring data to model output	7-Jan-19	12-Jul-19
	e) Compare dry deposition estimates to model output	7-Jan-19	12-Jul-19
	f) Report on air quality monitoring network optimization	7-Jan-19	27-May-19
	g) Develop and apply passive monitoring framework	3-Sep-18	27-Mar-18
	g) Address informative indicators	7-Jan-19	24-Jun-19
	g) Address other points in the outline; write draft chapter	1-Apr-19	31-Aug-19
1.3. **Human health analyses**	a) Evaluate KPI results for 2017-2018	7-Jan-19	28-Feb-19
	c) Assess relevance of passive monitoring data	1-Apr-19	30-Jun-19
	d) Address KPI and informative indicator	1-Apr-19	30-Jun-19
	e) Address other points in the outline; write draft chapter	1-Apr-19	31-Jul-19
1.4. **Vegetation analyses**	a) Evaluate visual veg inspection results for 2014-2018	3-Dec-18	27-May-19
	b) Evaluate S, F in Hemlock needle results for 2014-2018	3-Dec-18	27-May-19
	c) Address KPI and informative indicator	7-Jan-19	24-Jun-19
	d Address other points in the outline; write draft chapter	1-Apr-19	26-Aug-19
1.5. **Soils analyses**	a) Evaluate results of long-term plot sampling *	3-Sep-18	31-Jul-19
	b) Evaluate implications of long-term plot results	7-Jan-19	31-Jul-19
	c) Rerun SSMB and CL models	7-Jan-19	31-Jul-19
	d) Address KPIs and informative indicators	7-Jan-19	26-Aug-19
	e) Address other points in the outline; write draft chapter	1-Apr-19	26-Aug-19
1.6. **Lakes / aquatic ecosystems** analyses	a) Re-run the SSWC, ESSA-DFO, CL models	7-Jan-19	31-Jul-19
	b) Evaluate water sampling results 2013-2018	3-Sep-18	31-Jul-19
	c) Address KPI and informative indicators	7-Jan-19	31-Jul-19
	d) Address other points in the outline; write draft chapter	1-Apr-19	26-Aug-19
2.1. Prepare **draft EEM 2019 Comp. Review Report For ENV**		24-Jun-19	31-Oct-19
2.2 Prepare **Summary Report for KPAC**		2-Sep-19	31-Mar-20
3. **ENV review** of draft EEM 2019 Comprehensive Review Report **		1-Nov-19	13-Dec-19
4. Prepare **final EEM 2019 Comprehensive Review Report**		2-Jan-20	28-Feb-20
5. Stakeholder engagement	a) KPAC mtng to present Comp. Review approach	25-Mar-19	15-May-19
	b) KPAC meeting updates on Comp. Review process	20-Nov-19	15-Dec-19
	c) KPAC workshop to present Comp. Review results	1-Mar-20	30-Apr-20
Design of EEM Program post-2019			
Done collaboratively with Rio Tinto, QPs, and ENV		3-Feb-20	30-Apr-20



* If exceedance is expected in some areas, in summer 2019 the sampled soils will be analyzed for exchangeable base cations (Soils analysis task 1h in the Technical Memo)

** Date for finalization is dependant on the nature and extent of comments received from ENV.

*** Comprehensive review schedule will be re-evaluated, modified and re-baselined following completion and finalization of the Terms of Reference for undertaking the 2019 Comprehensive Review.

M = milestone updates for ENV

K = milestone updates for KPAC

[LastPage bookmark – do not delete]