



Prince Rupert Airshed Study

Summary

September 2016

BRITISH COLUMBIA MINISTRY OF ENVIRONMENT
ENVIRONMENTAL PROTECTION DIVISION
REGIONAL OPERATIONS BRANCH

1 Executive Summary

LNG export facilities proposed for the Prince Rupert area represent additional emissions to an airshed that supports a flourishing marine transport industry. To understand potential constraints and prepare for necessary permitting decisions, the BC Ministry of Environment commissioned a high-level study of the Prince Rupert area (identified in Figure 1)..The study considered the potential effects of nitrogen dioxide, sulphur dioxide, and fine particulate matter on four receptor groups: human health, vegetation, soils, and lakes.

Results from eight different LNG build-out scenarios showed that most receptors were predicted to be at low to moderate risk in many areas., However, established effects-thresholds may be exceeded at specific locations (primarily in industrial areas) owing to the combination of existing and proposed emissions. Results indicate that impact assessment in support of Environmental Assessment Certification and subsequent permitting will require modelling and analysis using refined emissions estimates and site specific field data to manage the risk from future industrial emissions in the Prince Rupert area.

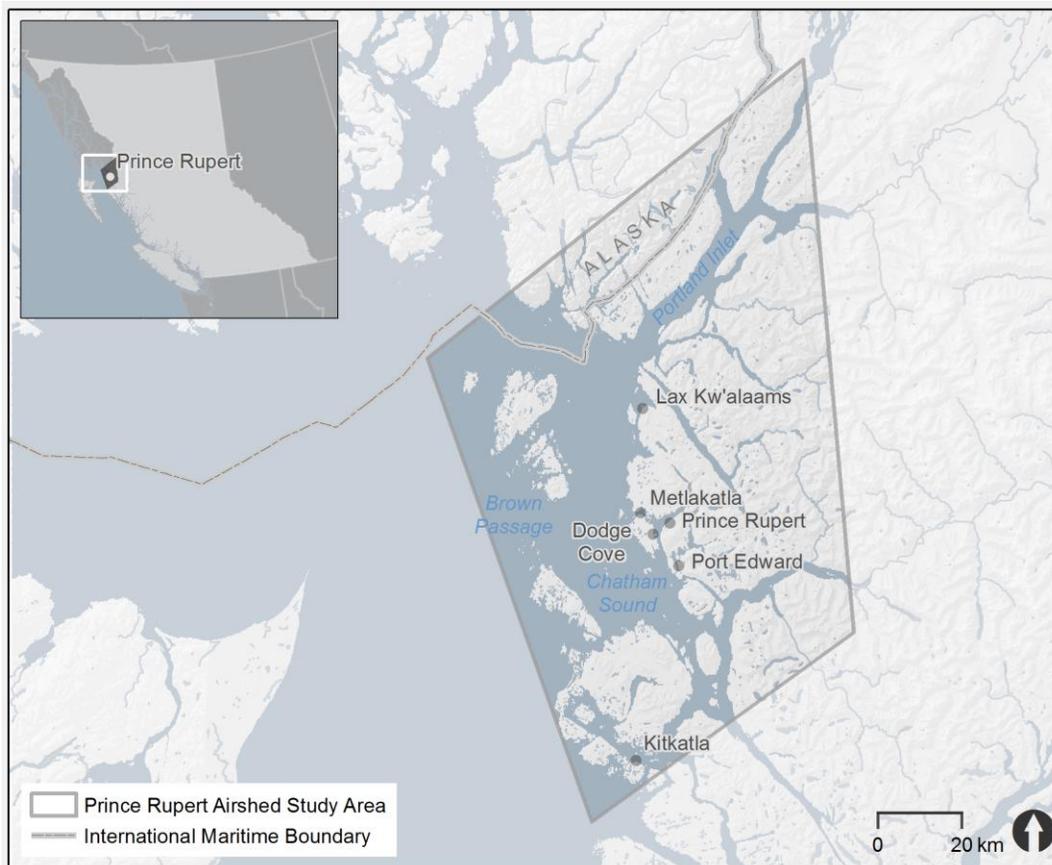


Figure 1. The Prince Rupert Airshed Study area.

2 Introduction

The Port of Prince Rupert (Port) is a protected deep water harbour connected to rail transport and is among the closest North American ports to Asian markets. It is well-suited for bulk shipping and has attracted exports of wood products (logs, pellets, and pulp), grain, coal, and containers. It is also strategically located for additional export opportunities including liquefied natural gas (LNG), potash, and other natural resources. For these reasons Prince Rupert is currently, and in the future

will be, an important centre for the transportation of products and resources. Processing, loading, and transporting bulk resources typically require the release of air emissions; as the facilities utilizing the Port grow and change, the emissions profile in this largely unconfined airshed will need to be managed to avoid potential effects.

Numerous LNG export facilities and expanded marine terminals have been proposed for the Prince Rupert area. The British Columbia (BC) Ministry of Environment (MOE) commissioned the Prince Rupert Airshed Study to understand the potential effects that proposed emissions of nitrogen oxides (NO_x – this is the sum of nitric oxide (NO) and nitrogen dioxide (NO_2)), sulphur dioxide (SO_2), and fine particulate matter ($\text{PM}_{2.5}$) might have on human health, vegetation, soil (representing terrestrial ecosystems) and lakes (representing aquatic ecosystems) in the Prince Rupert area. Air dispersion modelling was used to predict concentrations and deposition of contaminants reflecting the combination of existing and predicted emissions with regional meteorology and physical geography. Model results were compared to established thresholds to assess the potential effects of contaminants on human health and the environment, given the proposed development of LNG in association with existing industrial discharges. The study was completed by ESSA Technologies in collaboration with Trent University, Trinity Consulting, and Risk Sciences International.

The study had two phases. In Phase I, eight LNG build-out scenarios were examined and assessed for potential effects of air emissions. In Phase II, an additional scenario was considered using revised emissions estimates based upon refined engineering and design, fewer proxies, and more up-to-date information from existing sources. A base scenario was also added in Phase II. Phase I outputs are reflected in “*Prince Rupert Airshed Study Volume 1 and 2 Reports*”. Phase II outputs are reflected in “*Prince Rupert Airshed Study Supplementary Report*” The Supplementary report is based off of a significantly improved data set and the results of in the Supplementary report should be relied on by decision makers with Volume 1 and 2 providing background information and methodology.

NO_2 , SO_2 , and $\text{PM}_{2.5}$ are recognized as having possible harmful effects on human health¹ and are managed using national and provincial standards or objectives². Concentrated NO_x and SO_2 are also known to cause direct (visible injury and growth impairment from exposure to these gasses) and indirect (acidification and eutrophication from deposition of nitrogen and sulphur compounds) effects on vegetation³. Acidification and eutrophication of soils and surface waters are well documented in Europe and Eastern North America where emissions of NO_x and SO_2 were historically very high, though are now substantially reduced. Avoiding acidification and eutrophication in BC is a commitment the province made as a signatory of the Canadian Council of Ministers of Environment (CCME) Acid Rain Strategy⁴

3 Air Dispersion Modelling in the Prince Rupert Airshed

Air dispersion and deposition models are tools for estimating concentrations of air pollutants and deposition rates due to industrial or other emissions sources. Output from these models are driven by actual meteorology, terrain, elevation and land use data (all of which affect air movement), as well as detailed information about emission sources. The name of this particular dispersion model is CALPUFF.

The Prince Rupert airshed is largely unconfined to the south and west with low rolling terrain that is classified as the Hecate Lowlands. The northern and eastern extent of the airshed is bounded by

¹ (World Health Organization 2006)

² (BC Ministry of Environment 2016)

³ (Federal Environmental Agency of Germany 2004)

⁴ (Canadian Council of Ministers of the Environment 1998).

the Coast Range, and feature mountains rising to approximately 1200 m. The prevailing winds are southeasterly, with lesser westerly and northwesterly winds in season. These variables were taken into account by the air dispersion model.

4 Emission Scenarios

The cumulative emissions of eight scenarios are shown in Figure 2. SO₂ and PM_{2.5} emissions changed relatively little among scenarios as their main source was shipping and was not influenced by varying LNG turbine configurations and emission reduction technologies. In contrast, NO_x emissions strongly responded to scenarios with partial build-out and emissions reduction technologies. The scenario with the most recent and updated emissions information (from LNG proponents and the Port activities) is F_R_U. The scenario representing current emissions is the Base.

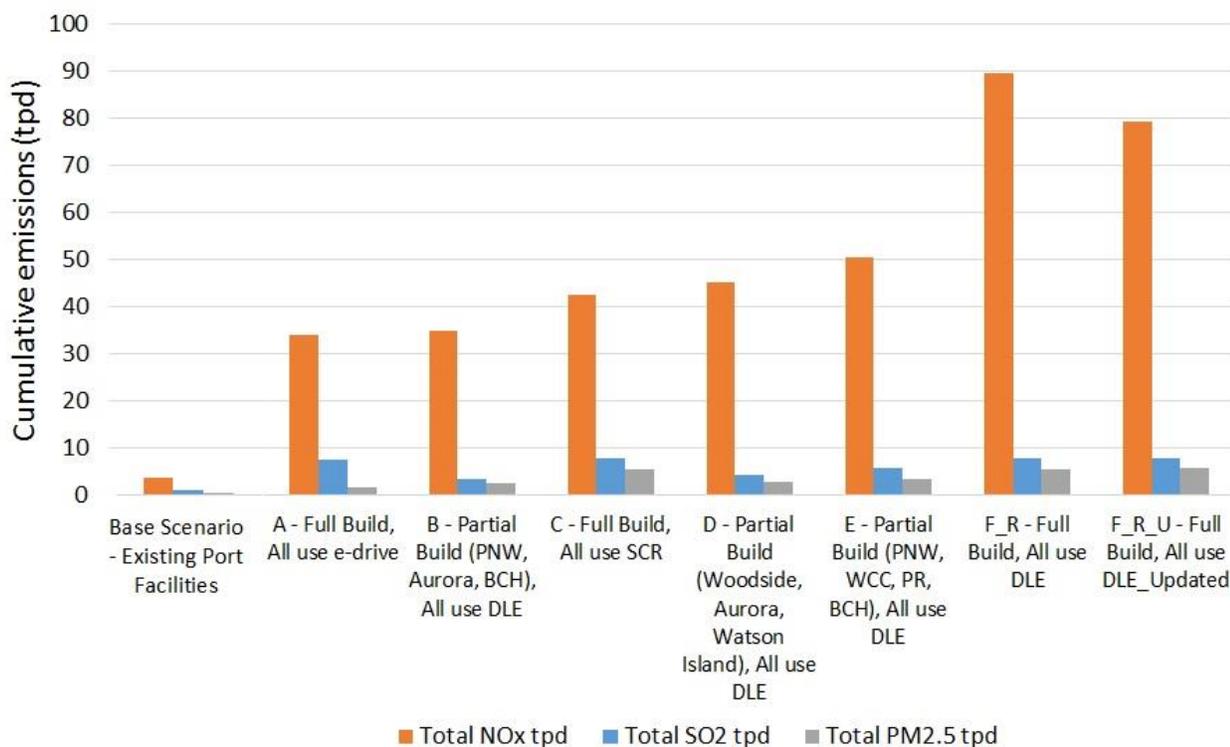


Figure 2. The cumulative emissions in tons per day (tpd) by scenario. E-drive refers to electric turbines, DLE refers to dry low emissions technology, and SCR refers to selective catalytic reduction technology.

5 Human Health

The science and knowledge on the potential impacts from SO₂, NO₂, and PM_{2.5} on human health is emerging. Effects vary due to variations in chemical and physical properties with time, region, meteorology, and source as well as level of exposure, other contaminants in the air, and individual's current health condition. Exposure to short-term high levels of NO₂ and SO₂ can impair lung function and increase respiratory distress, particularly in exercising asthmatics. PM_{2.5} can impair respiratory systems and pulmonary function⁵.

⁵ (World Health Organization 2006)

Modelled concentrations were compared to the BC Air Quality Objectives for fine particulate matter (PM_{2.5}) and the BC Interim Air Quality Objectives for SO₂ and NO₂. The results are intended to provide an indication of the level of management that may be required in this area.

Potential effects on human health were assessed at 34 different locations (Figure 3). Results indicate that a limited number of objective exceedances are predicted for areas near the industrialized areas of Prince Rupert Harbour. The same areas of concern were identified across all scenarios (including the Base case), indicating that existing emissions may play an important role in determining regional air quality. The results suggest that detailed modelling and analysis will be necessary to support airshed management and the issuance of air permits that are protective of human health.

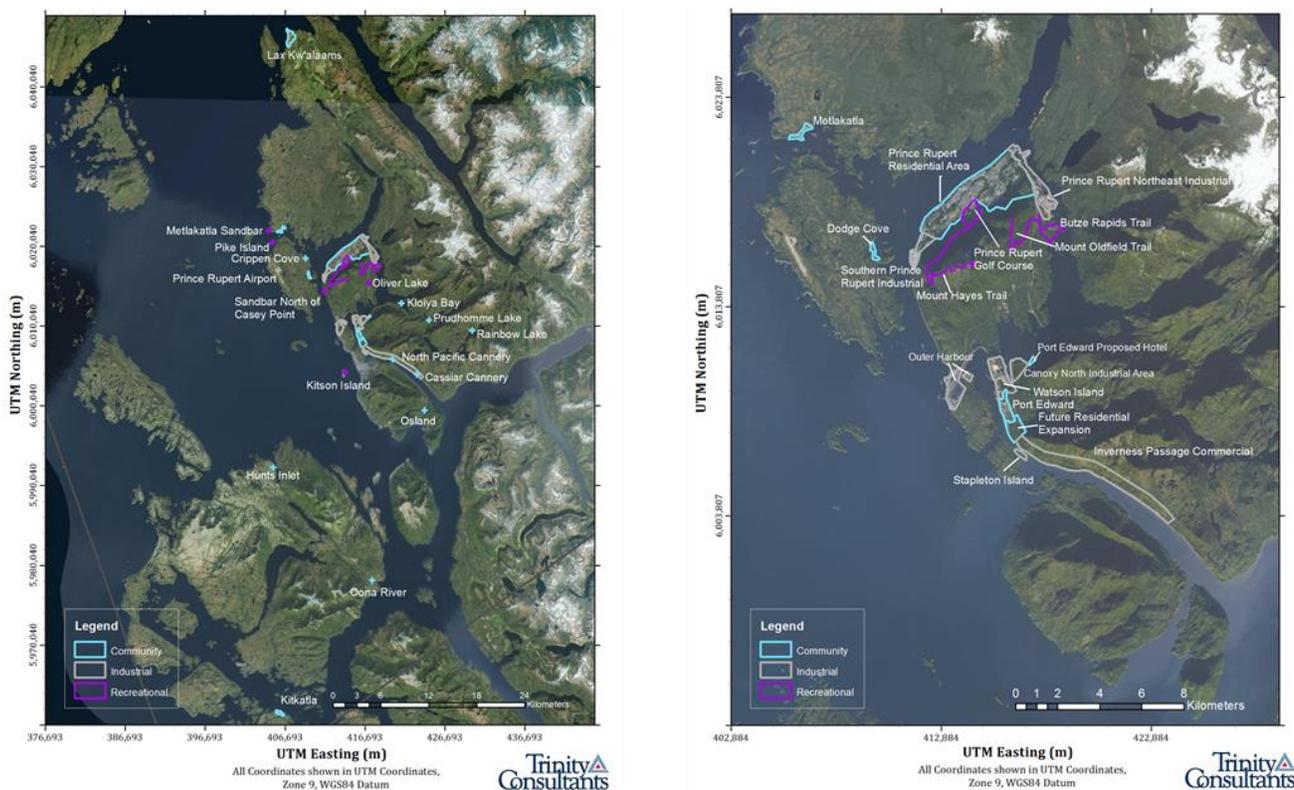


Figure 3. Left panel: location of the community, industrial and recreational/cultural receptors assessed in the study. Right panel: zoomed location of the community, industrial and recreational/cultural receptors assessed in the study.

6 Vegetation

NO_x and SO₂ are both known to directly affect vegetation (either through visible injury to leaves or reductions in growth) when exposures surpass thresholds in concentration, time, or some critical combination of the two⁶. Effects on perennial vegetation can accumulate over multiple growing seasons, causing growth reductions or declines in plant vigour. This study made comparisons of predicted concentrations to both short-term (1, 3 and 24 hour durations) exposure thresholds as recognized by the CCME and US EPA, and annual average concentration thresholds which are standards used in North America and Europe. Exceedances of thresholds for vegetation were constrained to existing industrial areas, though the impacts to sensitive lichens were predicted for a

⁶ (Vallero 2014)

larger area including forest ecosystems. Lichen communities near proposed and existing emissions sources are predicted to undergo changes in composition, with localized losses of the most sensitive species. While visible injury to vegetation is not likely, this does not preclude the potential for indirect effects such as shifts in species composition owing to acidification or eutrophication.

7 Soils and Terrestrial Ecosystems

Emissions of NO_x and SO_2 result in acidic deposition that can potentially acidify forest soils, which can mobilize dissolved aluminum in soil and adversely affect tree health⁷. Additionally, while nitrogen is an essential nutrient that is often limiting to forests, an increase in nitrogen deposition can lead to nitrogen leaching and changes in plant community composition (favouring select species to the exclusion of others); this is referred to as eutrophication. In terrestrial ecosystems lichens are typically considered the most sensitive indicator of plant composition change under elevated atmospheric sulphur and nitrogen concentrations.

The effects assessment on soils was based upon critical loads analysis, an assessment approach with global recognition. A critical load is the amount of deposition that an ecosystem is able to receive before adverse effects are expected according to present knowledge.

The spatial arrangement of source emissions, in combination with meteorology and physical geography result in a modelled deposition plumes of sulphur and nitrogen that extend to the north and west (Figure 4). The highest deposition, depicted in yellow and green, is spatially limited to regions near proposed facilities. Results from the F_R_U scenario indicate that 4 to 10 km² may exceed the critical load of acid deposition. The risk of eutrophication, indicating a shift in species composition, is predicted over an area between 5 and 94 km².

⁷ (Legge 1990)

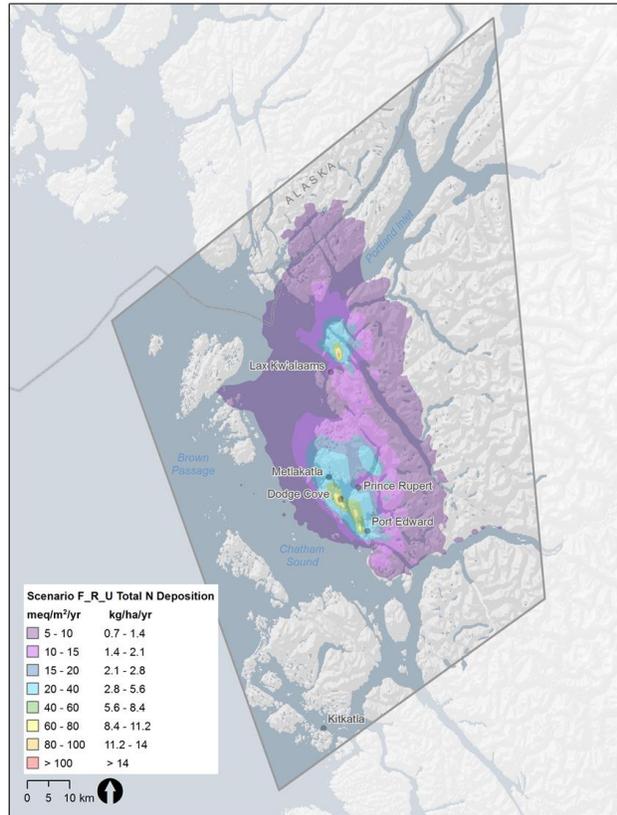
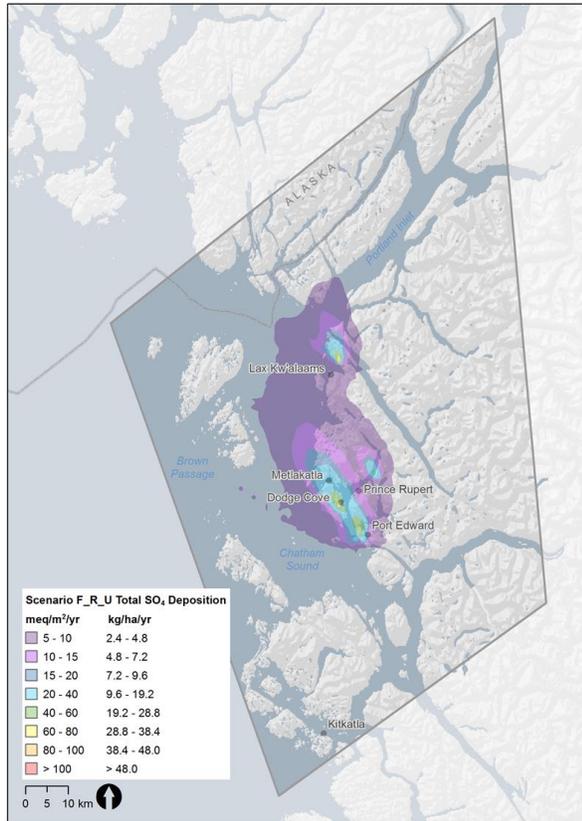


Figure 4: Total sulphur deposition (as sulphate) and nitrogen deposition under the highest emissions scenario.

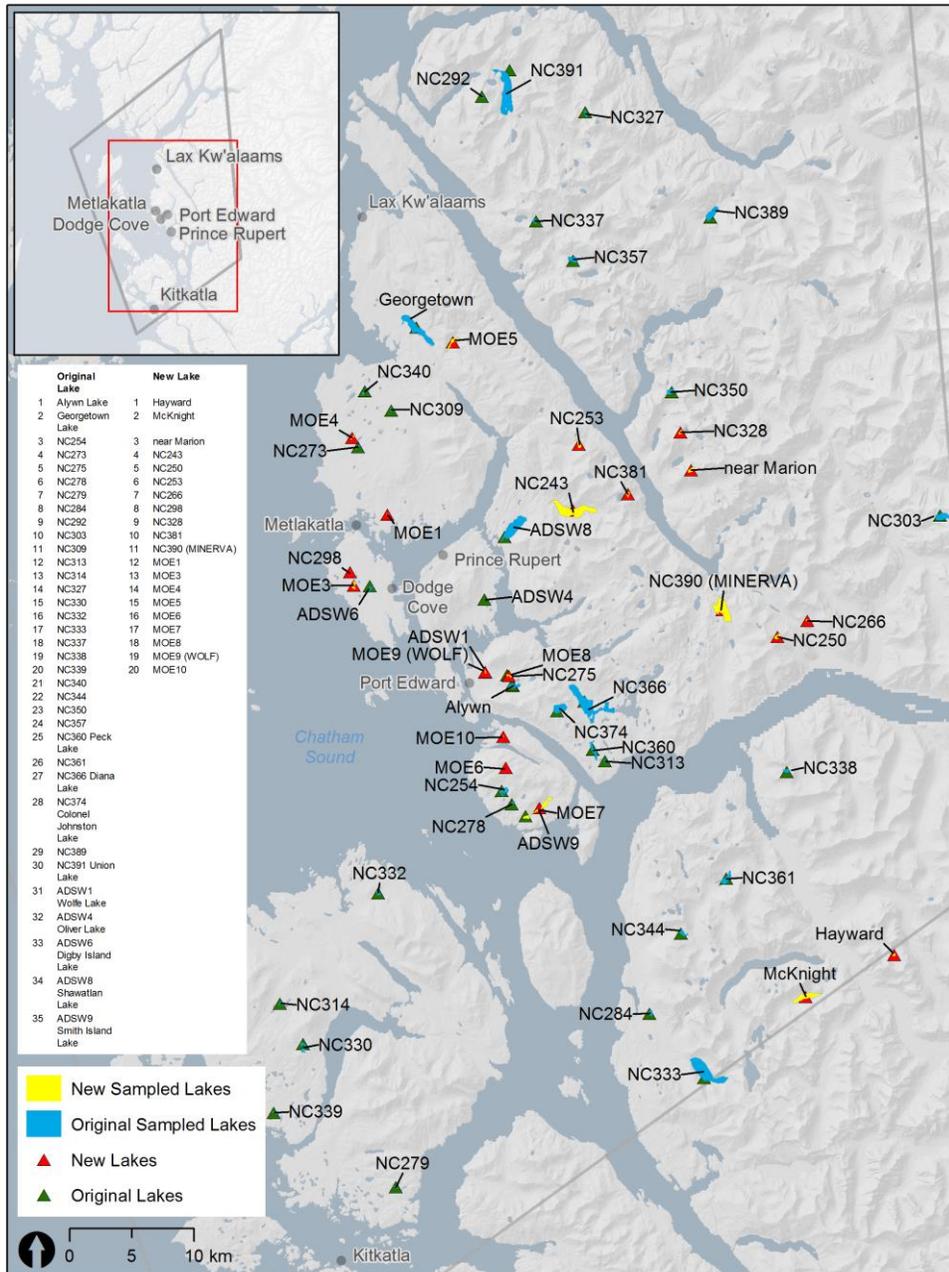


Figure 5: Map of the study area showing the 35 original lake samples and the 20 additional lakes sampled for supplementary analysis.

8 Aquatic Ecosystems

The deposition of sulphur and nitrogen compounds to surface waters, including lakes and streams, can cause changes in water chemistry such as decreases in lake pH (acidification) or increases in nutrient availability (eutrophication). These changes can influence aquatic life, and if large enough, can cause the loss of sensitive species including fish, plankton, invertebrates, and aquatic plants. Critical loads of acidity and nitrogen were compared to sulphur and nitrogen deposition estimates in order to assess the potential effects on 51 lakes in the study area. Predicted changes in pH owing to acidic deposition were also modelled.

Results of the F_R_U scenario indicate one lake may be at risk of exceeding the critical load of acidity. The estimated pH changes are all below the biologically significant threshold of more than 0.3 pH units, therefore the risk of acidification for the lakes is categorized as low to moderate. The analysis for eutrophication shows a moderate risk of impact to lakes, with greater risk to small lakes close to emissions sources.

9 Recommendations

When decision makers are reviewing this information they need to pay attention to both the Phase I and Phase II documents. The *Prince Rupert Airshed Study Supplementary Report* is based off of a significantly improved data set and the results of in the Supplementary report should be relied on by decision makers with the *Prince Rupert Airshed Study Volume 1 and 2 Reports* providing background information and methodology.

Though the Prince Rupert airshed is largely unconfined and commonly has adequate winds for air dispersion, existing and proposed emissions in combination with periods of calm winds may pose risks to sensitive human and environmental receptors, particularly in areas near emissions sources. Recommendations for proponents and government decision makers arising from the study for impact assessment and environmental monitoring of LNG emissions include:

- Follow the *Guidelines for Air Quality Dispersion Modelling in British Columbia* using the same meteorological datasets and same regional source emissions inventory.
- Conduct critical loads analysis as outlined in the BC MOE Guidance for the Assessment of Acidification and Eutrophication of Aquatic Ecosystems and the Critical Load Screening Guidance for Acidification and Eutrophication of Terrestrial Ecosystems.
- When assessing potential human health impacts, complement the characterization according to the CCME management levels with histograms or similar characterizations of the relative frequency of concentration estimates without background levels.
- Undertake baseline studies for:
 - air pollutants such as NO_x, SO₂, PM_{2.5} and possibly others, with network design based on air dispersion modelling results and in consultation with the BC MOE;
 - deposition of nitrogen, sulphur and other important parameters for the assessment of critical loads, in consultation with the BC MOE;
 - vegetation, in order to document the composition, distribution, and health of the sensitive plant communities and ecosystems;
 - soil sampling and geochemical analysis for regions with deposition predicted to exceed the critical load of acidity, and;
 - lakes, to fill gaps in coverage of lakes in the northern part of the study region, as well as on various islands.
- When development proceeds, conduct coordinated monitoring in the following areas:
 - air quality and deposition at the local level with collocated surface meteorological stations, particularly monitoring to confirm the magnitude and spatial extent of the predicted (modelled) concentrations and deposition, particularly in areas identified with predicted exceedances;
 - vegetation monitoring and assessment (with a focus on sensitive lichens);
 - soil geochemical analysis to confirm critical load estimates, and;

- lakes and streams within the predicted plume of deposition particularly north of Digby Island, and in the Prince Rupert, Port Edward, Metlakatla, Dodge Cove, and Lax Kw'alaams drinking water supply areas.

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Supplementary Report



ESSA

35
YEARS

Prince Rupert Airshed Study

Note: This is a Supplementary Report to Volumes 1 and 2 of the Prince Rupert Airshed Study, which represents a refined data set based on facility design improvements, an updated emissions inventory, additional receiving environment information, and the addition of a base scenario. Reference to Prince Rupert Airshed Study results should include the information contained in this Supplementary Report as well as Volume 1 and 2.



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Prince Rupert Airshed Study Supplementary Report

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Venn Pass, from Mount Hays looking to Metlakatla village (credit: Gary Robinson, used by permission).

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List of Abbreviations and Terms

Symbols and Abbreviations

Δ	delta, meaning quantitative change (e.g., Δ ANC or Δ pH)
<	is less than what follows
\leq	is less than or equal to what follows
>	is greater than what follows
\geq	is greater than or equal to what follows
AAC	Annual Allowable Cut
Al	aluminum
ANC	acid neutralizing capacity
ANN	Annette Island upper air station
AQO	air quality objectives
AQTDR	Air Quality Technical Data Report
ASC	acid sensitivity class
BC	British Columbia
BC MOE	British Columbia Ministry of Environment
BMT	British Columbia Baseline Thematic Mapping
CAAQS	Canadian Ambient Air Quality Standards
CALMET	a diagnostic 3-dimensional meteorological model that forms a component of the CALPUFF system
CALPOST	a post-processing package that forms a component of the CALPUFF system
CALPUFF	an air quality dispersion model that forms part of an advanced non-steady state meteorological and air quality modelling system of the same name
CAPMON	Canadian Air and Precipitation Monitoring Network
CCME	Canadian Council of Ministers for the Environment
CDED	Canadian Digital Elevation Dataset
CGIAR	Consultative Group on International Agricultural Research
COPD	Chronic Obstructive Pulmonary Disease
CONCAL	Method for calculating water conductivity developed by the US Environmental Protection Agency (EPA)
CL	critical load
CLF	critical load function
CO ₂	carbon dioxide



DEM	digital elevation model
DFO	Fisheries and Oceans Canada
DIN	dissolved inorganic nitrogen
DLE	dry low emissions
DOC	dissolved organic carbon
DS1, DS2	Data set 1, data set 2 (sampled lakes)
EA	environmental assessment
ECA	Emission Control Area
EMEP	European Monitoring and Evaluation Programme
ESRL	Earth System Research Laboratory
FAB	First-order Acidity Balance model
GAQM	Guideline on Air Quality Models
GIS	geographic information system
GSHHG	Global Self-consistent, Hierarchical, High-resolution Geography
HNO ₃	nitric acid
ISHD	Integrated Surface Hourly Database
KAA	Kitimat Airshed Assessment study
KMP	Kitimat Modernization Project
LNG	liquefied natural gas
MAML	Mobile Air Monitoring Laboratory
MCHEM	chemical transformation scheme
MDISP	dispersion coefficients switch setting
MESOPUFF II	A chemical transformation scheme (used in this study only for Scenario F_M)
MM5	5 th generation mesoscale model (data from this model used in sensitivity analyses of CALPUFF model output)
MODIS	Moderate Resolution Imaging Spectroradiometer program
MOE	British Columbia Ministry of Environment
n	number (sample size, e.g., “n=6”)
N	nitrogen
NAAQS	US EPA National Ambient Air Quality Standards
NADP	National Atmospheric Deposition Program
NCDC	National Climatic Data Center
NDBC	National Data Buoy Center



$(\text{NH}_3)_2\text{SO}_4$	ammonium sulphate
NH_3NO_3	ammonium nitrate
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NO_2	nitrogen dioxide
NO_3	nitrate
NO_x	nitrogen oxides
PM	particulate matter
$\text{PM}_{2.5}$	particulate matter up to 2.5 micrometers in diameter
PRG	Prince Rupert Grain
PRAS	Prince Rupert Airshed Study
PRLNG	Prince Rupert LNG
PRPA	Prince Rupert Port Authority
QA/QC	quality assurance/quality control
QP	qualified professional
RFP	Request for Proposals
RIVAD	A chemical transformation scheme (with ISORROPIA equilibrium)
S	sulphur
SCR	selective catalytic reduction
SGTIBL	Sub-grid scale thermal internal boundary layers
SO_2	sulphur dioxide
SO_4	sulphate, a salt of sulphuric acid
SRP	soluble reactive phosphorus
SRTM	Shuttle Radar Topographic Mission
SSMB	steady state mass balance model
SSWC	steady state water chemistry (model)
STAR	SO_2 Technical Assessment Report for the Kitimat Modernization Project
TEU	twenty-foot equivalent units
TFL	tree farm license
US	United States (of America)
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WRF	Weather Research and Forecasting



Measurement Units

ha	hectares
hp	horsepower
km	kilometre
kg/ha	kilograms per hectare
kg/ha/yr	kilograms per hectare per year (units of deposition flux)
mg/l	milligrams per litre
mg/Nm ³	milligrams per standard cubic metre
meq/m ² /yr	milliequivalents per square metre per year
mtpa	mega tonne per annum (a measurement of production capacity for LNG liquefaction facilities)
ppb	parts per billion
ppm	parts per million
tpd	(metric) tons per day
µeq/L	microequivalents per litre (µ can also be shown as u)
µg/m ³	micrograms per cubic metre (µ can also be shown as u)
µmolc/L	micromoles of charges per litre (µ can also be shown as u)

Glossary of Terms

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
acidic episode	An event in a water body in which acidification of surface waters results in an acid neutralizing capacity of less than or equal to 0
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
alkalinity	Measures the ability of a solution to neutralize acids; the terms acid neutralizing capacity and alkalinity are sometimes used interchangeably
ambient	Of the surrounding area or environment



anion	An ion with more electrons than protons, giving it a negative charge, e.g., SO_4^{2-}
anthropogenic	Of, relating to, derived from, or caused by humans or related to human activities or actions
base cations	An alkali or alkaline earth metal (Ca^{2+} , Mg^{2+} , K^+ , Na^+)
base saturation	The proportion of total soil cation exchange capacity that is occupied by exchangeable base cations (i.e., by Ca^{2+} , Mg^{2+} , K^+ , Na^+)
catchment	See “watershed”
cation	An ion with fewer electrons than protons, giving it a positive charge, e.g., Ca^{2+}
climate	The average weather of a location over a long period of time
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
empirical	Derived from or guided by experience or experiment
eutrophication	The enrichment of an ecosystem with chemical nutrients, typically compounds containing nitrogen, phosphorus, or both
Gran ANC	The capacity of a solution to neutralize strong acids, determined by titration to the inflection point of the pH-alkalinity titration curve
higher vegetation	Vascular plants, i.e., those with conducting tissue such as angiosperms, gymnosperms, ferns (plants other than lichens and mosses)
hydrology / hydrologic	Pertaining to the movement, distribution, and quality of water
ion	An atom or molecule in which the total number of electrons is not equal to the total number of protons, giving it a positive or negative electrical charge
isopleth	Contour line on a map connecting places with the same value of some parameter, e.g., total sulphate deposition
leaching	The extraction of materials from a carrier into a liquid
morbidity	A diseased state or symptom
organic acids	Acids possessing a carboxyl ($-\text{COOH}$) group or phenolic ($\text{C}-\text{OH}$) group; includes fulvic and humic acids



percentile	A measure used in statistics indicating the value below which a given percentage of observations in a group of observations fall
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
saturation	The point at which a solution of a substance can dissolve no more of that substance
sea salt effect	The process by which hydrogen ions are displaced from the soil exchange complex by base cations (from neutral salts); the result is a short-term increase in the acidity of associated water; also referred to as the “sea salt effect”
strong acids	Acids having a high tendency to donate protons or to completely dissociate in natural waters (e.g., H_2SO_4 , HNO_3 , HCl , and some organic acids)
turbidity	The cloudiness of a fluid caused by suspended particles
watershed	The geographic area from which surface water drains into a particular lake or point along a stream
wet deposition	Transfer of substances from the atmosphere to terrestrial and aquatic environments via precipitation (e.g., rain, snow, sleet, hail, and cloud droplets); droplet deposition is sometimes referred to as occult deposition



Executive Summary

This report summarizes additional modelling and assessment of new emissions information that became available after the completion of the Prince Rupert Airshed Study. The LNG proponents are at different stages of development and the availability of detailed emissions data varies among the proposed facilities modelled in the study. New emissions estimates of NO_x, SO₂ and PM_{2.5} from port facilities and related shipping were used to create a Base Scenario that represents the current situation. These emissions estimates along with updated emissions estimates for LNG terminals were used to update scenario F_R, which was the “high emissions bookend” scenario from the Prince Rupert Airshed Study. Updates of emission data from the Port and from LNG proponents means fewer assumptions had to be made for the revised scenario, named F_R_U. The atmospheric dispersion and deposition modelling results from this updated scenario was then assessed for effects on human health, vegetation, soils and lakes using the same methods as were used for the scenarios examined in the Prince Rupert Airshed Study.

Compared to results for Scenario F_R, results for Scenario F_R_U showed a decrease in the maximum concentrations and eliminated the areas of higher concentration for all pollutants and averaging periods. A decrease was also evident in the spatial extent of concentration isopleths for all three pollutants, especially for the shorter averaging periods. Scenario F_R_U also showed lower deposition rates compared Scenario F_R. The model results for the Base Scenario were low when compared to the results for Scenario F_R_U, with only 6% of the total emission rate of Scenario F_R_U. The modelled results for the Base Scenario compared well to monitored data and the background concentrations from the modelling accurately or conservatively represented the existing air quality conditions.

Human Health Results

Scenario F_R_U had lower concentrations of the three atmospheric pollutants for each of their two averaging periods at most of the human health receptor locations compared with Scenario F_R. When considered across all of the six combinations of pollutants and averaging periods, there were eight instances of a change in a location from the Red category to the Orange category and four instances of a change from Red to Yellow. There were no instances of a new Red categorization for any pollutant or averaging period at any location under Scenario F_R_U.

For fine particulate matter (PM_{2.5}), results from Scenario F_R_U showed substantially lower concentrations at the human health receptor locations that had elevated concentrations under Scenario F_R for both the annual average and the 24-hour averaging period. For SO₂, there was a general pattern of lower concentrations at both the annual average and 1-hour average daily peak periods. For the location with the highest concentration, modelled concentrations for both SO₂ averaging periods were substantially lower. Considering the annual averaged NO₂ concentrations, most of the locations were categorized as Yellow under both scenarios. However, there were substantial decreases in the location with the highest modelled concentration, including a decrease of close to 80% with respect to the annual average. For the



highest concentration locations with respect to the 1-hour average daily peak concentrations of NO₂, there were decreases ranging from approximately 71% to 92%. For this averaging period, among the six locations that were categorized as Red under Scenario F_R, four of the locations transitioned from Red to Orange, one location transitioned from Red to Yellow, and one remained narrowly above the Red threshold in Scenario F_R_U.

Vegetation Results

Peak concentrations of SO₂ did not reach levels sufficient to raise concerns for the health of vegetation in Scenario F_R and that continued to be the case under Scenario F_R_U. In scenario F_R_U maximum 1-hour concentrations did not exceed the BC Interim Air Quality Guideline. Annual mean concentrations that exceeded the European and WHO critical levels of 20 and 10 µg/m³, respectively, did not exceed those thresholds under scenario F_R_U. The growing season daylight mean of 12 µg/m³ did exceed the 10 µg/m³ threshold; however, that level is not of concern for higher vegetation. The annual mean concentration intended to protect lichens (all hours versus daylight hours) was not exceeded.

Peak concentrations of NO₂ in Scenario F_R_U were less than one-quarter of those projected to occur in Scenario F_R and were well below those expected to cause visible injury to higher vegetation. Exceedances of thresholds of interest dropped substantially as well, with a change from 1,262 to 37 for the 1-hour BC guideline. Exceedances of the WHO guideline decreased from 1,115 to 31 under Scenario F_R_U. All exceedances were projected to occur within the industrialized area. The European critical level for NO₂ was not exceeded.

The spatial extents of projected elevated concentrations of SO₂ and NO₂ under Scenario F_R_U also decreased substantially and posed little or no concern to the health of both vascular and non-vascular plants. As a result, the risk category for both SO₂ and NO₂ under this updated scenario have been categorized as Low.

Terrestrial Ecosystem Results

The revised atmospheric modelling under Scenario F_R_U did not affect the risk category for terrestrial ecosystems compared with Scenario F_R. The areal exceedance of critical loads of acidity was 6.9 km² under F_R_U compared with 10.3 km² under F_R. Areal exceedance of critical loads of nutrient nitrogen similarly decreased; however, the magnitude of exceedance slightly increased for eutrophication. Overall, the risk categorization did not change between Scenarios F_R and F_R_U. Despite decreases in average deposition (sulphate and nitrogen) across the study domain under Scenario F_R_U compared with F_U (about 5% decrease for both sulphate and nitrogen), the decrease in the area of the effects domain (~8.5%) 'cancelled out' some of the gain owing to the lower deposition under scenario F_R_U.

Predicted exceedance under Scenario F_R_U is in the Moderate to Critical risk categories. This risk categorization is consistent with the Scenario F_R, with the higher categories based on nutrient N impacts. It is important to note that a critical risk categorization indicated



unacceptable areal exceedance (>5% of the effects domain). In this study, exceedance with respect to empirical nutrient N indicates an increased risk for change in epiphytic macro-lichen species composition. However, this does not preclude an increased risk for composition shifts in N-sensitive vascular plants.

Aquatic Ecosystem Results

The revisions to the atmospheric modelling assumptions in Scenario F_R_U did not affect the results for aquatic ecosystems of the 35 lakes analyzed in the Prince Rupert Airshed Study. Under Scenario F_R_U, the overall risk for lakes acidification would be Low since there were no critical load exceedances and the estimated pH changes were under the biologically significant threshold for all lakes. The risk category moves to Moderate when considering the new lakes added to the analysis for this supplementary report, as one lake showed an exceedance of its critical load for acidity.

In terms of the risk for eutrophication, the revised Scenario F_R_U did not result in any significant changes in the exceedances and the overall risk is still considered High for dystrophic lakes and Moderate for oligotrophic lakes. As oligotrophic lakes are believed to be the predominant lake type in the study area, the Moderate rating is more consistent with the criteria defined in section 6.1.4 of the PRAS.



1 Introduction

A Prince Rupert Airshed Study (PRAS) was undertaken in 2015 as a high-level scoping study of the potential combined effects of nitrogen dioxide (NO₂), sulphur dioxide (SO₂), and PM_{2.5} emissions on human health, vegetation, soil (representing terrestrial ecosystems) and lakes (representing aquatic ecosystems) in the Prince Rupert area (ESSA et al. 2015). The objective was to provide information that would help decision-makers understand and compare the potential effects of NO₂, SO₂, and PM_{2.5} on human health and the environment in an airshed context, given the proposed clusters of LNG and other industrial discharges. The study examined seven scenarios, each representing a different combination of existing and proposed stationary and mobile emissions sources and emission treatment levels.

The LNG proponents are at different stages of development, and the availability of detailed emissions data varies among the proposed facilities included in the study. After completion of the PRAS, more detailed information on estimated emissions from port facilities, LNG facilities, and non-LNG marine transport became available. Chemistry data also became available from more lakes in the study area. Additionally, results from the PRAS revealed a need to understand more about how future emissions would compare to the current situation.

Additional modelling and assessment was done to explore the sensitivity of predictions in the PRAS to the new information. The “high-emission bookend” scenario from the PRAS with the highest total emissions of NO_x, SO₂ and PM_{2.5} was scenario F_R, and this was the scenario chosen for re-analysis. The updated scenario is labelled F_R_U. The availability of updated emission data from the Port and from LNG proponents reduced the number of assumptions needed in Scenario F_R_U. The modelling results for scenario F_R_U as well as an updated assessment of the outcomes for human health, vegetation, soils and lakes are presented in this supplementary report, and explicitly compared with the results of scenario F_R from the PRAS.

The more detailed information on port-related emissions was also used to model a Base Scenario of current conditions. These results allow for comparison between current and projected future atmospheric concentrations of NO₂, SO₂ and PM_{2.5} under scenarios F_R and F_R_U.

2 Air Dispersion and Deposition Modelling

2.1 Revised Emissions for Atmospheric Modelling

The additional air dispersion and deposition modelling was conducted using updated emission source inputs (emission rates and stack parameters) for both the existing and future sources. The additional modelling analysis used the same modelling methodology described in the PRAS for meteorological data, receptor grids, post-processing methods, and background concentrations. A Base Scenario was modelled to allow comparison of air quality and deposition



rates between baseline conditions and possible future scenarios. The Base Scenario represents the activities at the existing facilities using actual data from 2013. All decisions regarding emission source updates were made in consultation with the BC Ministry of Environment (BC MOE), and the Prince Rupert Port Authority (PRPA) for existing port sources, through multiple discussions as referenced throughout this report.

2.1.1 Updates for Sources at Port Facilities

Activities at the existing facilities that are within the port boundary were re-evaluated in the modelling analysis, including the following:

- Ridley Island Coal
- Prince Rupert Grain
- Fairview (including Fairview North)
- Canadian National (CN) Railyard
- Tidal Transport
- Northland
- CN Aquatrain
- British Columbia (BC) Ferries
- Alaska Ferries
- SMIT Marine Tugboats¹
- BC Pilots²

With the exception of BC Ferries and Alaska Ferries, land-based and marine emissions were re-evaluated using new information provided by the PRPA. Other facilities or activities that had annual emissions of less than 2.5 tonnes of NO_x in 2013 were considered insignificant sources and were not included in the analyses³. The Base Scenario used emission rates based on actual 2013 activities. Scenario F_R_U included emissions from the existing Port Facilities based on projected emissions in 2020. The projected 2020 emissions have taken the future fuel standard and the use of renewable energy into account, along with the projected 2020 throughput rates.⁴ In addition to these facilities, data from Canpotex was included in Scenario F_R_U. Modelled emission rates and source parameters for all the Port Facilities are available in Appendix 1 and Appendix 2.

¹ SMIT Marine operates tugboats that assist the marine vessels for other facilities. Therefore, this facility was not modelled separately. The majority of total emissions from this facility (about 66%) were accounted for with other facilities' tug operations at berth. The model attributes the remaining 34% to in-transit emissions.

² Emissions from BC Pilots are from vessels that are travelling between the Port and anchor or other further locations, such as Triple Island, where the pilot of a vessel changes over. Therefore, the model assigned emissions from this facility to in-transit sources only.

³ The following PRPA existing facilities were not included in the analysis due to insignificant emissions (less than 2.5 tonnes NO_x in 2013): Westview Terminal, PRPA admin, and Transload.

⁴ All existing facilities, except Fairview, were conservatively assumed to have the same throughputs in 2020 as those in 2013. This assumption is conservative, because market conditions have resulted in lower throughput in 2014 and 2015 than in 2013, and market projections show no indication to expect increasing throughputs at these facilities. After the completion of Fairview Terminal's expansion, the total throughput of Fairview Terminal was anticipated to be 2 million twenty-foot equivalent units (TEUs) according to the Fairview AQTDR. Scenario F_R_U assumed the future throughput at Fairview reaches the full 2 million TEU capacity.



Land-based Emissions

Land-based emission sources included stationary point sources, rail yards, cargo handling equipment, and rail in-transit emissions.⁵ The stationary point sources included the baghouses and dust collectors at Ridley Island Coal and Prince Rupert Grain. Emission rates and stack parameters for these stationary point sources were obtained from the Pacific NorthWest LNG Environmental Assessment Application (Table 4-1, Appendix 4 of Appendix C). These modelled point-source emission rates represent emissions during operation at maximum capacity. These same inputs were included in both the Base Scenario and Scenario F_R_U.

Emissions from the rail yards at CN Railyard, Ridley Island Coal, Prince Rupert Grain and Fairview Phase I were also included in both scenarios. In addition to these, scenario F_R_U also included rail yard emissions from Fairview Phase II and Canpotex. Emission rates for the Base Scenario were provided by the PRPA. Rail yard emissions consist primarily of those produced by locomotive activities along the rail tracks at facilities for unloading or storage of cargo. Rail yard emissions were modelled as mobile emission sources rather than as point sources, because the movement of locomotives affects the dispersion of the plume. Although mobile emission sources are often characterized as area sources, this would not account for any plume rise due to the high temperature of the locomotive exhaust. To account for this, the source type was updated from a traditional area source to a buoyant area source to more accurately represent emissions from slow-moving locomotives.

Buoyant area sources are defined as squares in the CALPUFF model. As such, multiple square buoyant area sources were required to define a single rectangular rail yard. These sources were distributed evenly over the tracks where the locomotives are operated at each rail yard. Each rail yard contained three to eight area sources, depending on the shape and the total length of the tracks in that yard. Emission release height and elevation for Fairview and Canpotex were obtained from recent modelling analyses performed for these two facilities respectively (Stantec 2009a,b; Stantec 2011).⁶ It was assumed that the same release height and elevation for Fairview Phase II also apply to Phase I, and that the 4 m release height was a reasonable estimate for other facilities. The base elevations for Prince Rupert Grain, Ridley Island Coal and the CN Railyard were estimated based on elevation data from the Canadian Digital Elevation Dataset (CDED) and were adjusted for all sources at one facility to be consistent. Additionally, the buoyant area sources were characterized by effective velocity, temperature, effective radius and initial vertical spread. A weighted average velocity of 6.82 m/s, exhaust temperature of 359 K, and initial vertical spread of 3.44 m were used in modelling, based on test data for the Switcher type of locomotive as provided by the BC MOE.⁷

Land-based emissions also included emissions from cargo handling equipment at Ridley Island Coal, Tidal Transport and Fairview. Cargo handling equipment includes auxiliary equipment,

⁵ On-road vehicle emissions are not included in the analyses. In 2013, the total on-road emissions were 15.5 tonnes, approximately 90% of which occur on the highway. BC Ferries and Alaska Ferries do not have any land-based emission sources.

⁶ *Fairview Terminal Phase II Expansion Project - Terminal Air Quality Technical Data Report* (Stantec 2009a,b) (Fairview AQTDR) and *Canpotex Potash Export Terminal and Ridley Island Road, Rail and Utility Corridor - Air Quality Technical Data Report* (Stantec 2011) (Canpotex AQTDR).

⁷ Data provided by Dennis Fudge (BC MOE) on February 10, 2015, and confirmed by Dennis Fudge on August 26, 2015.



loaders, stackers, and cranes, etc. that are usually powered by diesel engines. As for rail yard emissions, it was more appropriate to model cargo-handling equipment emissions as buoyant area sources to account for plume rise of engine exhaust with high temperature. The size of these sources was defined by the area over which cargo-handling equipment is operated within each facility, and their modelling parameters were determined based on the dominant types of cargo-handling equipment (e.g., loaders and cranes) in each facility. Because most of the equipment was rated at 300 hp or higher, the temperature, effective velocity, and effective radius for these buoyant area sources were determined conservatively based on the exhaust characteristics of a typical 300 hp diesel engine as reported in publically available engine manufacturers' specifications. The initial vertical spread was determined based on a typical loader/crawler crane exhaust height of 3.5 m.⁸ The base elevations for Ridley Island Coal and Tidal Transport were estimated based on the CDED, while those for Fairview were assumed to be the same as the previously modelled rail yard sources at the terminal.

No updates were made to the rail in-transit modelling methodology, because the representation of rail lines in the PRAS modelling was appropriate. In this analysis, the outputs from previous modelling efforts were scaled based on the number of trains for the Base Scenario and Scenario F_R_U. For the Base Scenario, the number of trains that travelled to Fairview, Ridley Island Coal and Prince Rupert Grain in 2013 was provided by the PRPA. Under Scenario F_R_U, the number of trains was increased for Fairview (Phase I and Phase II) based on the future capacity of 2 million twenty-foot equivalent units (TEUs). The throughputs for Ridley Island Coal and Prince Rupert Grain in 2020 were conservatively assumed to remain the same as in 2013. The number of trains needed for Canpotex was obtained from Canpotex Air Quality Technical Data Report (AQTDR). The total number of trains modelled in this analysis represented approximately 60% of the number modelled originally, indicating that the rail in-transit emissions were conservatively estimated in the original modelling analyses. Scaling was accomplished using CALSUM.

Stationary emission sources are shown in Figure 2-1.

⁸ The exhaust height is divided by 2.15 for surface-based sources to calculate the model input value, sigma Z.



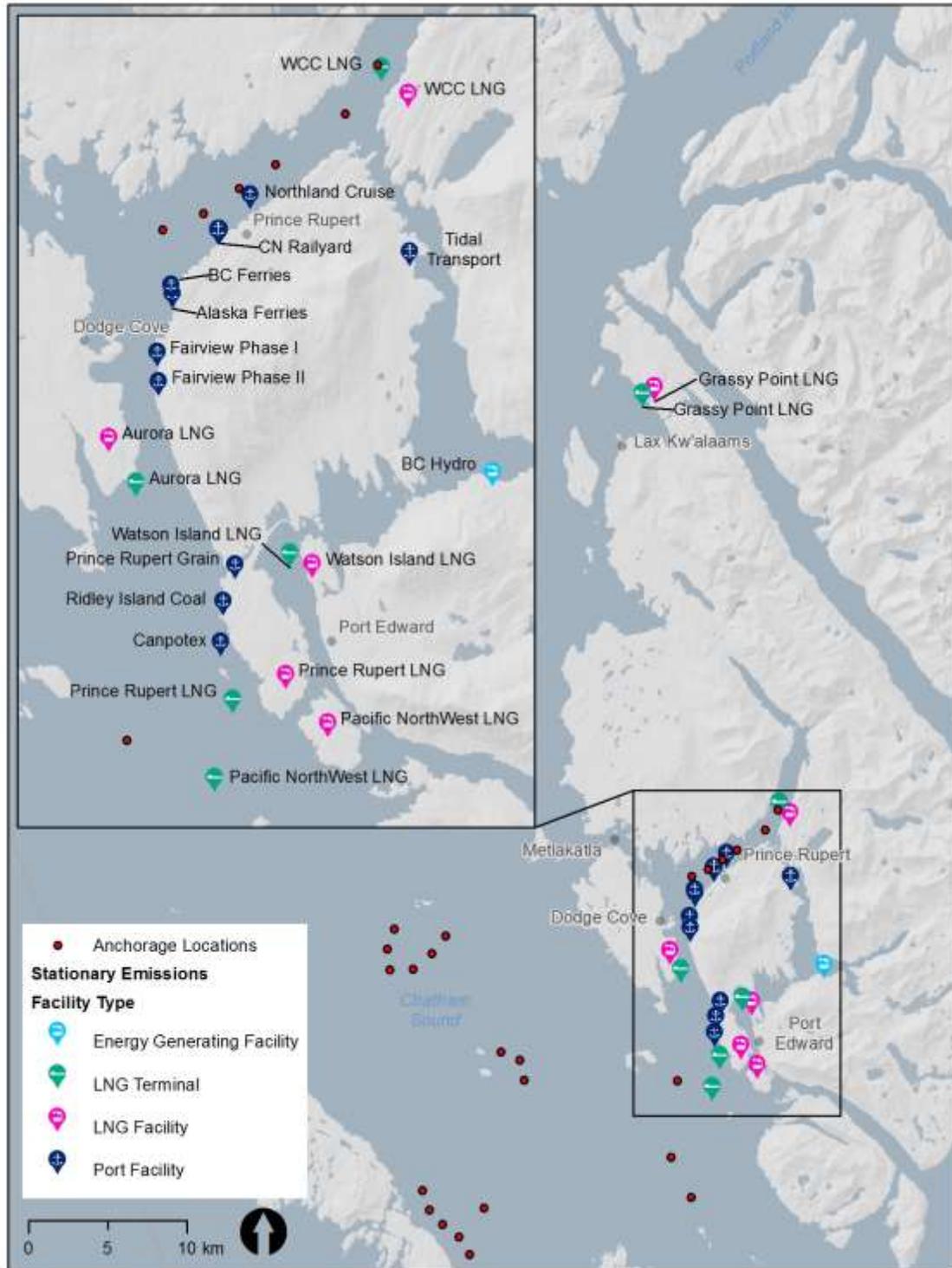


Figure 2-1. Locations of land-based stationary emission sources along with anchorage locations.



Marine Emissions

Marine emissions included those originating from marine vessels at berth, at anchorage locations, and in transit. All of the existing PRPA facilities discussed in the previous section have associated marine emissions except for the CN Railyard. All types of marine-emission sources were modelled as stationary point sources, with emission rates for both the Base Scenario and Scenario F_R_U provided by the PRPA.

Each Port Facility was modelled with one container ship, bulk carrier, or cruise ship at berth, depending on the type of facility. Models for some facilities included additional vessels as needed to reflect their operations. Fairview⁹, Canpotex, Ridley Island Coal, Prince Rupert Grain, and Northland have bulk carriers and container ships that are guided by tugboats. Therefore, one tugboat at berth was modelled for each facility, with the exception of the Fairview Phase II and Canpotex marine berths, which were each modelled with multiple tugboats according to their respective AQTDRs. Whether models accounted for emissions from multiple tugboats as opposed to a single tugboat was expected to produce only negligible differences in the overall modelling results, given the small amount of emissions from tugboats as compared to other vessels. In addition to tugs, an additional container ship (two in total) was modelled for Fairview under Scenario F_R_U to reflect the presence of a new marine berth after completion of the expansion project.

Emission rates for all facilities except Canpotex and BC and Alaska Ferries were provided by the PRPA. Emission rates for Canpotex bulk carriers were obtained from Canpotex AQTDR. Since the emissions provided in Canpotex AQTDR assumed 1% sulphur content in marine fuel, the SO₂ and PM_{2.5} emissions in this analysis were adjusted downward to account for the 0.1% sulphur limit for North American Emission Control Area (ECA) starting January 1, 2015.¹⁰ For Fairview, the future emissions were scaled upward from actual emissions in 2013 to reflect a future throughput of 2 million TEUs following expansion, and were adjusted for the use of shorepower at berth.¹¹ Future marine-based emission rates from other facilities retained the 2013 Base Scenario emissions values. The future marine emissions were also adjusted downward to account for the ECA 0.1% sulphur fuel requirement. PRPA did not have information rated to BC and Alaska Ferries, therefore emission rates for ferries as obtained from the Pacific NorthWest LNG Environmental Assessment Application (Stantec 2014)¹² remained unchanged from the original modelling.

⁹ Fairview North has a separate berth from the main terminal. The berth emissions for Fairview North were combined with the Fairview berth emissions, because the emissions from Fairview North are minimal compared to the emissions from the main terminal.

¹⁰ While the adjustment of emissions for the new sulfur standard were made, the emission rates for Scenario F_R_U conservatively assume that the same emission factors for the existing vessels apply in the future and no new vessels with lower factors will be used.

¹¹ The future throughput of 2 million TEUs was obtained from Fairview AQTDR. Shore power will likely be applied in the future for energy saving purposes. This analysis assumes 50% of total vessels at Fairview in the future will apply shore power starting after 15% of the total dock time has elapsed (to allow for hook-up time), per PRPA provided data.

¹² Table 4-1, Appendix 4 of Appendix C, *Pacific NorthWest LNG Environmental Assessment Application* (Pacific NorthWest LNG EA application).



The modelling analysis for both the Base Scenario and Scenario F_R_U also included emissions from twenty-four anchorage locations within the port boundary (Figure 2-1). Two anchorage locations in the inner harbour were mostly used for log ships (by Tidal Transport), whereas other anchorage locations are primarily used for bulk carriers, such as grain ships and coal ships. Scenario F_R_U emission rates for these facilities were adjusted downward to account for the lower sulphur content of the fuel and lower particulate emissions required for the North America ECA, assuming the number of hours and number of ships anchored at these locations in 2020 remain the same as those in 2013. Future anchorage emissions estimated based on 2013 data were conservative, because 2013 had a prolonged period of cold temperature that prolonged the required time at anchor within the port boundary.

Emission rates for in-transit marine vessels and tugboats were provided by the PRPA for each facility and distributed over the shipping route points leading from the study area boundary to the facility. In-transit emissions from container ships, bulk carriers, and tugboats escorting these vessels were distributed over the same series of points representing shipping routes used in the original modelling analysis. Emission rates were scaled up by 10% for points representing shipping routes within the inner harbour to account for the small additional movement of ships travelling between anchor locations and the facilities, as recommended by PRPA. Because emissions from tugboats assisting log ships for Tidal Transport occur mainly near inner harbour anchorages, the model assumed that 100% of these emissions originated from the end of the shipping route nearest the Tidal Transport anchorage locations.¹³ Similar to anchorage emissions, Scenario F_R_U emission rates for these facilities were also adjusted downward to account for the lower sulphur content of the fuel and lower particulate emissions required for the North America ECA, assuming the number of hours and number of ships travelled to each facility in 2020 remain the same as those in 2013.

Modelled source parameters for marine vessels were determined in consultation with PRPA and MOE:

- Stack diameters at berth and anchorage for the container ships and bulk carriers were obtained from Pacific NorthWest LNG EA application (unchanged from original modelling).
- Stack diameters for in-transit emissions are weighted averages for the type of ships travelling on the route.
- Modelled stack temperature is 345 °C (618 K) for all vessels at berth and anchor, and 300 °C (573 K) for all vessels in-transit.¹⁴ In-transit stack temperatures are expected to be lower than those at anchor because the main engine exit temperature is expected to be lower than the auxiliary engine.

¹³ PRPA provided in-transit data for existing port facilities but not for BC and Alaska Ferries, because the relevant information was not available to PRPA. Future shipping data for Canpotex was also not developed by PRPA because it is unlikely that full construction of Canpotex will be completed in the foreseeable future. Therefore, shipping emissions for the ferries and Canpotex are not included in Scenario F_R_U.

¹⁴ Berth and anchor temperatures were selected in consultation with BC MOE and PRPA, based on Port of Los Angeles Baseline Air Emission Inventory – 2001, available at https://www.portoflosangeles.org/DOC/REPORT_Final_BAEI.pdf (accessed February 2, 2016).



- Locations for the container ships and bulk carriers at berth were obtained from the Pacific NorthWest LNG EA. Under Scenario F_R_U, locations of Canpotex vessels and Fairview Phase II vessels were obtained from Canpotex AQTDR and Fairview AQTDR, respectively.
- Other stack parameters for cargo vessels and tugboats, including stack height, and exit velocity are determined based on the type of ships and information available in Marine Emission Inventory Tool developed by Transport Canada. Tug stack height for Prince Rupert Grain and Ridley Island Coal is site-specific information provided by PRPA.
- All source parameters for BC and Alaska Ferries were obtained from the Pacific NorthWest LNG EA application.
- Canpotex bulk carrier stack parameters were assumed to be the same as for the bulk carriers used at Ridley Island Coal. Tugboat stack parameters for Prince Rupert Grain were conservatively used for Canpotex tugboats.
- Fairview Phase I stack parameters for container ships and tugboats are applied to sources for Fairview Phase II.

2.1.2 Updates for LNG Facilities

All emissions from proposed LNG facilities were evaluated under Scenario F_R_U. BC MOE requested updated information from proponents for the updated modelling effort. The LNG proponents are at different stages of development and the availability of detailed emissions data varies among proponents. The following proponents provided updated source inputs with more recent design information:

- Prince Rupert LNG
- Pacific NorthWest (PNW) LNG
- Aurora LNG
- WCC LNG

No new information was provided for Grassy Point LNG, Watson Island LNG and BC Hydro. Therefore, emissions from these facilities were not updated in this analysis, except for the emission rates from thermal oxidizers for Grassy Point LNG and Watson Island LNG.¹⁵ Previously, the thermal oxidizer at Pacific NorthWest LNG was used as a proxy for Grassy Point LNG due to outlier emissions. In this modelling analysis, NO_x emissions from the Grassy Point LNG thermal oxidizer were taken directly from Grassy Point LNG's original information response, and the SO₂ emissions were calculated as described below. Emissions from LNG facilities were not included in the Base Scenario, as these facilities have not yet been constructed.

¹⁵ However, emission rates of all sources at Grassy Point LNG were updated in this analysis compared to the original assessment, which used Pacific Northwest LNG as a proxy for Grassy Point LNG. This modelling analysis uses the proponent provided data in February 2015.



Land-based Emissions

Pacific NorthWest LNG, Aurora LNG and WCC LNG provided updated information regarding the emission sources on land, including liquefaction turbines, power generators, acid gas thermal oxidizers, flares, and heaters. The source inputs were modelled as provided with the following assumptions made:

- Aurora LNG provided one source location for each type of the emission unit although the facility will have three trains according to the project description. The emission units were modelled as provided. This approach is conservative for most locations¹⁶ due to emission releases being concentrated from one location for each source type.
- WCC LNG did not provide locations for the thermal oxidizer and flare, and provided limited information on the flare. These two sources were combined and assumed to be located 50 m east and 100 m north of the location of Train 1 Turbine 2, near the flare based on facility layout drawings. SO₂ emissions for WCC LNG's flare were combined into WCC LNG's thermal oxidizer due to limited information and low emissions from WCC's flare.
- Pacific NorthWest LNG provided updated land source information in early December 2015 but not the locations of these updated sources. The propylene, ethylene and methane turbines were thus placed at the end of each train (2 for each train), near the location of the compressor gas turbine drivers provided for the original assessment. The heaters were placed at the south end of each train, and the thermal oxidizer 50 m south of Heater #3.
- Pacific NorthWest LNG power generators' modelled emission rates use the sum of the proponent provided emission rates for each activity, assuming the provided rates were annual average rather than the maximum from each activity.
- Pacific NorthWest LNG fired gas heaters' modelled emission rates use the sum of the proponent provided emission rates for each fuel type, assuming annual average from each fuel type rather than the maximum from each fuel type.

Modelled SO₂ emissions from thermal oxidizers for Grassy Point LNG and Watson Island LNG in the original assessment had previously been based on proxies from other facilities.¹⁷ In this updated analysis, the SO₂ emissions were calculated based on the production capacity of each LNG facility. The change to using calculated rates allows for transparent communication of the basis of the assumptions. The calculated SO₂ emission rate was based on a total sulphur concentration of 9 mg/Nm³ removed from the feed gas, assuming all sulphur removed is in the form of H₂S and combusted at the thermal oxidizers. Calculations are presented in Appendix 2.

Marine Emissions

Marine emissions from LNG terminals include those from vessels at berth and from vessels travelling from the study area boundary to LNG facilities and back. Vessel emissions at berth for

¹⁶ Modelling three source emission rates emitting from a single stack is conservative for all locations other than those immediately downwind of the unknown locations of the stacks 2nd and 3rd stacks not modelled.

¹⁷ The SO₂ emissions provided by Grassy Point LNG were outside the bounds of the expected range, and Watson Island LNG did not provide modelling data.



Pacific NorthWest LNG remained the same as what were originally modelled based on proponent data. For facilities that did not provide emission rates, calculations were completed following the methodology described below. The emission calculations are provided in Appendix 2.

Data provided by Prince Rupert LNG for this modelling analysis were used to model vessel emissions at berth at their terminal. WCC LNG provided detailed inputs for LNG vessel and tugboats berth emissions calculations, including emission factors, engine load factors, and time of manoeuvring and hotelling. Since the other proponents did not provide marine emissions, the emissions at berth were calculated using WCC LNG's inputs as reasonable proxies, adjusted for the production capacity for each facility. The number of LNG carriers modelled at berth was determined based on the size of the production capacity of the facility: two carriers for Aurora LNG and Grassy Point LNG, and one carrier for Watson Island LNG. Pacific NorthWest LNG and Prince Rupert LNG marine berths have higher emissions than other terminals overall, especially NO_x emissions, because conservative emission factors and load factors were used for these two terminals, as compared to WCC LNG and the emission factors required under current marine engine regulations. The low NO_x emission factor used by WCC LNG aligns with the emission standard that is applicable to newer marine vessels.¹⁸

Since WCC LNG is the only proponent that provided detailed inputs for in-transit shipping emissions calculations, these inputs were used as reasonable proxies for the other five LNG terminals, with the number of LNG vessels per year and travel time as variables.¹⁹ The numbers of LNG vessels per year for the other five LNG terminals were obtained from the respective Environmental Assessment project descriptions. The roundtrip travel time within the study area for the other five LNG terminals was determined based on the shipping routes. The number of vessels and shipping routes remained consistent with what was originally modelled. The travel speeds entering the study area and nearing Prince Rupert Port were back-calculated based on the travel time provided by WCC LNG and the travel distance for WCC LNG.

2.1.3 Comparison of LNG Emission Rate Intensities

Table 2-1 presents the emission intensity of each LNG facility representing the total modelled emission rate from each facility for Scenario F_R_U with respect to each facility's production rate.

¹⁸ According to WCC LNG provided background information, WCC LNG will use new build LNG carriers that meet US EPA's Tier III Standard (outlined under 40 CFR Part 1042).

¹⁹ Prince Rupert LNG provided emission rates for in-transit marine emissions. However, the shipping route indicated by the provided data only covers a small portion of the area for this study. The background information for calculating the in-transit emissions was not available to scale or refine the emission rates to match the study area. Therefore, the in-transit marine dataset provided by Prince Rupert LNG was not used in this modelling analysis.



Table 2-1. Emission Intensities of Stationary Sources at LNG Facilities for Scenario F_R_U

LNG Facility	Production Rate	Scenario F_R_U Emission Intensity for Stationary Sources ¹ (t/d per mtpa)		
	(mtpa)	Total SO ₂	Total NO _x	Total PM _{2.5}
Grassy Point LNG	20	0.073	1.090	0.046
Pacific NorthWest LNG	19.2	0.018	0.192	0.023
WCC LNG	30	0.018	0.209	0.017
Prince Rupert LNG	21	0.094	0.583	0.049
Aurora LNG	24	0.106	0.871	0.066
Watson Island LNG	2	0.165	0.574	0.082

1. As discussed in Section 2.1.2 the emission rates for thermal oxidizers at Grassy Point LNG are based on calculations developed by Trinity, assuming a feed gas sulphur content of 9 mg/Nm³. The emissions from Watson Island LNG use Triton LNG as proxy; therefore, the emission intensities for this facility are not discussed below.

For land-based emissions from LNG facilities, Pacific NorthWest LNG, WCC LNG, and Aurora LNG provided emission data near the end of 2015 for this updated modelling effort that took into account the most recent design information. Grassy Point LNG provided data in the original PRAS assessment, which was unchanged for this analysis. The NO_x emission rates vary considerably among LNG facilities, with the emission intensity ranging from 0.19 tonnes per day NO_x per million tonnes per annum (t/d per mtpa) to 1.09 t/d per mtpa.²⁰ The highest intensity is 0.942 t/d per mtpa, while the next highest is 0.583 t/d per mtpa (approximately 40% lower). While the reason for this disparity is unknown, this variation may be due to the facility with highest emission intensity using more conservative NO_x emission factors in estimating the emission rates.

The emission intensity of SO₂ also varies substantially among LNG facilities, ranging from 0.02 t/d per mtpa to 1.00 t/d per mtpa.²¹ The thermal oxidizer, which combusts the sulphur removed from the feed gas makes up the vast majority of SO₂ from the LNG facilities. The intensity of *provided* SO₂ emission rate from only the thermal oxidizers ranges from 0.006 tonnes per day per million tonnes per annum (t/d per mtpa) up to 1.00 t/d per mtpa²² based on the proposed production rate for each facility. The wide range of SO₂ intensity indicates a wide variety of assumptions made by proponents about the sulphur and H₂S content of feed gas and the fraction of that sulphur that must be removed in the acid gas removal unit. According to the background information provided by proponents, the assumptions used to develop the SO₂ emission rates from thermal oxidizers was based on an inlet total sulphur concentration ranging

²⁰ Based on Watson Island LNG emission rates modelled in the original assessment (used Triton, an LNG facility modelled in the Kitimat Airshed Effects Assessment, as a proxy assuming the same capacity as Triton, i.e., 2 mtpa), and proponent provided data for the other five LNG facilities.

²¹ As noted later in the paragraph, the maximum SO₂ intensity of 1.00 t/d per mtpa represents the provided data from Grassy Point LNG, but the SO₂ emission rates from the Grassy Point LNG thermal oxidizers were updated to align with expectations. Accounting for the update, the modelled SO₂ intensity from Grassy Point was 0.07 t/d per mtpa.

²² The 0.006 t/d per mtpa to 1.00 t/d per mtpa does not match the table, because these emission intensities are calculated based on proponent provided data for only thermal oxidizers at the LNG facilities, not all the stationary sources at these facilities. The thermal oxidizer emission rate associated with 1.00 t/d per mtpa is considered an outlier and was replaced with an estimate representative of the remaining facilities.



from 6 milligrams per standard cubic metre (mg/Nm^3) up to $115 \text{ mg}/\text{Nm}^3$.²³ Some differences in sulphur feed gas assumptions were expected, because different proponents will be drawing their feed gas from different gas fields. However, the extent of the variation also indicated differences in other assumptions such as the species of sulphur in question and to what level it must be removed to meet the requirements of downstream equipment or end-market specifications. For example, one proponent assumes that the only compound removed from the stream and combusted by the thermal oxidizers is hydrogen sulfide, while other proponents assume that all sulphur compounds are removed from the stream and combusted by the thermal oxidizers.

The $\text{PM}_{2.5}$ emission intensity ranges from 0.017 t/d per mtpa to 0.066 t/d per mtpa (not considering Watson Island LNG). The variation also indicates different assumptions applied to the provided emission rates for $\text{PM}_{2.5}$. WCC LNG has the lowest $\text{PM}_{2.5}$ emission intensity while being the largest proposed LNG facility of 30 MTPA. $\text{PM}_{2.5}$ emission calculations are typically based on the fuel gas composition and sulphur content of the gas, assumptions which likely varied from site to site.

2.1.4 Emission Updates Summary and Discussion

Total emissions from the Base Scenario and Scenario F_R_U, as well as the full build Scenario F_R evaluated in the PRAS are summarized in Table 2-2. Scenario F_R_U represents a full build future operation scenario, with data provided by proponents that accounts for updated design information, and more accurate existing facility information. Figure 2-2 presents relative emissions of each contaminant for these three scenarios.

Many of the updates in this modelling analysis involved use of emission rates developed and provided by PRPA for existing port facilities in Scenario F_R_U. In the original modelling analysis, PRPA provided reports that were prepared by proponents to support their Environmental Assessments or permit applications that frequently applied overly conservative or out-dated assumptions. Compared to the emission rates modelled for Scenario F_R, SO_2 and $\text{PM}_{2.5}$ emissions from all port facilities show a decrease under Scenario F_R_U, largely due to accounting for the new marine fuel standard (0.1% sulphur limit for North American ECA). There is a slight increase in the total NO_x emission rate from Scenario F_R to Scenario F_R_U from port facilities, which is expected due to the larger number of port emission sources (such as the addition of marine vessels at anchorage and cargo handling equipment).

²³ One proponent provided an emissions estimate for thermal oxidation that was more than 10 times greater than the next highest estimate (based on $115 \text{ mg}/\text{Nm}^3$ sulphur content of the feed gas). As the proponent stated that actual Sulphur values would be significantly lower than this unusually high estimate, it was considered an outlier and was replaced with an estimate representative of the remaining facilities. The updated thermal oxidizer SO_2 was based on Trinity's calculation provided in Appendix 2, assuming a feed gas sulphur content of $9 \text{ mg}/\text{Nm}^3$.



Table 2-2: Emissions summary comparison between the two new scenarios and Scenario F_R from the PRAS.

Scenario Name	Description	Total SO ₂	Total NO _x	Total PM _{2.5}
		tpd	tpd	tpd
Base Scenario	Existing Port Facilities	1.2	3.5	0.5
Scenario F_R_U	Updated Full Build Scenario	7.8	79.3	5.6
Scenario F_R	Full Build Scenario in the PRAS	7.8	89.5	5.4

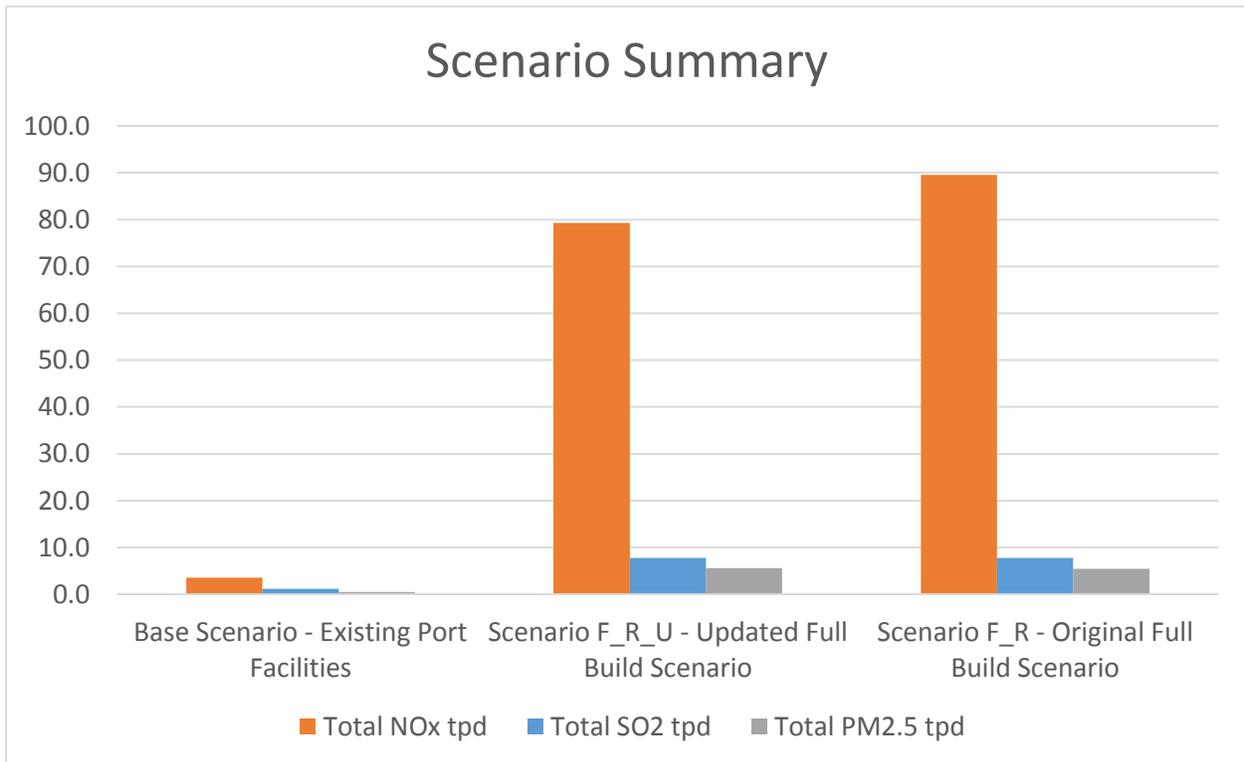


Figure 2-2: Bar chart illustrating cumulative emissions by scenario.

Figure 2-3, Figure 2-4, and Figure 2-5 provide greater detail for each of the bars in Figure 2-2 by showing the contributions of modelled facility and source type to the total emissions of NO_x, SO₂ and PM_{2.5}, respectively. As shown in these figures, Scenario F_R_U has higher emissions from Aurora LNG, and lower emissions from LNG terminals, LNG shipping and Port Facilities terminals. The figures also illustrate how the emission intensities vary considerably among LNG proponents. While the reason for this disparity is unknown, some facilities may have made assumptions that are more conservative than others. The LNG model emission rates (with a few exceptions noted in the previous sections) come directly from proponents. The various LNG facilities are at different stages of development and detailed design engineering may not have been available for each. Section 2.1.3 includes more discussion of the variation in emission intensities.



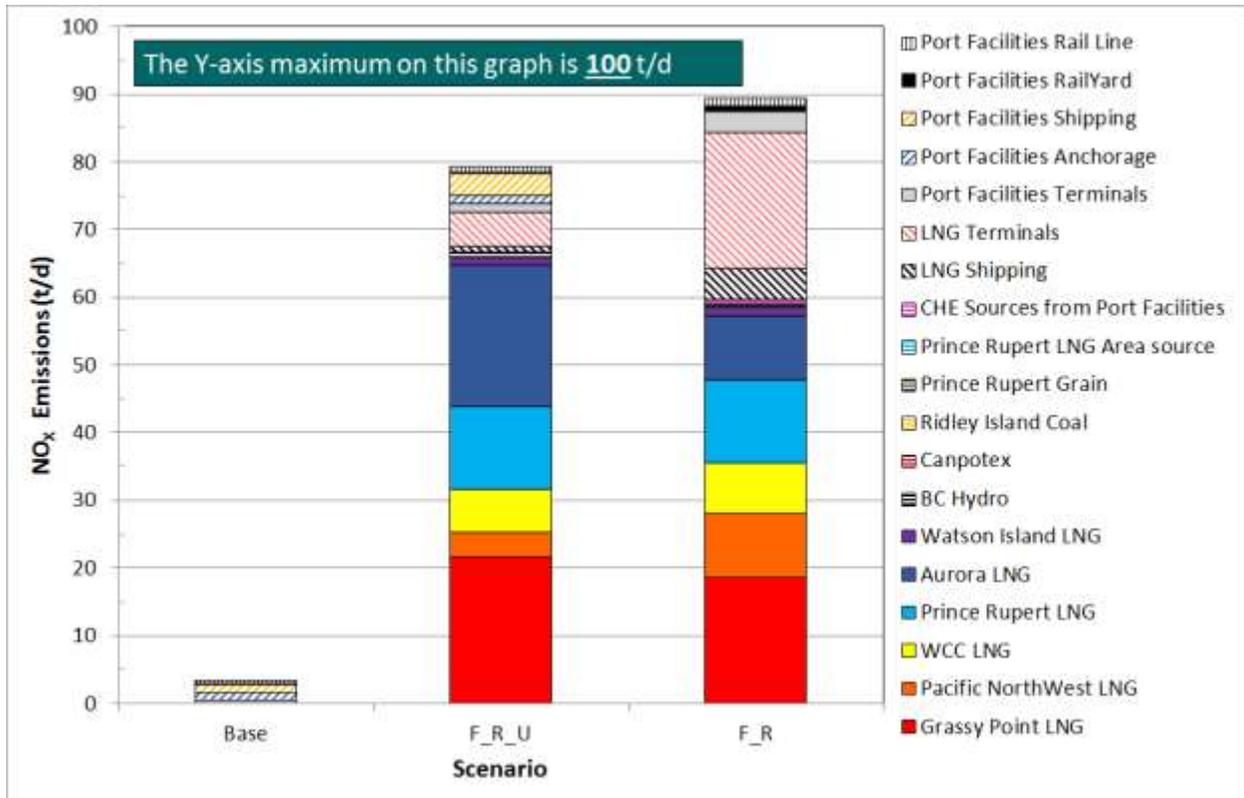


Figure 2-3: Cumulative contributions of NO_x from different sources in each emission scenario.

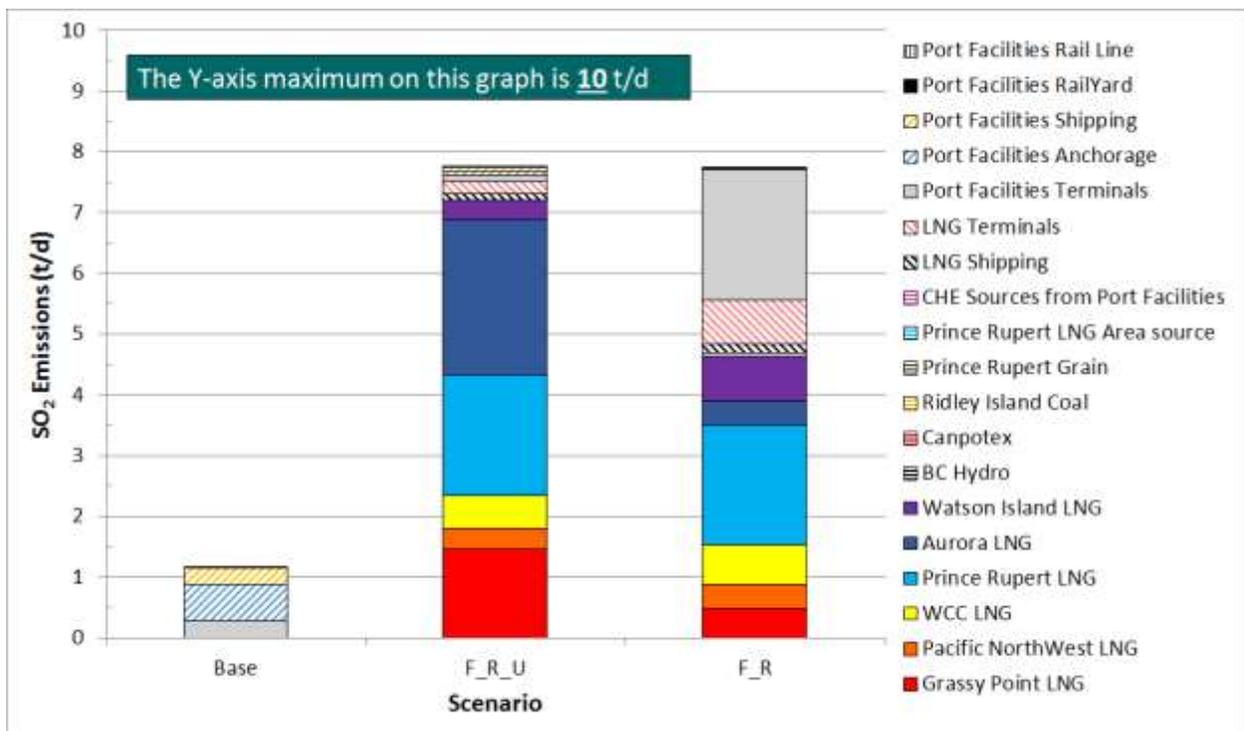


Figure 2-4: Cumulative contributions of SO₂ from different sources in each emission scenario.



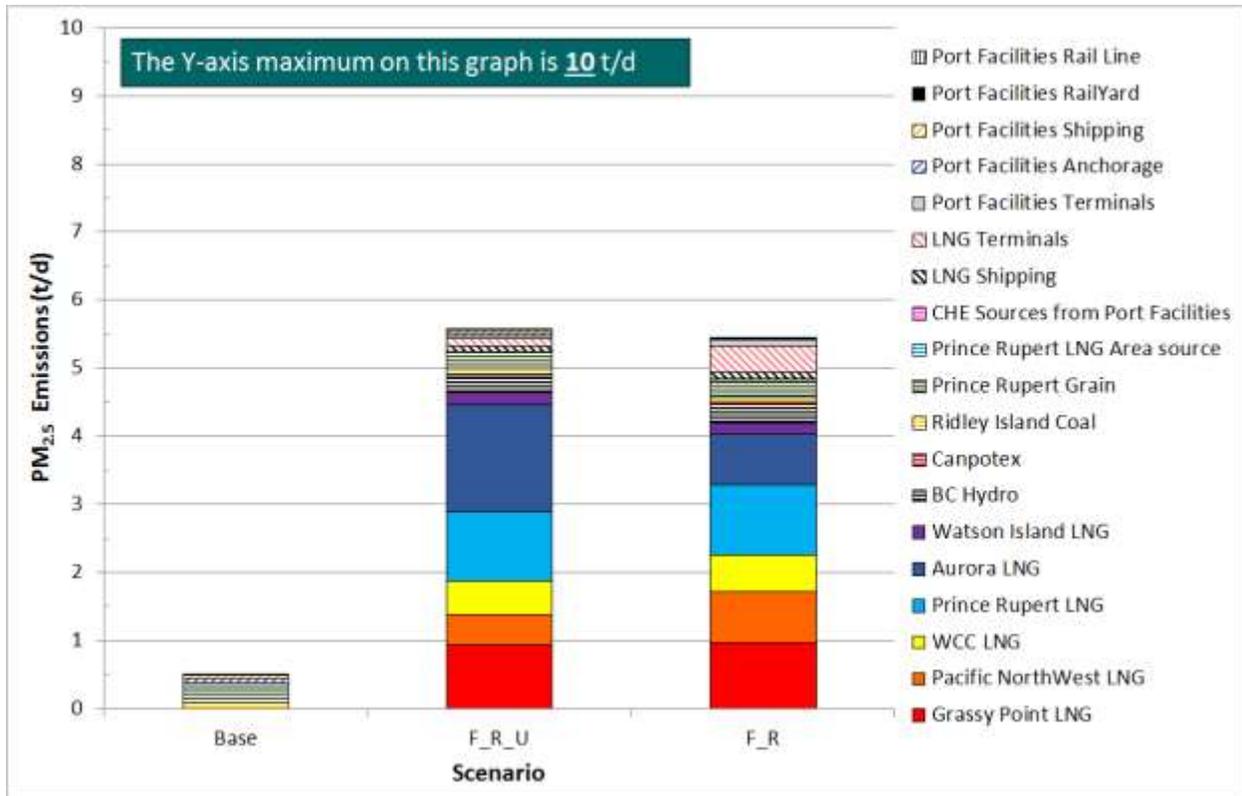


Figure 2-5: Cumulative contributions of PM_{2.5} from different sources in each emission scenario.

Compared to Scenario F_R, the major differences in Scenario F_R_U include the following:

- Additional emissions from added Port Facilities, including CN Railyard, Tidal Transport, CN Aquatrain, SMIT Marine and Pacific Pilots;
- Addition of shipping emissions from marine vessels for the Port Facilities;
- More realistic and less conservative basis of the emissions from Port Facilities;
- LNG facility updates with recently provided proponent data;
- Consideration of emission limits or fuel standards that became effective after the submittal of publicly available project descriptions or applications.

2.2 Overall Conclusions

Compared to results for Scenario F_R, the Scenario F_R_U modelled results show a decrease in the maximum concentrations and eliminates the areas of high concentration for all pollutants and averaging periods. The specific locations of decrease in highest concentrations and model input changes most likely to cause these decreases are further discussed in Section 3.3. A decrease in the extent of isopleths at the same concentrations levels was also observed for all pollutants, especially for the shorter averaging periods such as 1-hour and 24-hour.

As discussed in Sections 2.1 and 2.2, several small facilities were modelled in Scenario F_R_U that had not been previously included in Scenario F_R. However, the updated assumptions and



refinements to emission calculations lead to the total NO_x emissions in Scenario F_R_U to drop by approximately 10% compared to the emissions modelled for Scenario F_R. Total Emissions of SO₂ remained nearly constant, and PM_{2.5} emission rates increased only slightly. As a result of this overall decrease or relatively similar total emission rate, combined with refinements to source characterization, the updated model results predict lower concentrations and deposition rates from the future emission sources overall as compared to Scenario F_R. Sections 2.3.1 through 2.3.3 further discuss these the changes in model results for each scenario. The decreases in modelled concentrations are primarily due to:

- Corrections of LNG berth and shipping emission rates due to lower NO_x emission factor, more detailed and complete information provided by proponents;
- Refinement of port facilities with more accurate data, including lower sulphur in fuel and separate the dust collectors at Prince Rupert Grain and Ridley Island Coal;
- Refinement of inputs to rail line emissions; and
- Refinement of rail yard source characterization.

As expected, the model results for Base Scenario were extremely low compared to Scenario F_R_U. Base Scenario total emissions are 15%, 4%, and 9% of Scenario F_R_U total emission rates for SO₂, NO_x, and PM_{2.5}, respectively. As such, the Base Scenario model results were also only a small fraction of the Scenario F_R_U results. Additionally, a comparison between the monitored data and modelled results for Base Scenario was performed. As further discussed in Section 2.3.6, the modelled results for the Base Scenario compare as expected to the monitored data, and the comparison shows that the background concentrations added to model results accurately or conservatively represent the existing air quality conditions.

2.3 Details Supporting Overall Conclusions

All modelled concentrations were added with background concentrations representing natural background plus existing industrial and regional emission sources for SO₂, NO₂ and PM_{2.5} in the Prince Rupert area. The background concentrations remain unchanged from the original assessment, as detailed in Section 2.2.1 of the original PRAS report. The background concentrations are also discussed in Section 2.3.6 of this report. This section discusses the modelled results with background concentrations for Base Scenario, Scenario F_R_U and Scenario F_R. In order for the Base Scenario and updated future scenario to be directly comparable, background concentrations were added to the Base Scenario model results. The addition of the background concentrations provides some degree of “double counting” because of the inclusion of the large number of existing sources in all model scenarios. However, the comparison in Section 2.3.6 demonstrates that background concentrations are needed to account for the contribution from regional sources not included in the Base Scenario model (e.g., ground transportation, personal vehicle traffic, comfort heating, fugitive emissions from road dust, etc.). For the purposes of this screening-level study, adding this level of conservatism promotes the screening/protective nature of the study goals.



2.3.1 Modelled NO₂ Concentrations

Figure 2-6, Figure 2-7 and Figure 2-8 show the 98th percentile of the daily peak 1-hour NO₂ concentrations (8th highest daily peak at each location) for Base Scenario, Scenario F_R_U and Scenario F_R.

Figure 2-9, Figure 2-10 and Figure 2-11 show the annual NO₂ concentrations for Base Scenario, Scenario F_R_U and Scenario F_R. Note that Scenario F_R plots are copies of those presented in the original PRAS report. Versions of the Scenario F_R NO₂ concentration plots zoomed on the area of highest concentration are included as in Figures 4-5 and 4-6 of the original PRAS report for 1-hour NO₂ and annual NO₂, respectively.

The concentrations in the Base Scenario extend close to where the existing Port Facilities are located, which aligns with expectations. There is a noticeable difference between Scenario F_R_U and Scenario F_R. The area of higher concentrations near Fairview in Scenario F_R plots does not exist in Scenario F_R_U plots, which indicates that the highest concentrations in the previously modelled scenarios were due to overly conservative emission rates and source characterization of the Port Facilities. However, the concentrations at Lax Kw'alaams show a slight increase in Scenario F_R_U compared to Scenario F_R. This increase in NO₂ near at Lax Kw'alaams is due to Scenario F_R_U using proponent-provided data for Grassy Point LNG's thermal oxidizer, which has higher NO_x emissions than the proxy data used originally.



Prince Rupert Airshed Study
98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Base Scenario

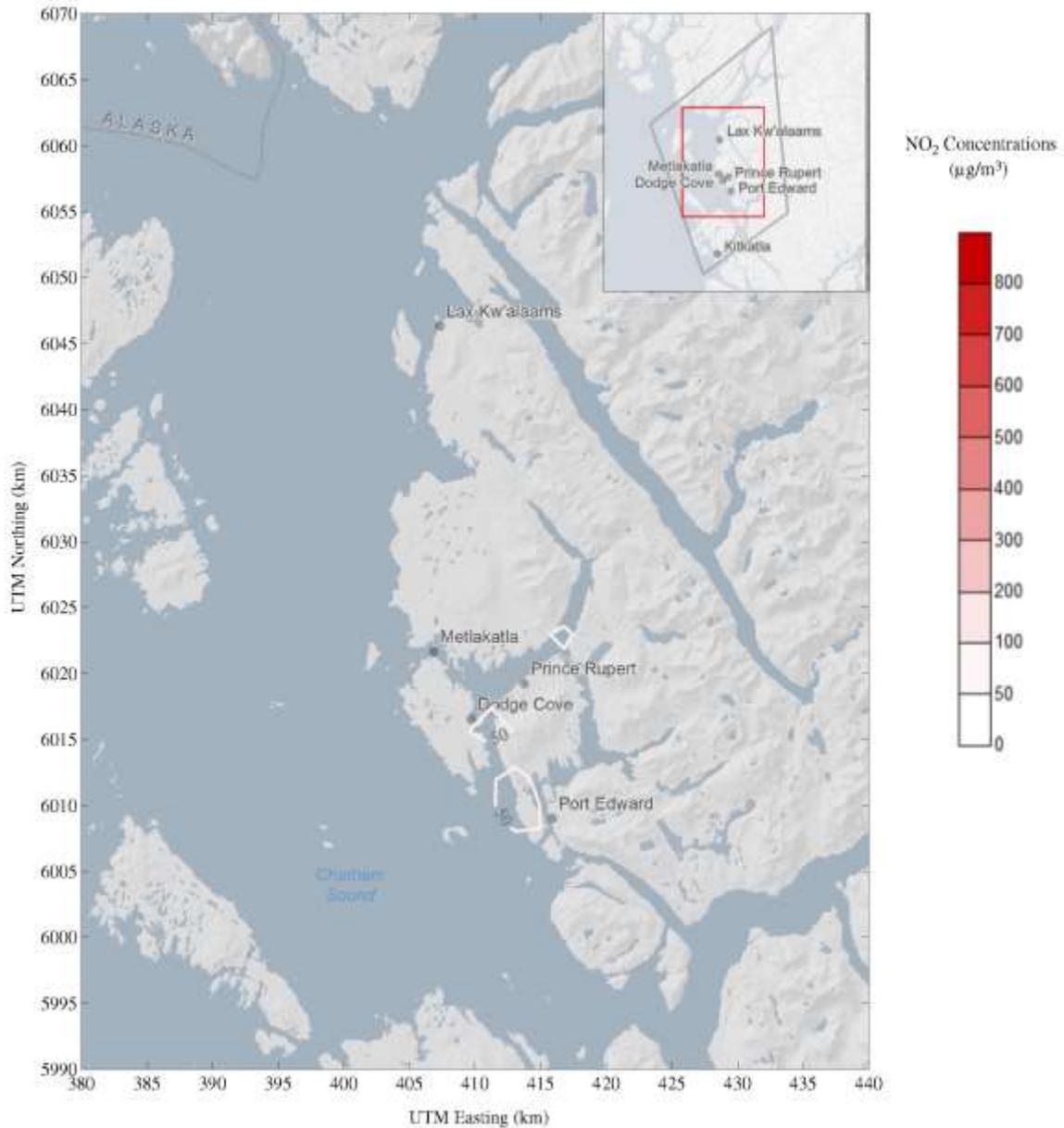


Figure 2-6: Base Scenario, 98th percentile NO₂ concentration, 1-hour average. The modelled NO₂ concentrations include a background concentration of 24 µg/m³.



Prince Rupert Airshed Study
98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario F_R_U

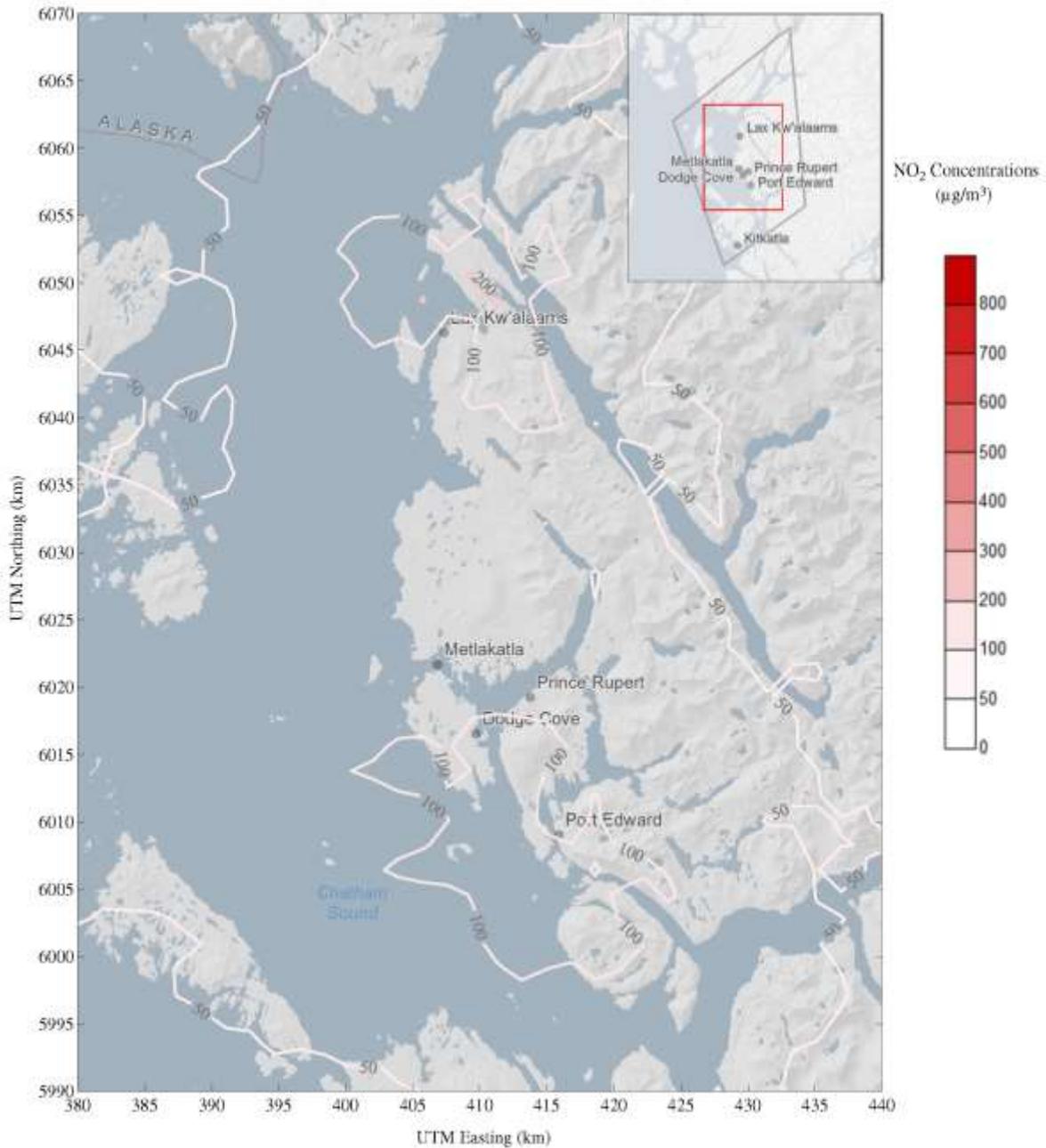


Figure 2-7: Scenario F_R_U, 98th percentile NO₂ concentration, 1-hour average. The modelled NO₂ concentrations include a background concentration of 24 µg/m³.



Prince Rupert Airshed Study
98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario F_R

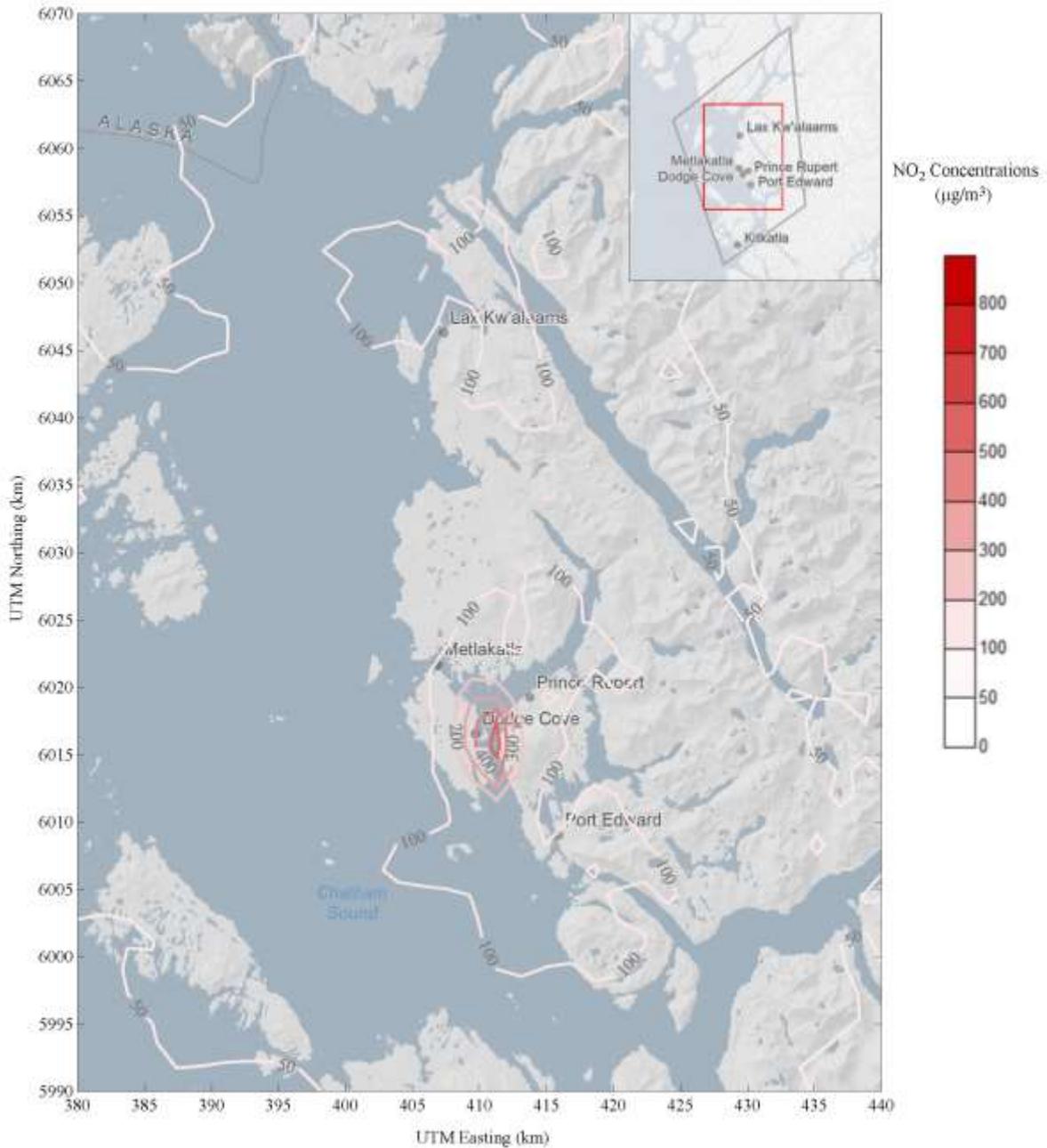


Figure 2-8: Scenario F_R, 98th percentile NO₂ concentration, 1-hour average. The modelled NO₂ concentrations include a background concentration of 24 µg/m³.



**Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year
Base Scenario**

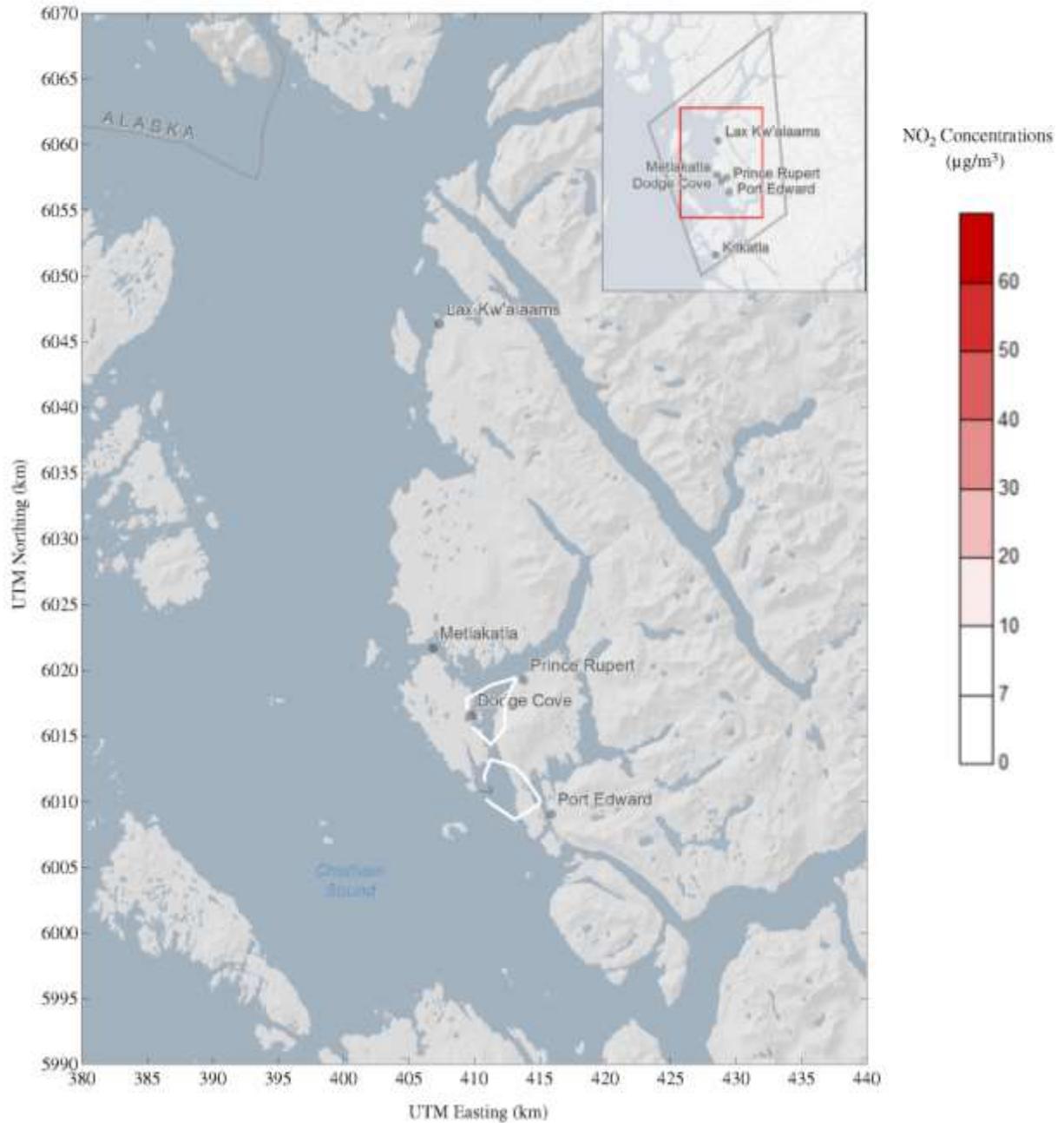


Figure 2-9: Base Scenario, NO₂ concentration, annual average. The modelled NO₂ concentrations include a background concentration of 5.6 µg/m³.



**Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario F_R_U**

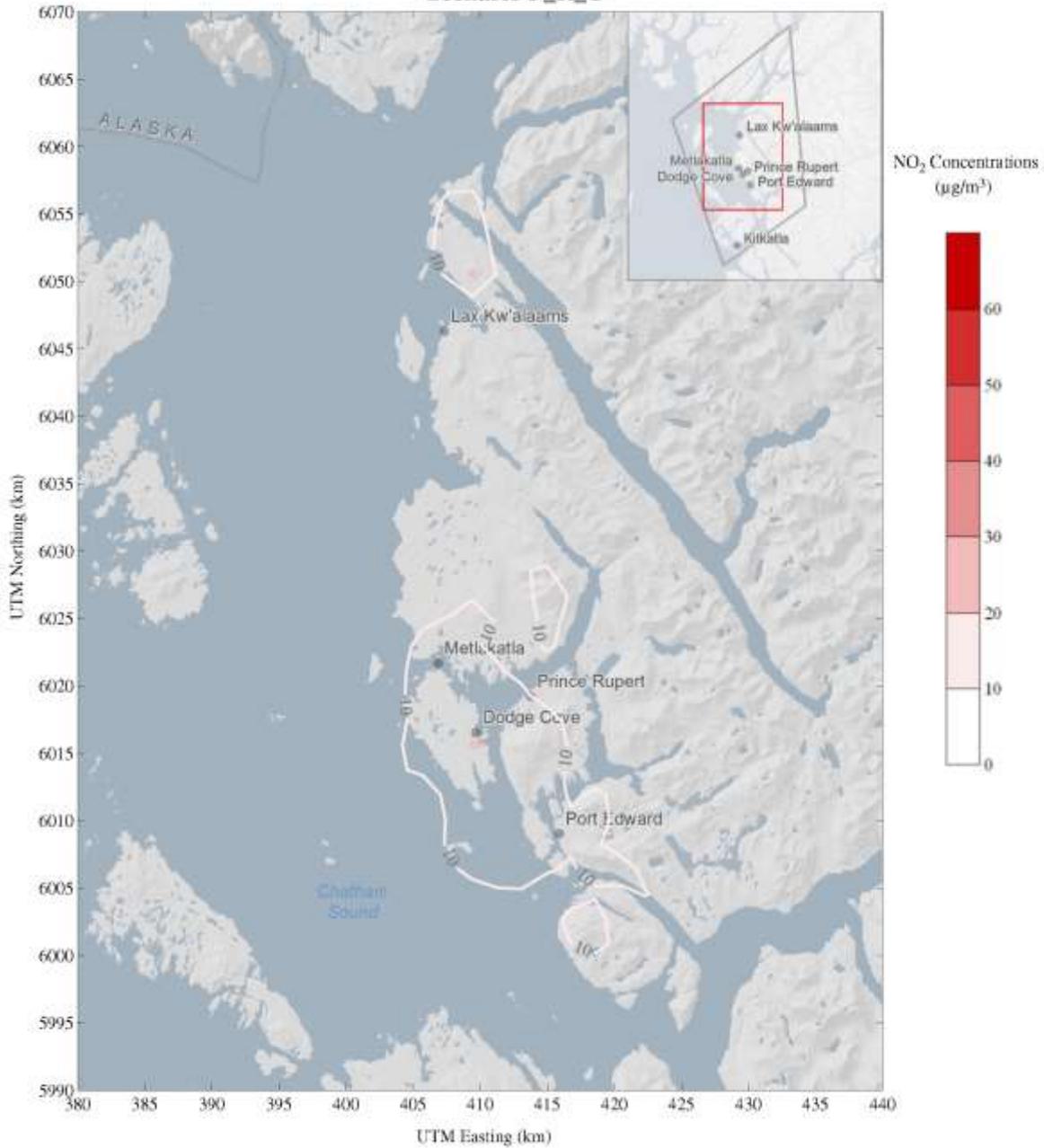


Figure 2-10: Scenario F_R_U, NO₂ concentration, annual average. The modelled NO₂ concentrations include a background concentration of 5.6 µg/m³.



Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario F_R

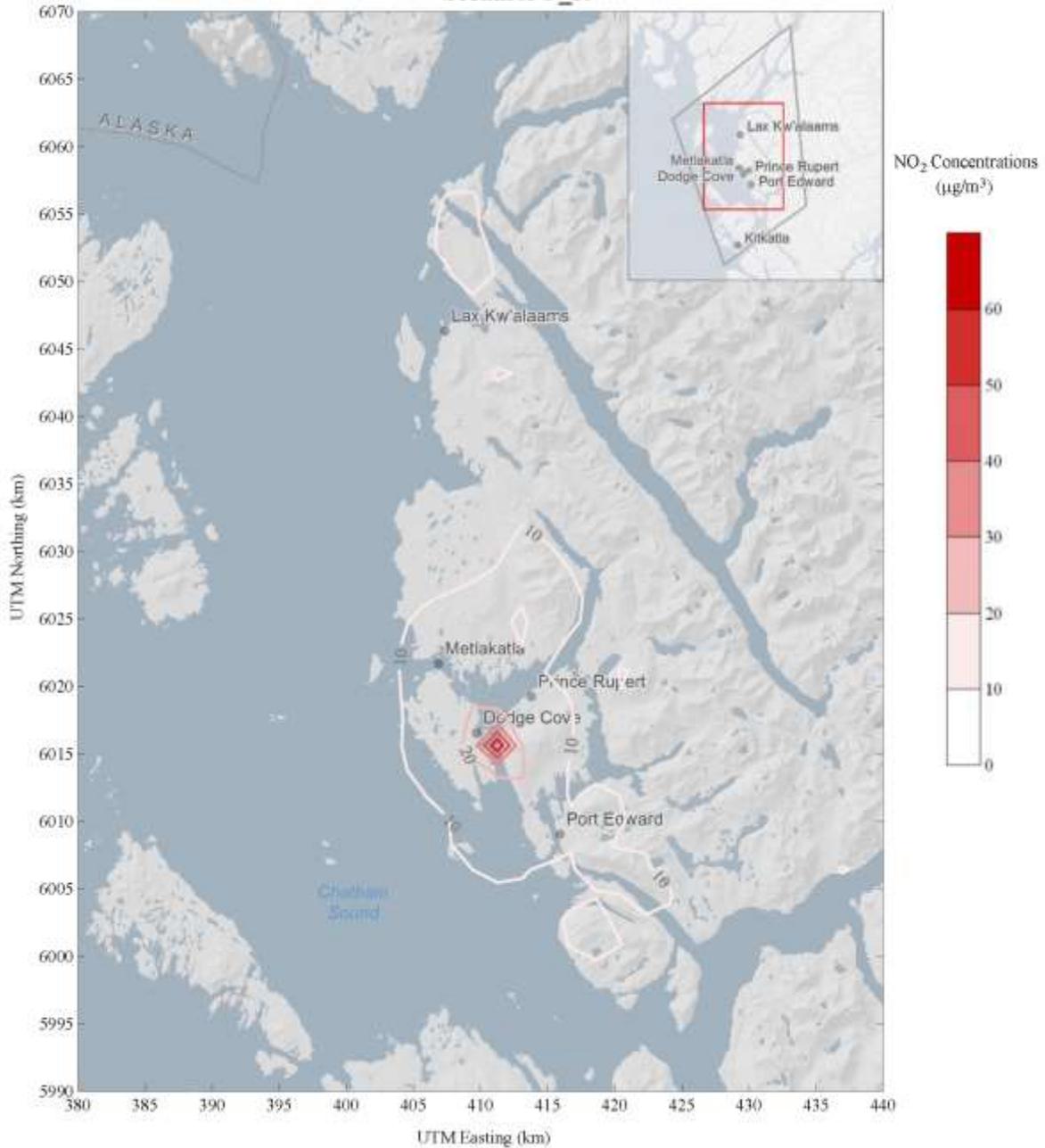


Figure 2-11: Scenario F_R, NO₂ concentration, annual average. The modelled NO₂ concentrations include a background concentration of 5.6 µg/m³.



2.3.2 Modelled SO₂ Concentrations

Figure 2-12, Figure 2-13 and Figure 2-14 show the 99th percentile of the daily peak 1-hour SO₂ concentrations (4th highest daily peak at each location) for Base Scenario, Scenario F_R_U and Scenario F_R. Figure 2-15, Figure 2-16 and Figure 2-17 show the annual SO₂ concentrations for Base Scenario, Scenario F_R_U and Scenario F_R. Note that Scenario F_R plots are copies of those presented in the original PRAS report. Versions of the Scenario F_R SO₂ concentration plots zoomed on the area of highest concentration are included as in Figures 4-3 and 4-4 of the original PRAS report for 1-hour SO₂ and annual SO₂, respectively.

Consistent with Base Scenario NO₂ figures, the extent of concentrations are close to where the existing Port Facilities are located. Additionally, both Figure 2-12 and Figure 2-15 show that the short-term concentrations are mostly from vessels at anchorage, and the emissions dispersed well over longer averaging periods.

There is also a noticeable difference between Scenario F_R_U and Scenario F_R in SO₂ concentrations. Due to lower SO₂ emissions from mobile sources and the thermal oxidizer at Aurora, the extent of the isopleth at 50 µg/m³ decreased substantially in the Scenario F_R_U 1-hour SO₂ plot. Similarly to NO₂ concentrations, the SO₂ concentrations at Lax Kw'alaams show a slight increase in Scenario F_R_U compared to Scenario F_R, because Scenario F_R_U used calculated SO₂ emission rates for Woodside thermal oxidizers, which have higher SO₂ emissions than previously modelled proxy emission rates.



Prince Rupert Airshed Study
99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Base Scenario

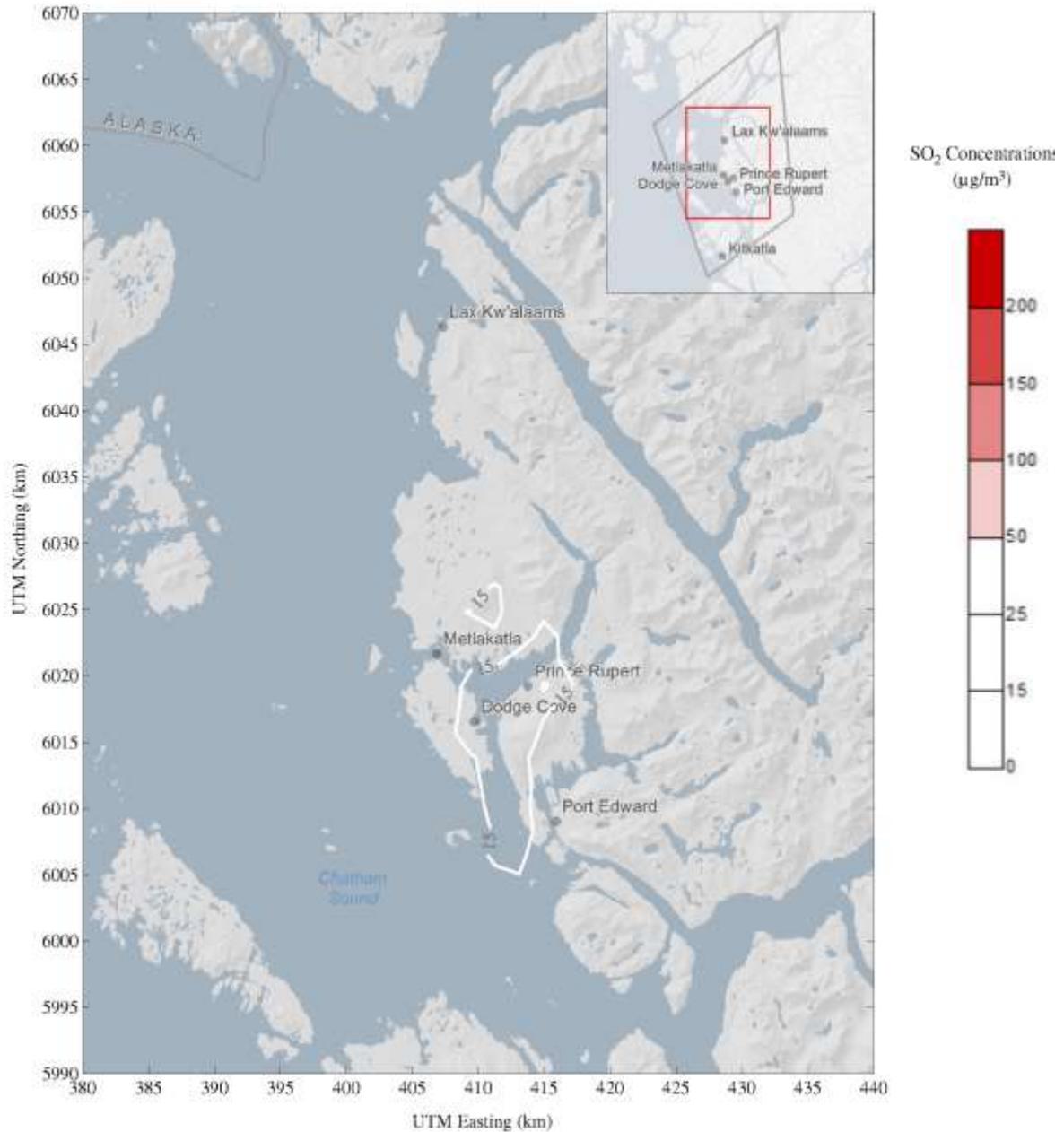


Figure 2-12: Base Scenario, 99th percentile SO₂ concentrations, 1-hour average. The modelled SO₂ concentrations include a background concentration of 11 µg/m³.



Prince Rupert Airshed Study
99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario F_R_U

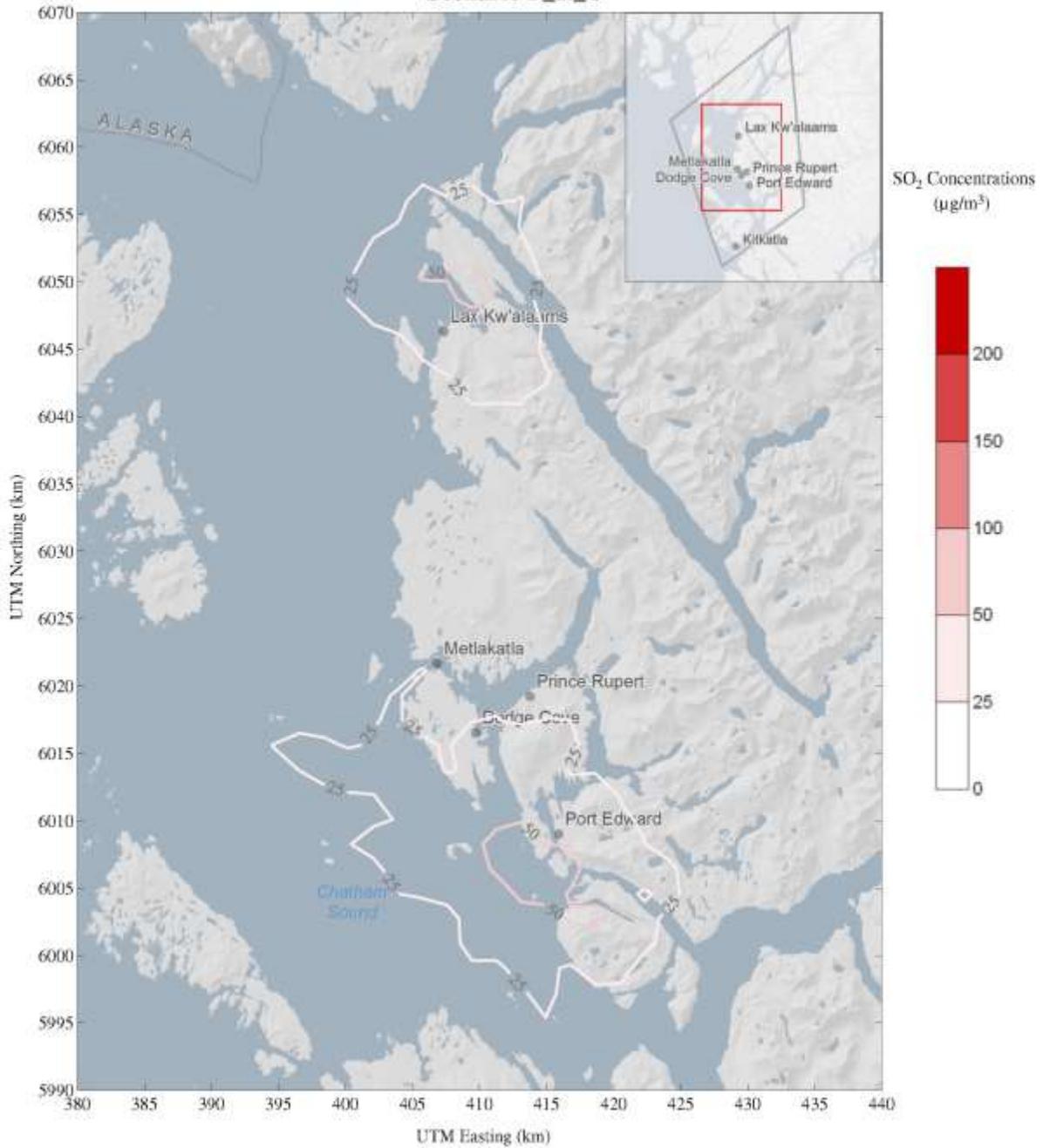


Figure 2-13: Scenario F_R_U, 99th percentile SO₂ concentrations, 1-hour average. The modelled SO₂ concentrations include a background concentration of 11 µg/m³.



Prince Rupert Airshed Study
99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario F_R

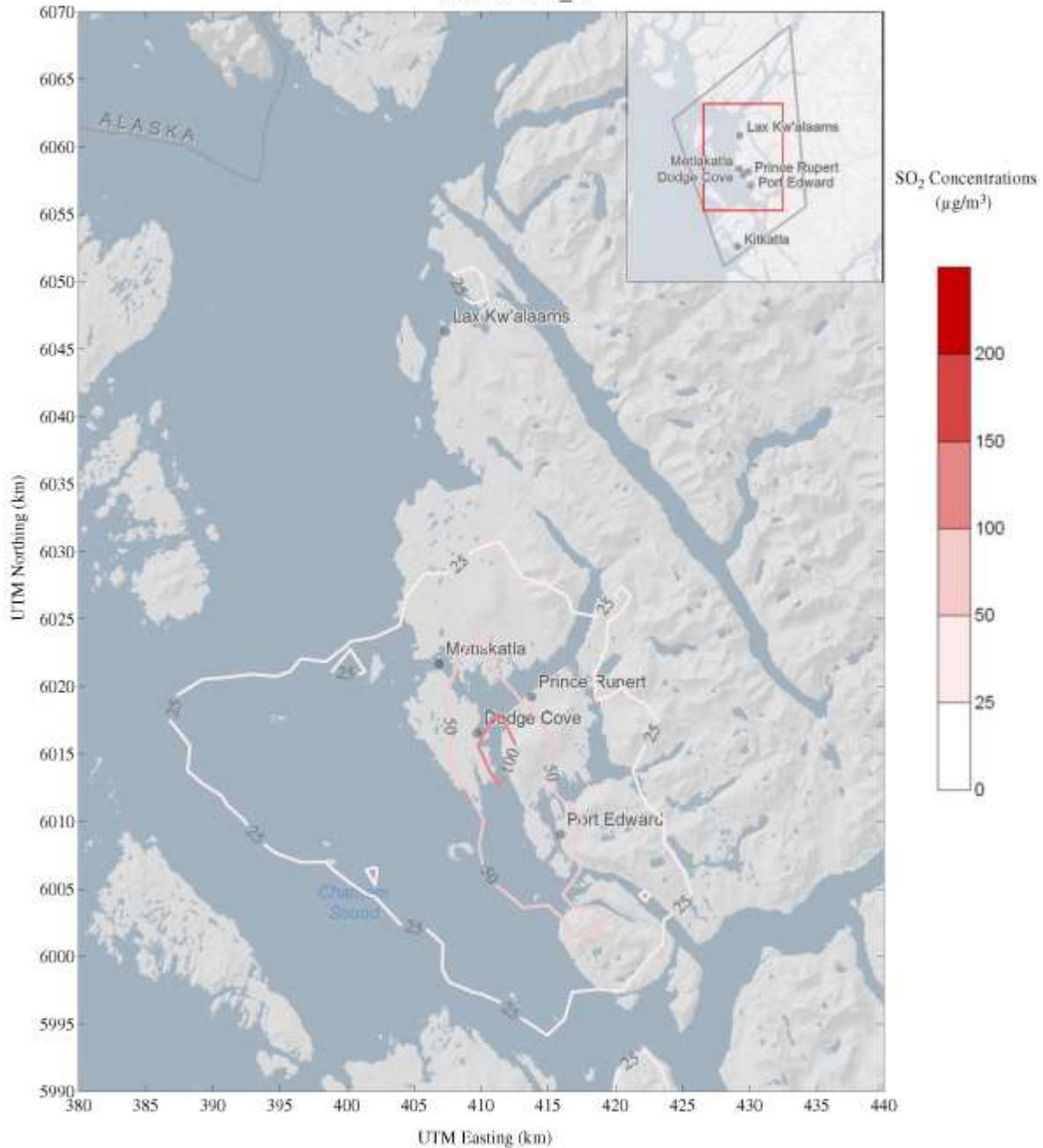


Figure 2-14: Scenario F_R, 99th percentile SO₂ concentrations, 1-hour average. The modelled SO₂ concentrations include a background concentration of 11 µg/m³.



**Prince Rupert Airshed Study
SO₂ Concentrations, Annual Average
2012 Meteorological Year
Base Scenario**

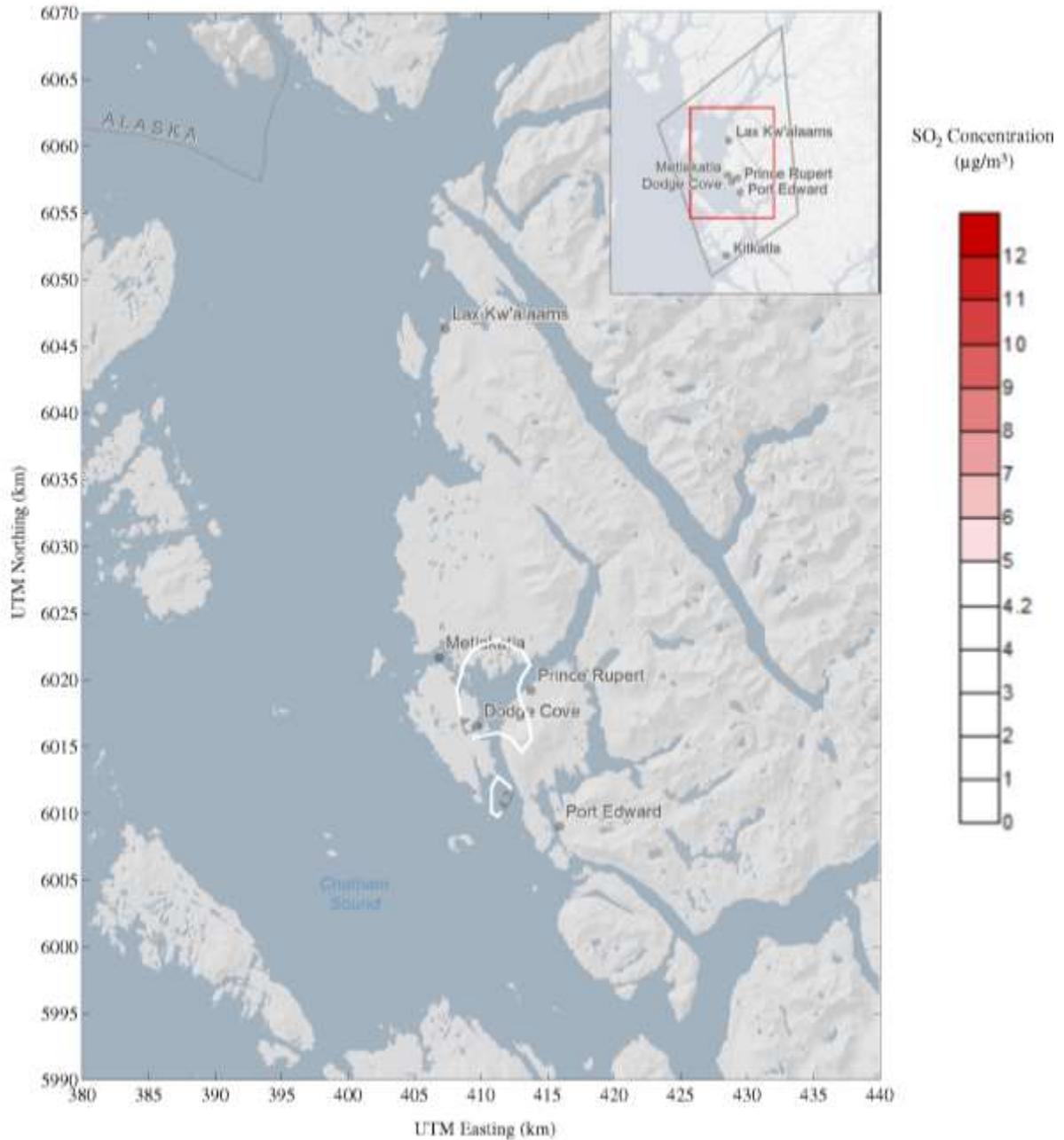


Figure 2-15: Base Scenario, SO₂ concentration, annual average. The modelled SO₂ concentrations include a background concentration of 4 µg/m³.



Prince Rupert Airshed Study
SO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario F_R_U

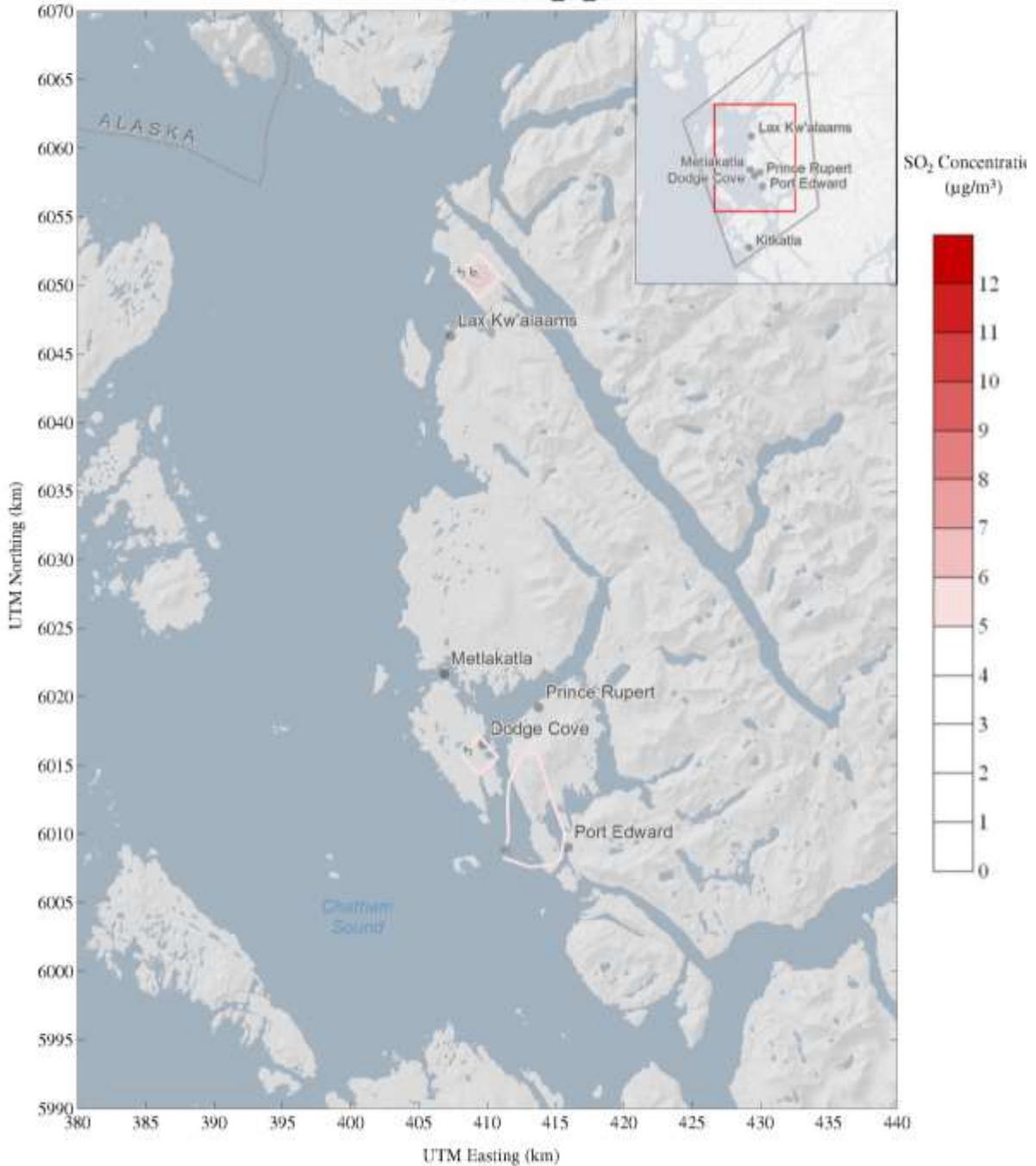


Figure 2-16: Scenario F_R_U, SO₂ concentration, annual average. The modelled SO₂ concentrations include a background concentration of 4 µg/m³.



**Prince Rupert Airshed Study
SO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario F_R**

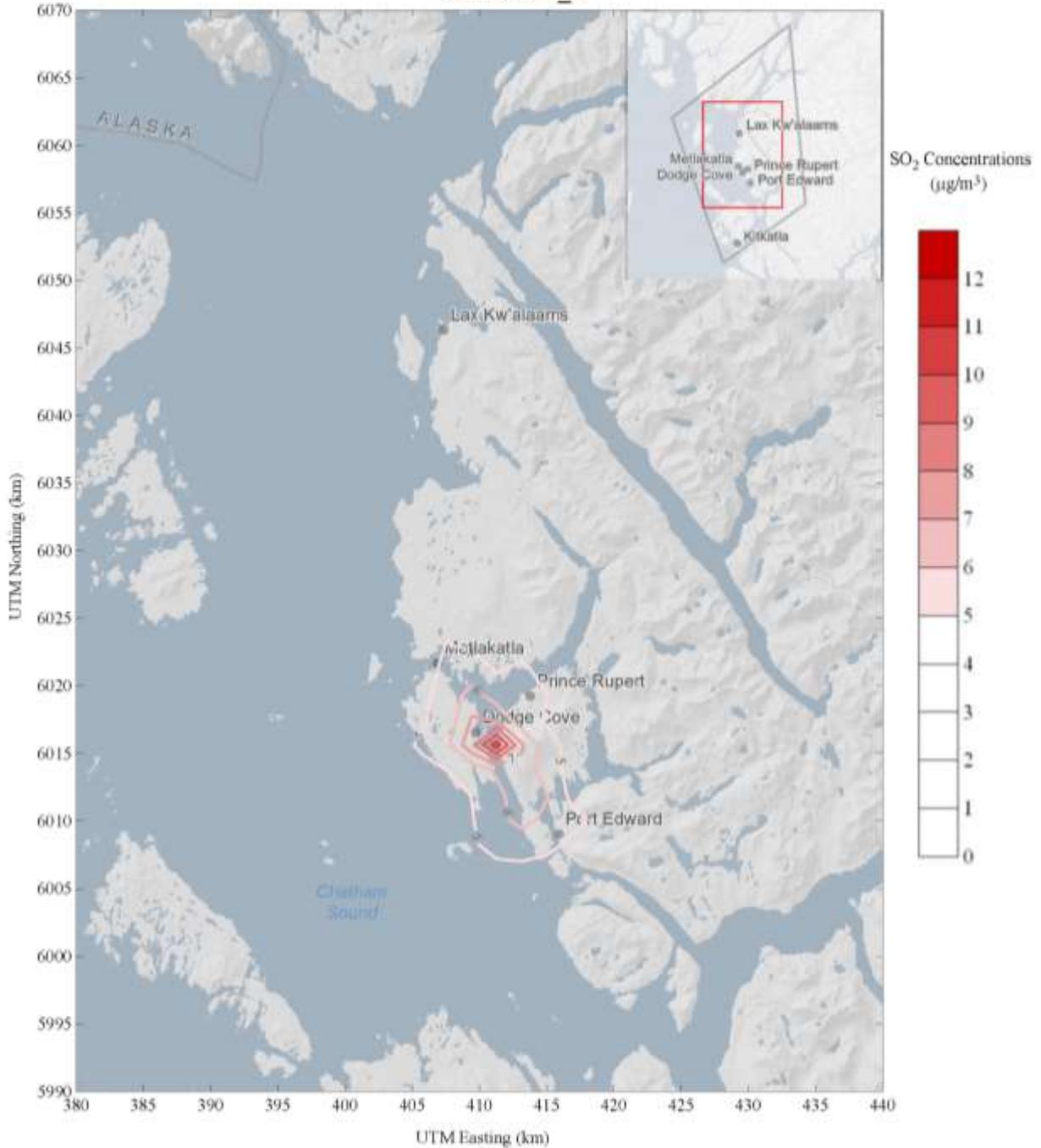


Figure 2-17: Scenario F_R, SO₂ concentration, annual average. The modelled SO₂ concentrations include a background concentration of 4 µg/m³.



2.3.3 Modelled PM_{2.5} Concentrations

Figure 2-18, Figure 2-19 and Figure 2-20 show the 98th percentile 24-hour PM_{2.5} concentrations (8th highest daily peak at each location) for Base Scenario, Scenario F_R_U and Scenario F_R. Figure 2-21, Figure 2-22 and Figure 2-23 show the annual PM_{2.5} concentrations for Base Scenario, Scenario F_R_U and Scenario F_R. The highest concentrations are close to Prince Rupert Grain, because the dust collectors at Prince Rupert Grain account for 50% of the PM_{2.5} emissions of all sources in the Base Scenario.

PM_{2.5} 24-hour plots show similar isopleths at 12.5 µg/m³ between Scenario F_R and Scenario F_R_U. Compared to the change in SO₂ and NO₂ 1-hour concentrations between Scenario F_R and Scenario F_R_U, the difference in PM_{2.5} contours is less remarkable. The minor difference is in line with expectations, given that PM_{2.5} has lower overall emission rates in all scenarios and fewer changes to emission rates from Scenario F_R to Scenario F_R_U. Additionally, the high background concentration of 7 µg/m³ accounts for over half of concentration at the 12.5 µg/m³ isopleths.

PM_{2.5} annual plots show a slightly more noticeable difference between Scenario F_R_U and Scenario F_R. Figure 2-22 does not show isopleths at 8 and 10 µg/m³, and the extent of isopleth at 6 µg/m³ is appreciably smaller compared to Figure 2-23. This is mostly likely due to the refinement of characterization of dust collectors at Prince Rupert Grain and Ridley Island Coal.



**Prince Rupert Airshed Study
98th Percentile PM_{2.5} Concentrations, 24 hour Average
2012 Meteorological Year
Base Scenario**

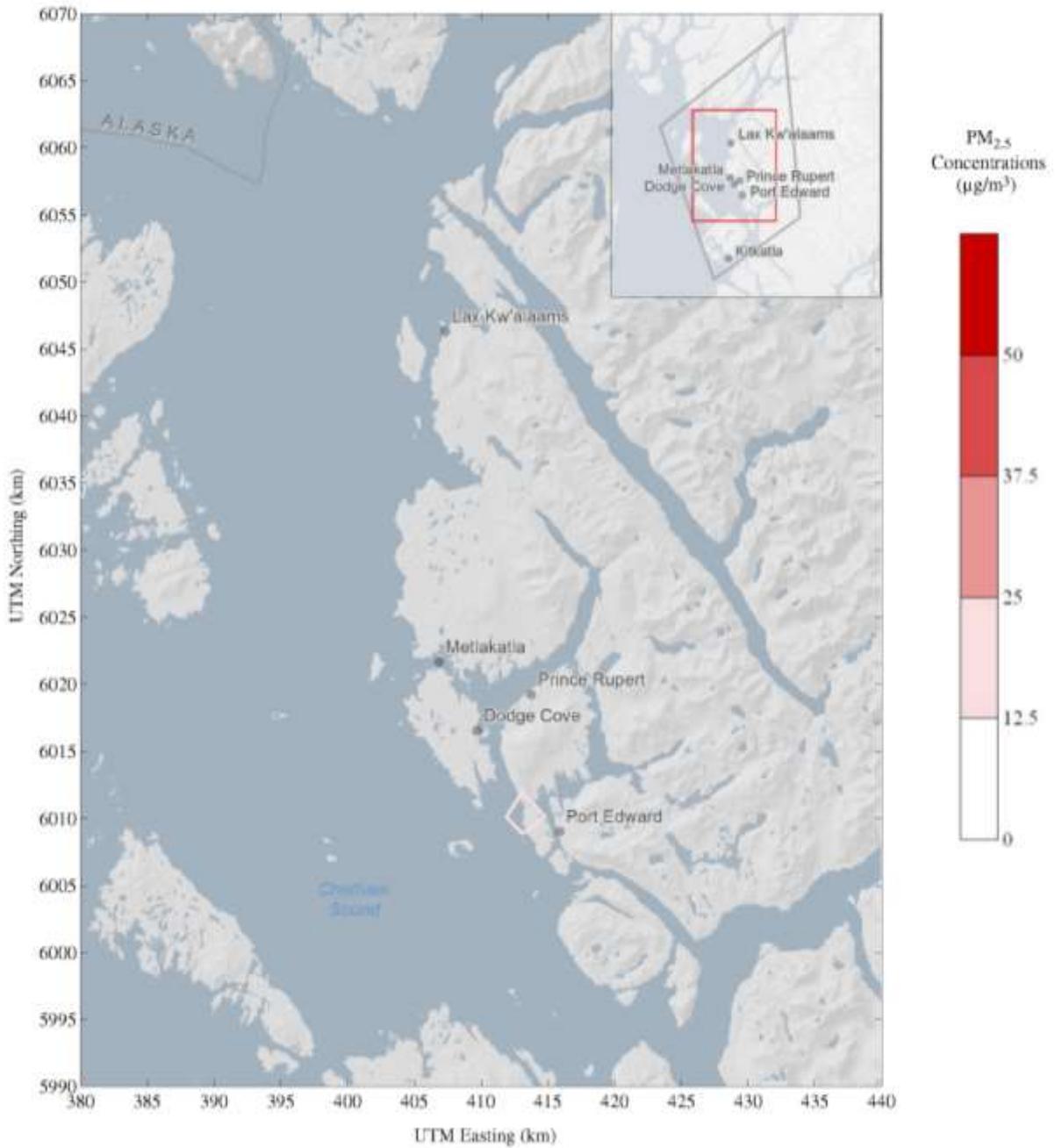


Figure 2-18: Base Scenario, 98th percentile PM_{2.5} concentrations, 24-hour average. The modelled PM_{2.5} concentrations include a background concentration of 7 µg/m³.



Prince Rupert Airshed Study
98th Percentile PM_{2.5} Concentrations, 24 hour Average
2012 Meteorological Year
Scenario F_R_U

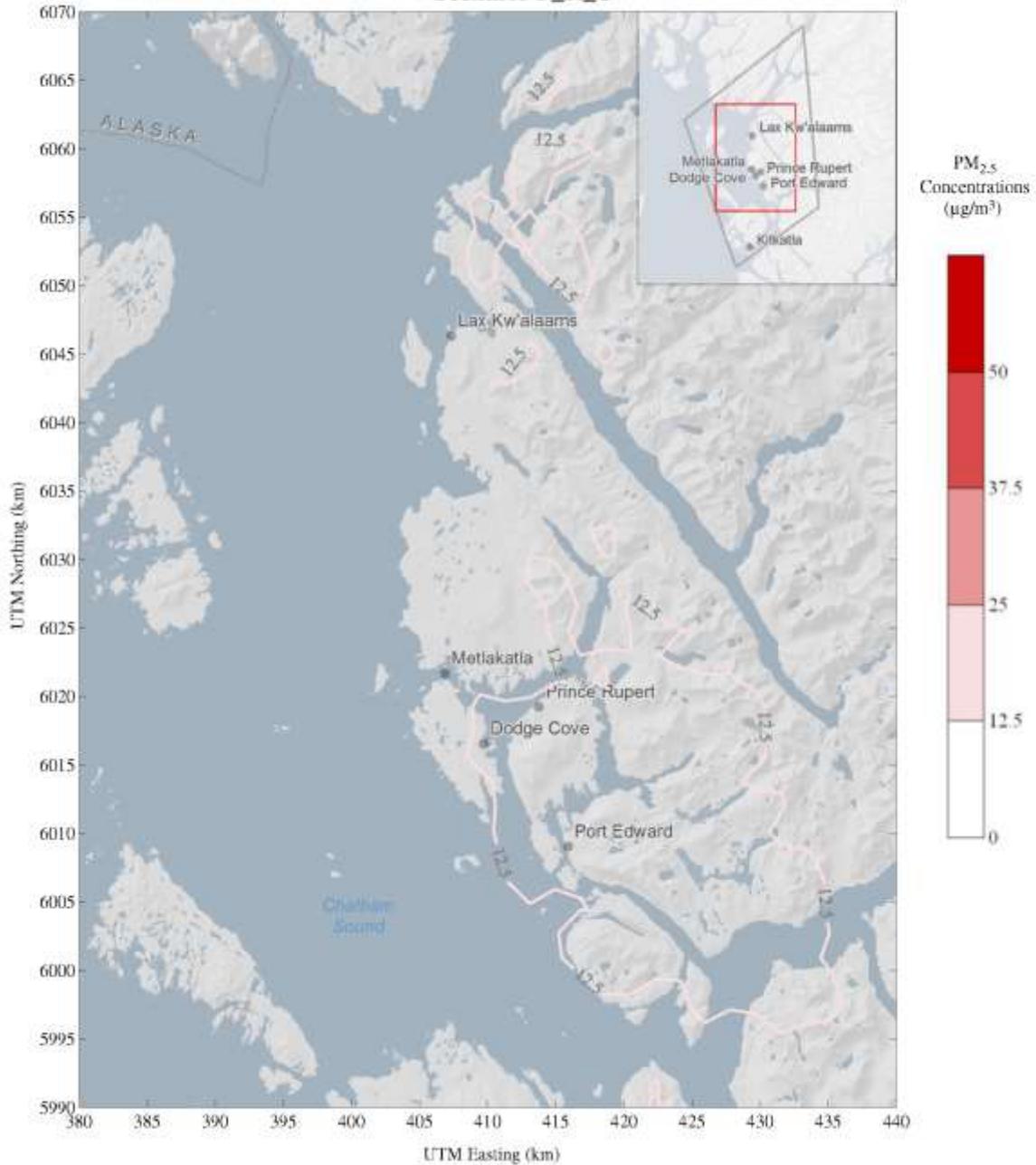


Figure 2-19: Scenario F_R_U, 98th percentile PM_{2.5} concentrations, 24-hour average. The modelled PM_{2.5} concentrations include a background concentration of 7 µg/m³.



**Prince Rupert Airshed Study
98th Percentile PM_{2.5} Concentrations, 24 hour Average
2012 Meteorological Year
Scenario F_R**

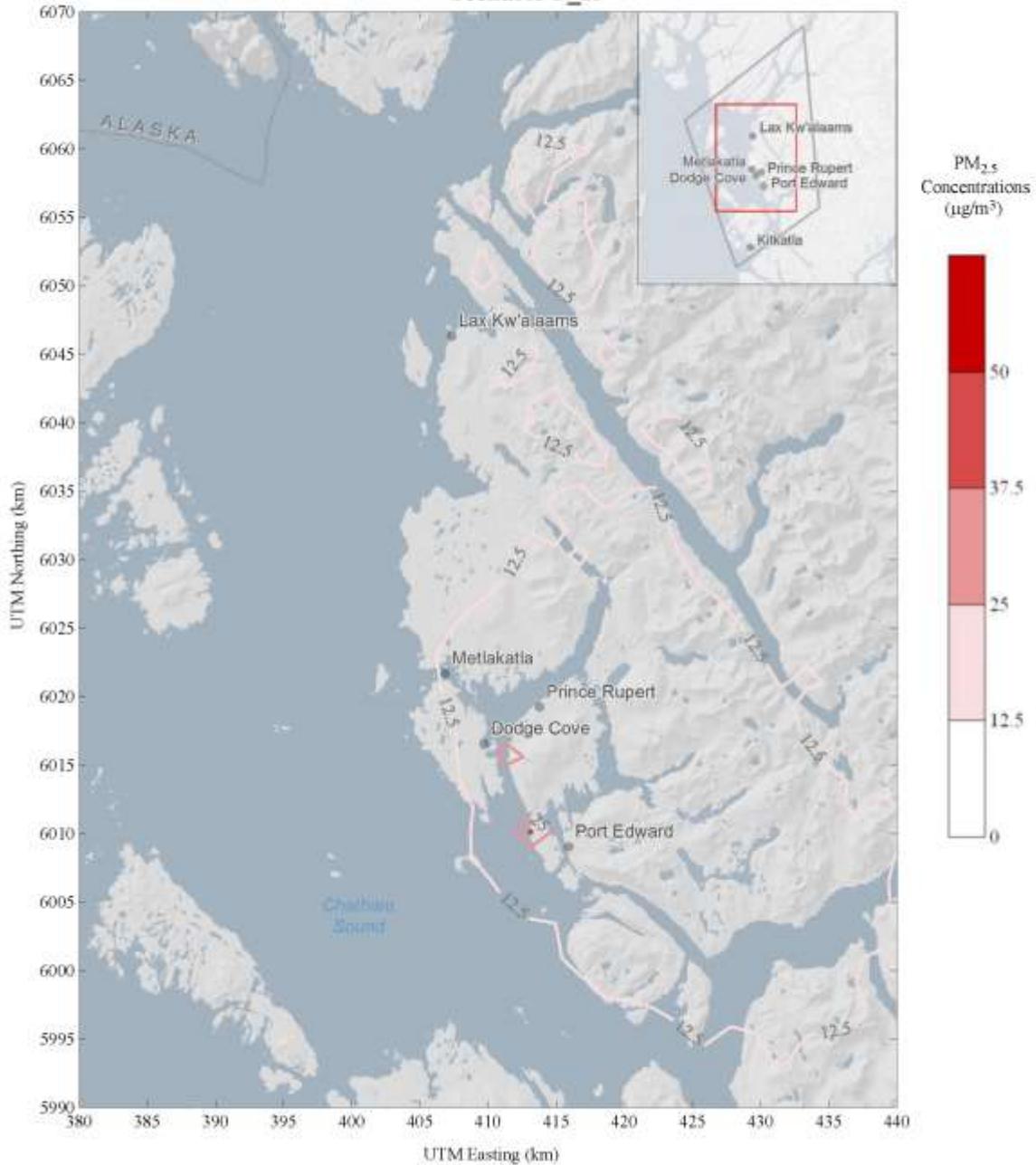


Figure 2-20: Scenario F_R, 98th percentile PM_{2.5} concentrations, 24-hour average. The modelled PM_{2.5} concentrations include a background concentration of 7 $\mu\text{g}/\text{m}^3$.



Prince Rupert Airshed Study
PM_{2.5} Concentrations, Annual Average
2012 Meteorological Year
Base Scenario

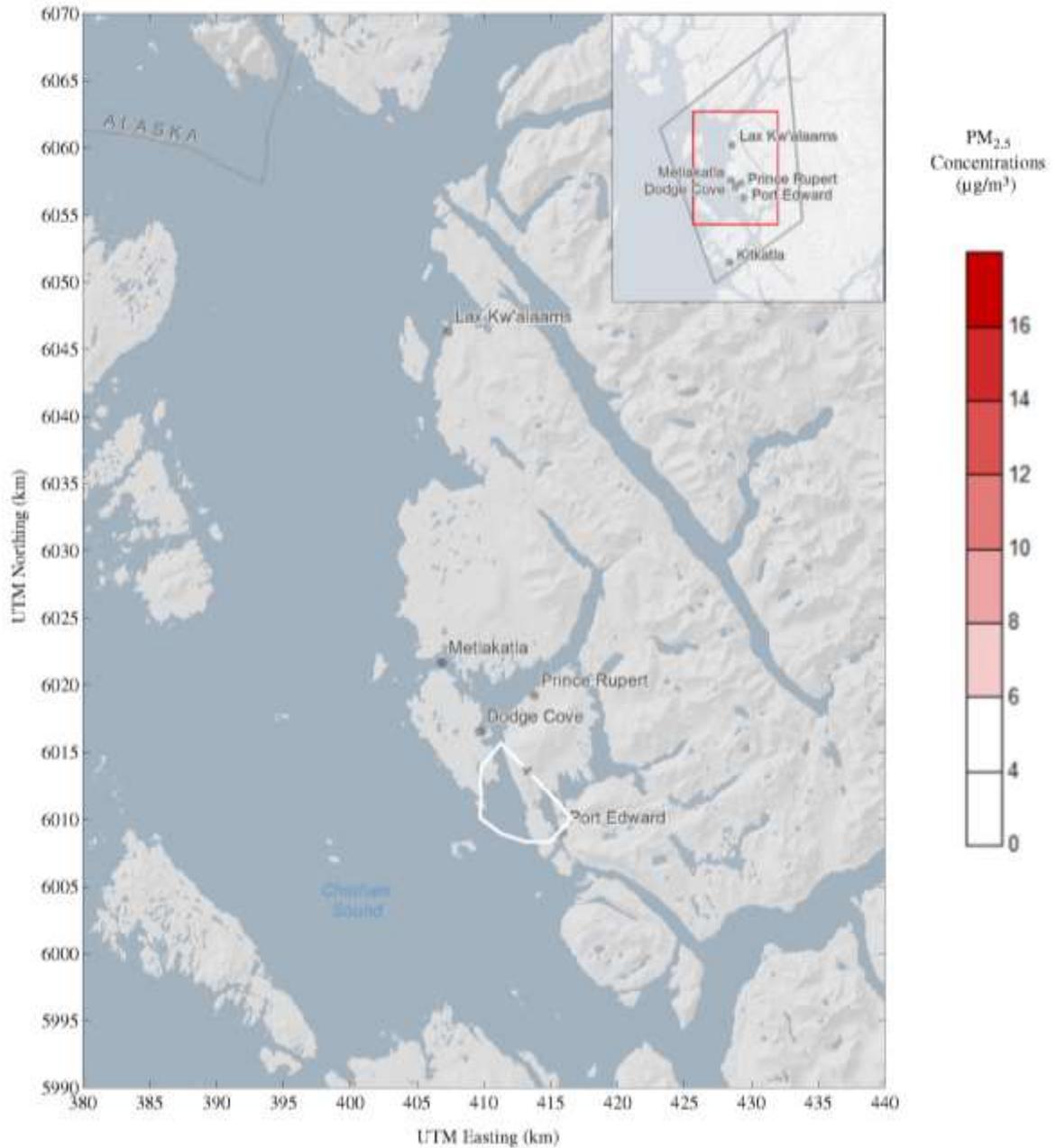


Figure 2-21: Base Scenario, PM_{2.5} concentration, annual average. The modelled PM_{2.5} concentrations include a background concentration of 3.5 µg/m³.



**Prince Rupert Airshed Study
PM_{2.5} Concentrations, Annual Average
2012 Meteorological Year
Scenario F_R_U**

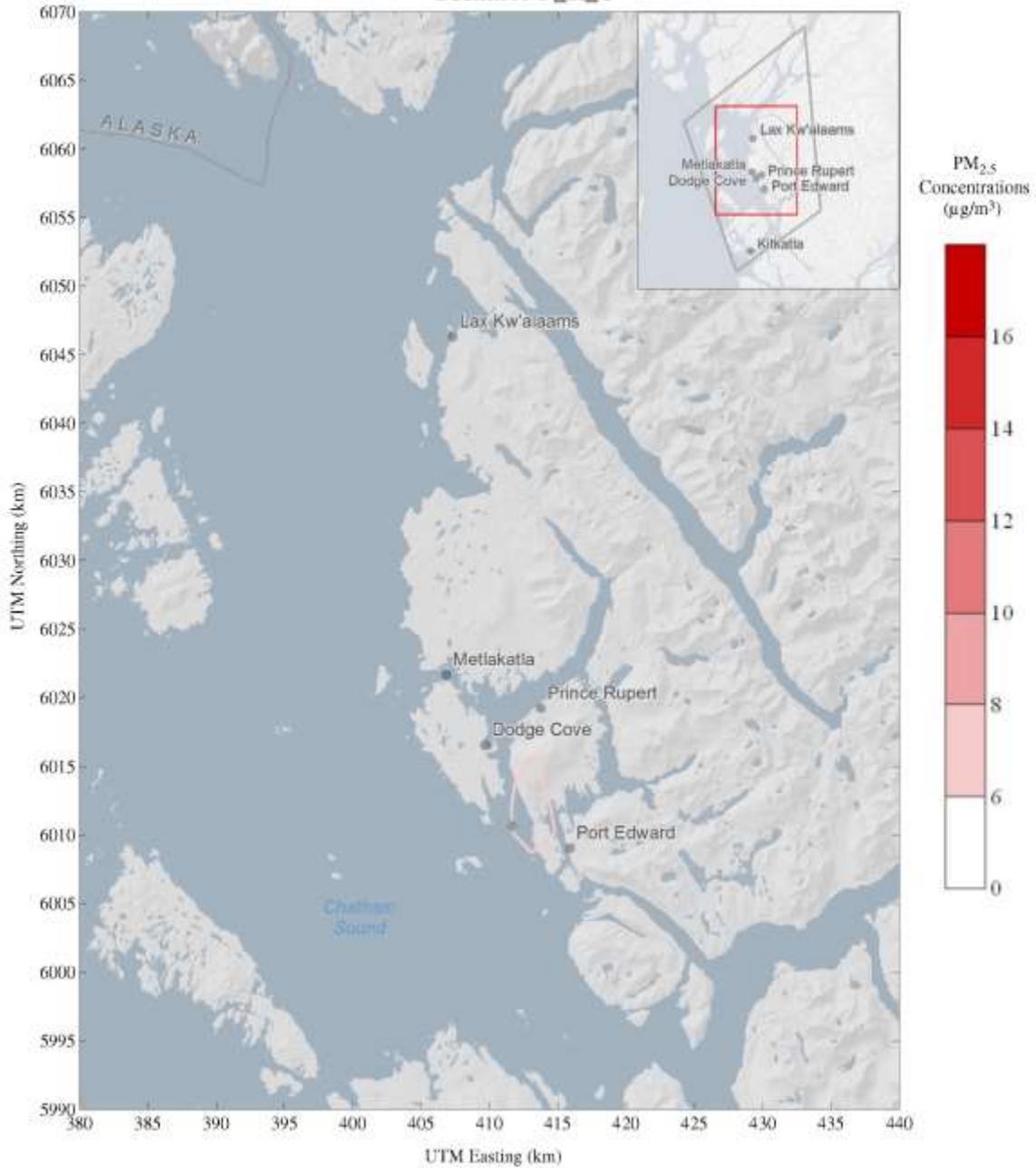


Figure 2-22: Scenario F_R_U, PM_{2.5} concentration, annual average. The modelled PM_{2.5} concentrations include a background concentration of 3.5 µg/m³.



**Prince Rupert Airshed Study
PM_{2.5} Concentrations, Annual Average
2012 Meteorological Year
Scenario F_R**

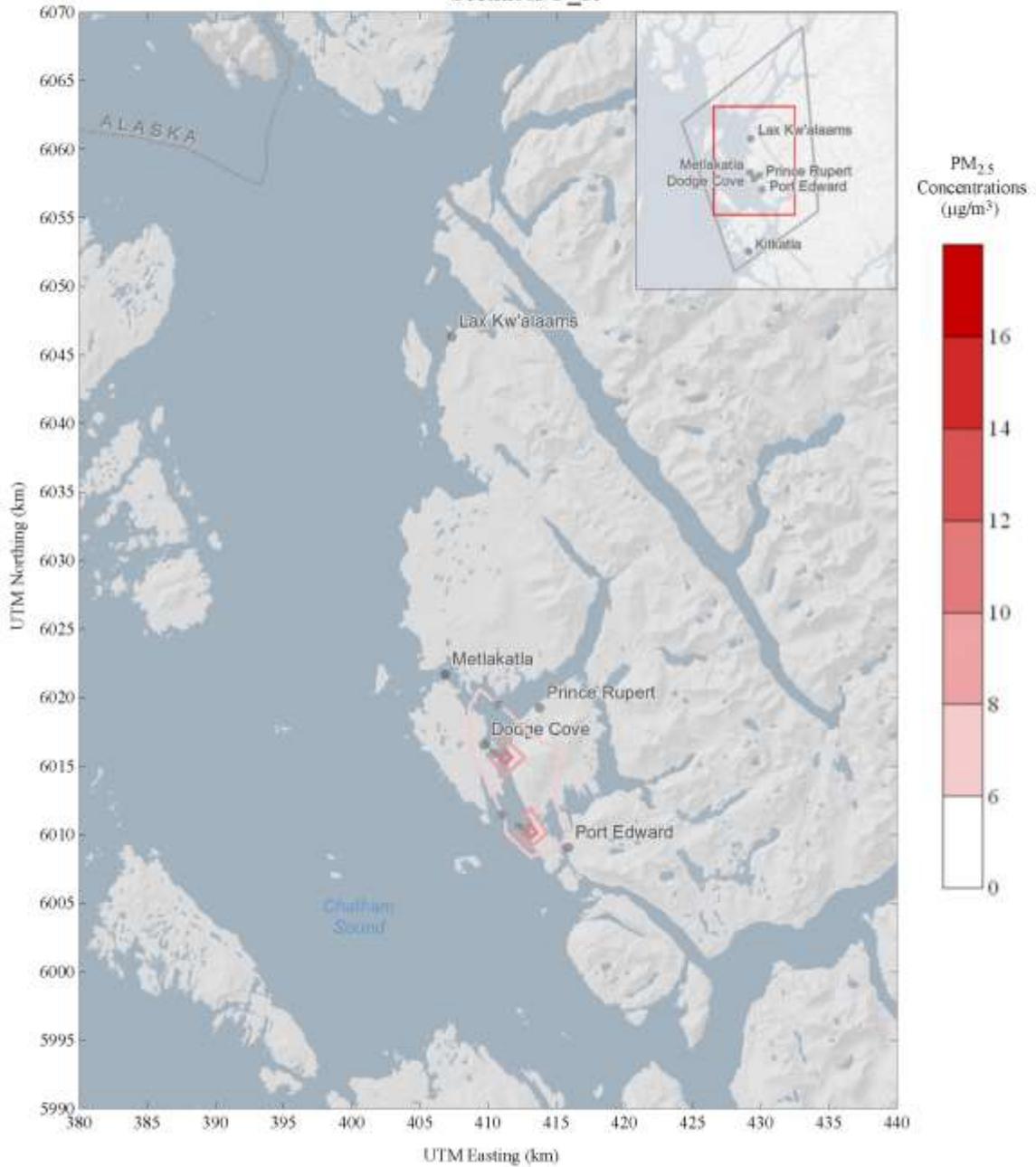


Figure 2-23: Scenario F_R, PM_{2.5} concentration, annual average. The modelled PM_{2.5} concentrations include a background concentration of 3.5 µg/m³.



2.3.4 Total Nitrogen Deposition Model Results

Total nitrogen deposition under the Base Scenario, Scenario F_R_U and Scenario F_R is shown in Figure 2-24, Figure 2-25, and Figure 2-26, respectively.

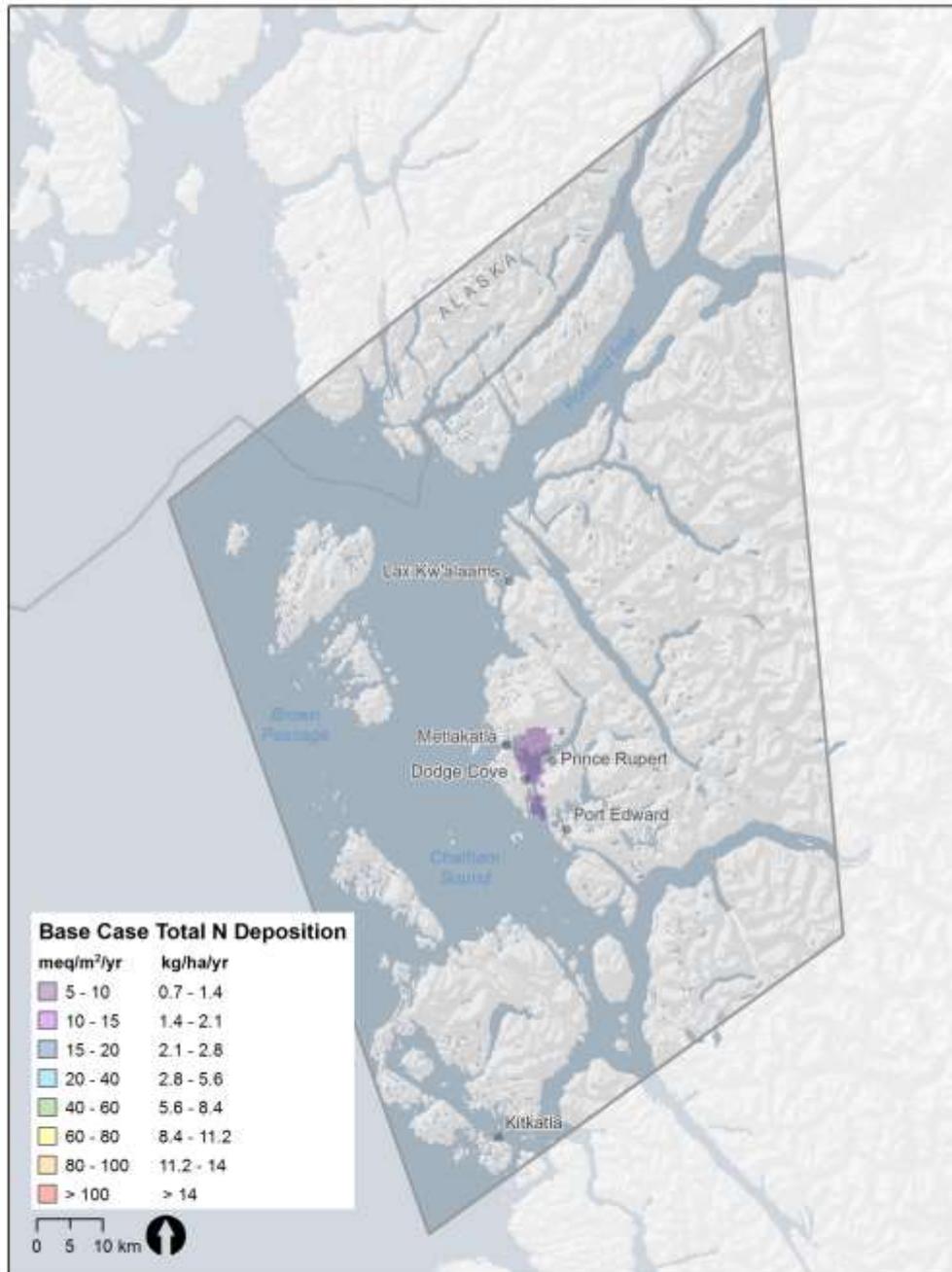


Figure 2-24: Base Scenario total nitrogen deposition, expressed in both units of acidity (meq/m²/yr), and as nitrogen (kg/ha/yr) for the annual averaging period.



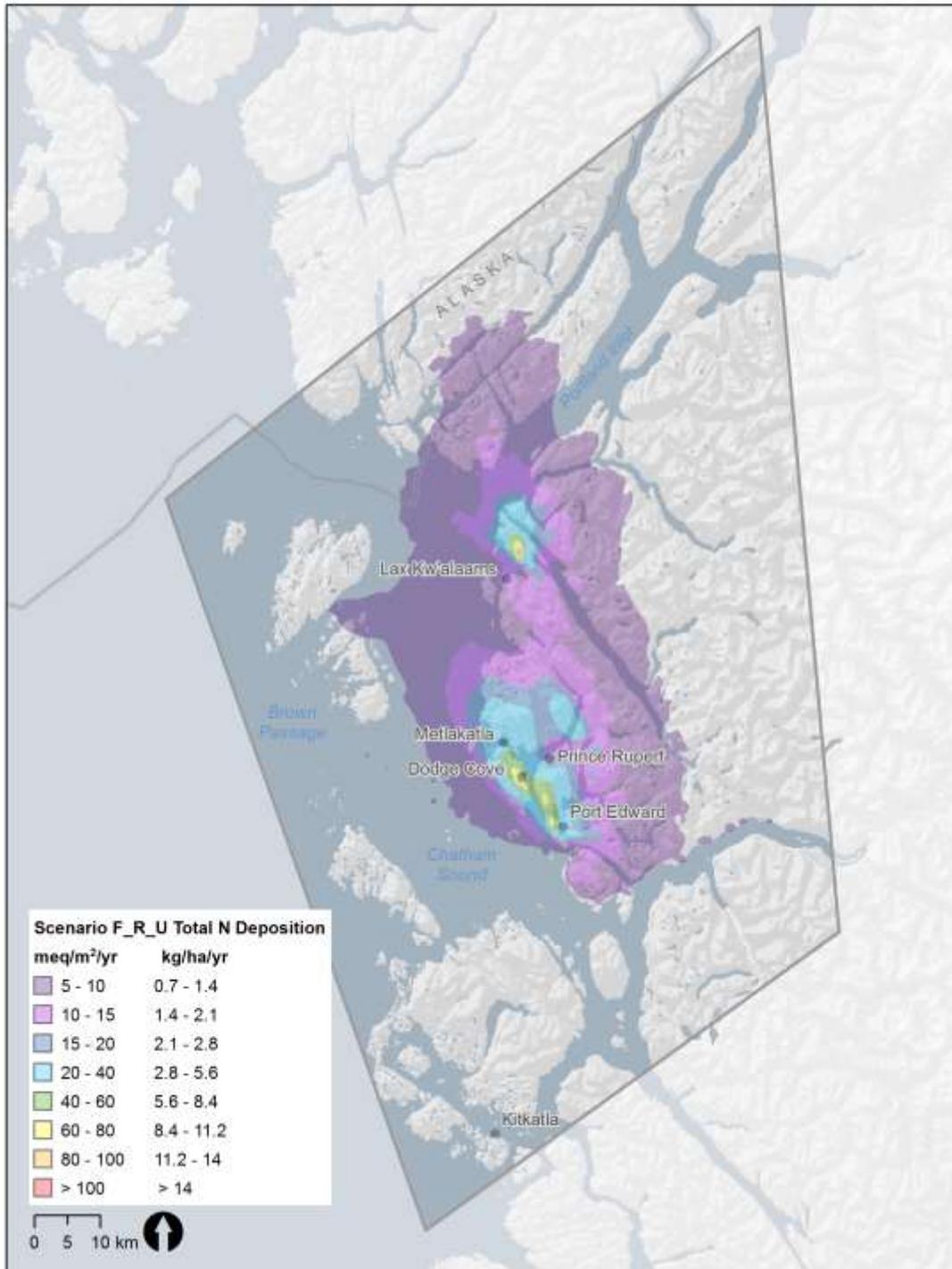


Figure 2-25: Scenario F_R_U, total nitrogen deposition, expressed in both units of acidity (meq/m²/yr), and as nitrogen (kg/ha/yr) for the annual averaging period.



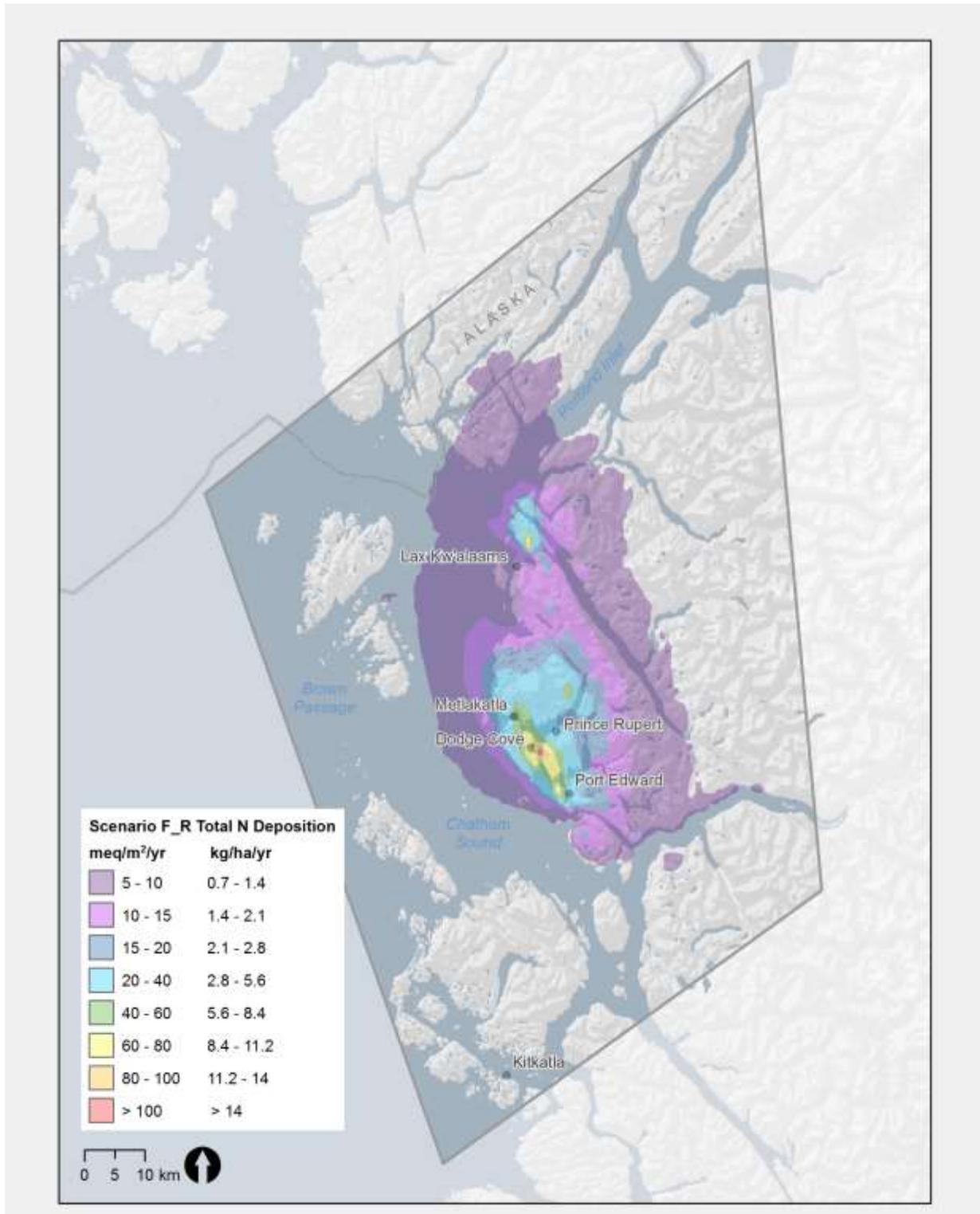


Figure 2-26: Scenario F_R, total nitrogen deposition, expressed in both units of acidity (meq/m²/yr), and as nitrogen (kg/ha/yr) for the annual averaging period.



2.3.5 Total Sulphur Deposition Model Results

Total sulphur deposition under the Base Scenario, Scenario F_R_U and Scenario F_R is shown in Figure 2-27, Figure 2-28 and Figure 2-29, respectively.

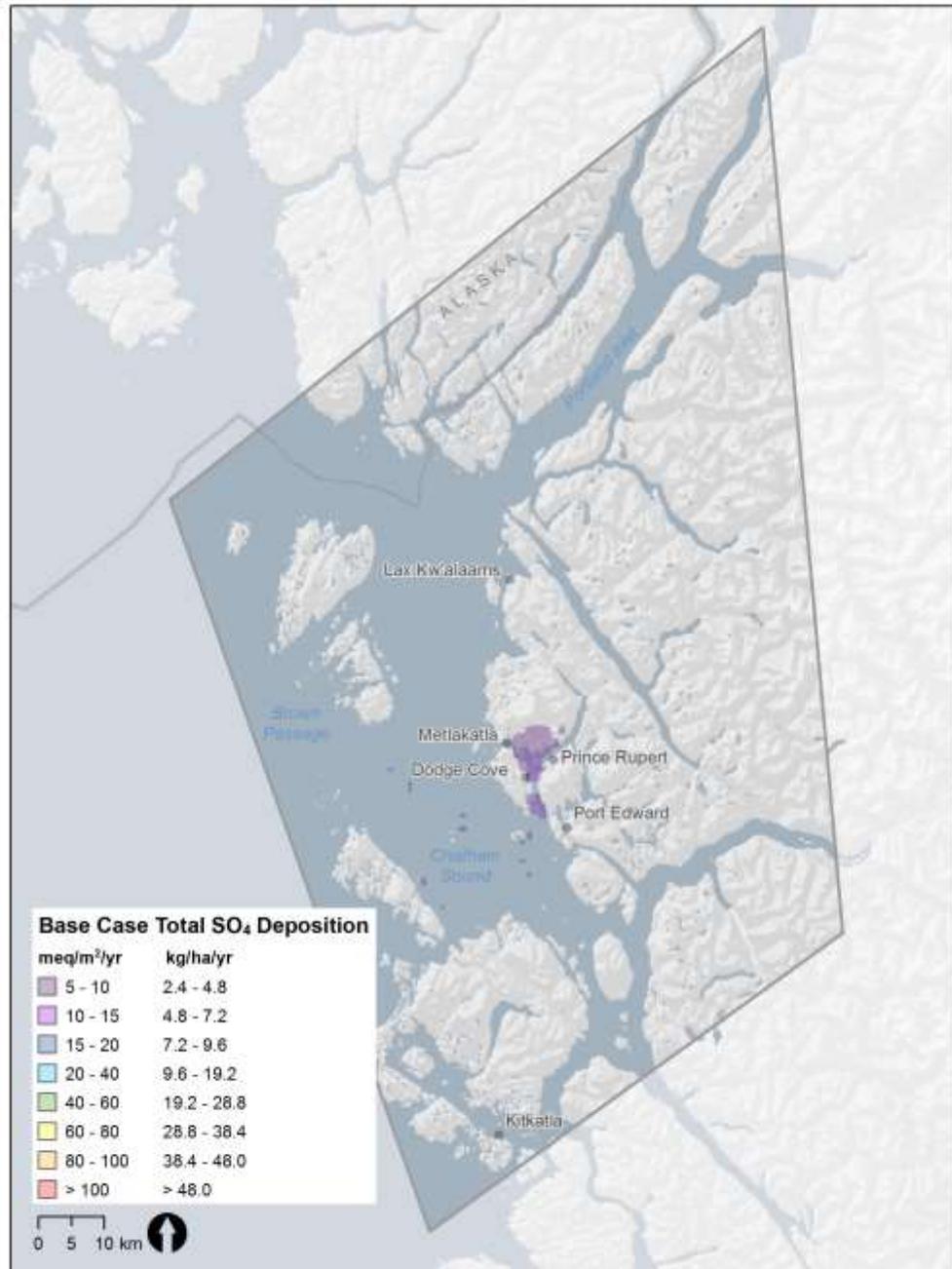


Figure 2-27: Base Scenario total sulphur deposition expressed in both units of acidity (meq/m²/yr), and as sulphate (kg/ha/yr), for the annual averaging period.



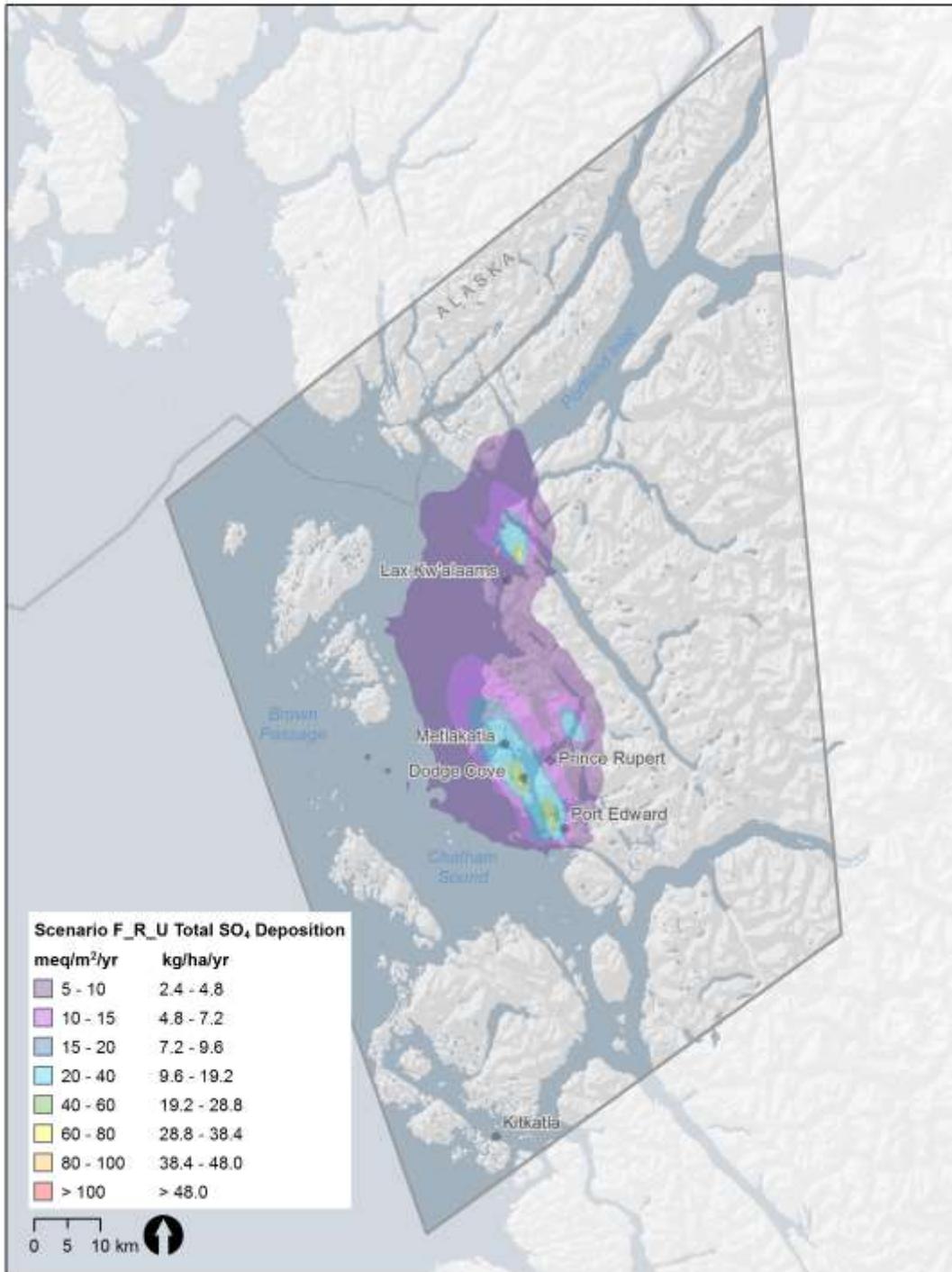


Figure 2-28: Scenario F_R_U, total sulphur deposition expressed in both units of acidity (meq/m²/yr), and as sulphate (kg/ha/yr), for the annual averaging period.

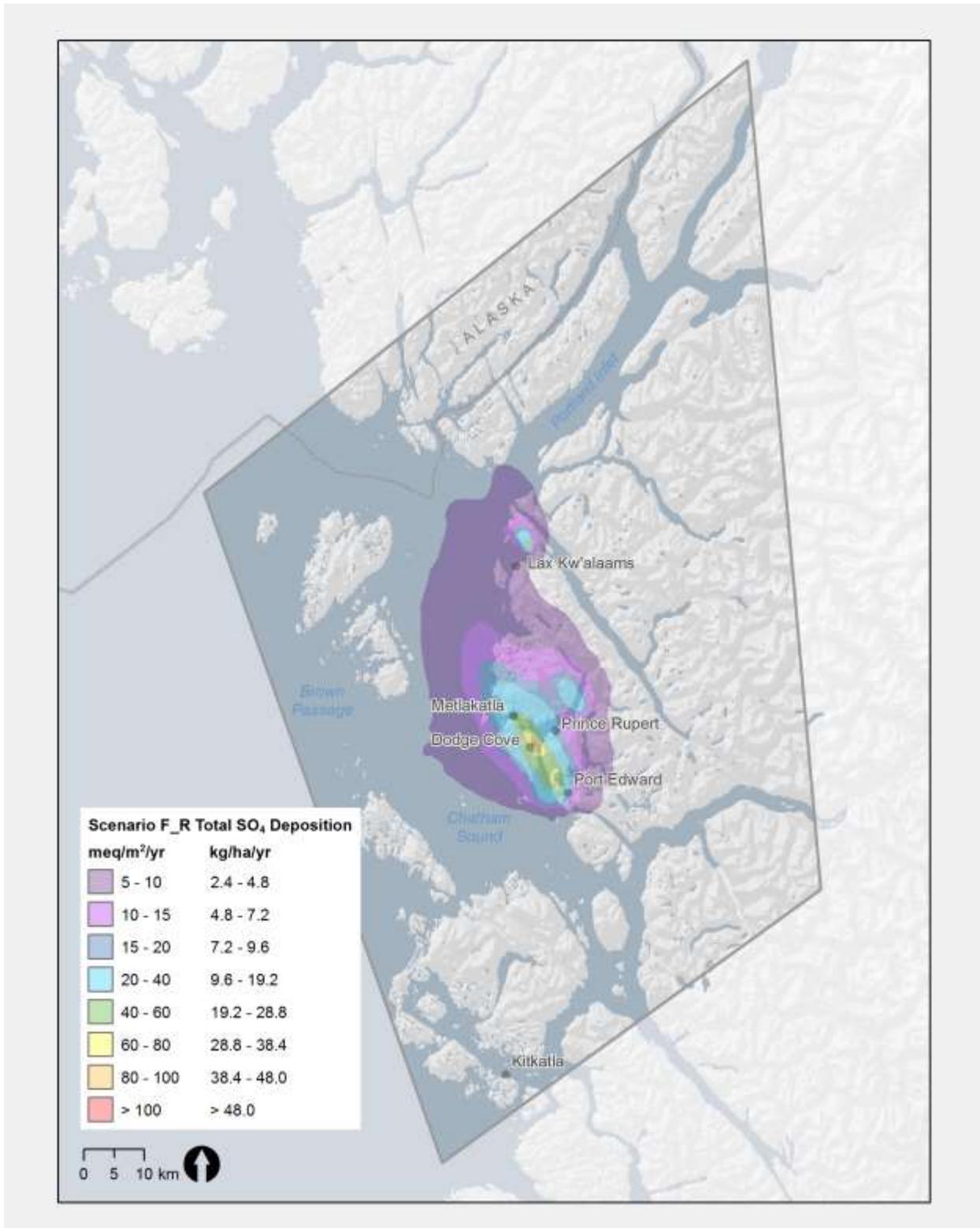


Figure 2-29: Scenario F_R, total sulphur deposition expressed in both units of acidity (meq/m²/yr), and as sulphate (kg/ha/yr), for the annual averaging period.



2.3.6 Comparison between Base Scenario Model Results and Monitored Data

This section summarizes modelled Base Scenario concentrations compared to monitored concentrations. As mentioned in the PRAS report, ambient air quality was monitored by the Mobile Air Monitoring Laboratory (MAML) temporarily from April 14 to August 15, 2013 (about 4 months). The MAML was placed at Water Street in Prince Rupert during that period. Modelled Base Scenario concentrations at the nearest receptor (UTM Easting 412.643 km, Northing 6,018.420 km)²⁴ without any background concentration are compared to the monitored data.

Generally speaking, background concentrations are intended to serve as a conservative representation of natural background plus existing sources (including non-industrial sources such as vehicle traffic). Therefore, a comparison of modelled Base Scenario to background concentrations serves as a check to confirm that background concentrations appropriately represent existing air quality in Prince Rupert.

- If Base Scenario model results are appreciably *higher* than monitored concentrations, the comparison would indicate that the Base Scenario source characterization may be overly conservative.
- If Base Scenario model results are appreciably *lower* than monitored concentrations, the comparison would indicate that the Base Scenario source characterization may not have captured the majority of Base Scenario (existing) emission sources.
 - Note that Base Scenario model results are expected to be somewhat lower than monitored concentrations, because the Base Scenario model includes existing industrial sources, but excludes other regional sources such as vehicle traffic and residential heating.
- If Base Scenario model results are *higher* than background concentrations, the comparison would indicate the background concentrations may not be as conservative as intended.

Also note that the model meteorological year (2012) is different from the year that the monitoring data were measured (2013); thus, the concentrations cannot be compared directly. Rather, a general comparison is included to serve as a check of the Base Scenario model results, and also as a check of the background concentrations added to model results for all scenarios.

Table 2-3 and Table 2-5 summarize the comparison between modelled and monitored concentrations. Table 2-4 and Table 2-6 show a comparison between Base Scenario model results and the applied background concentrations.²⁵ These comparisons affirm the checks outlined above:

²⁴ The MAML was placed on Water Street, Prince Rupert (latitude 54.305962N, longitude 130.342344W), and this receptor is the closest to this location among all modelled receptors.

²⁵ The selection of background concentrations added to all modelled scenarios considered the monitoring data collected using the MAML in Prince Rupert, but were primarily based on year-round continuous monitors located in nearby airsheds.



- The Base Scenario model results are *lower* than monitored concentrations for all pollutants for all averaging periods. The lower modelled concentrations for all pollutants are expected, because not all regional/existing sources are included in the Base Scenario model (e.g., ground transportation, personal vehicle traffic, comfort heating, fugitive emissions from road dust, etc.).
 - The period average modelled concentration accounts for approximately 47% of the monitored value for SO₂, while the percentage rate for NO₂ and PM_{2.5} are much lower (11% and 18%, respectively).
 - This closer alignment between modelled and monitored SO₂ concentrations is expected, because SO₂ emissions typically come almost entirely from industrial and marine sources. The comparison may indicate that the model may have under-estimated or omitted some industrial SO₂ emissions. However, the modelled and monitored SO₂ levels are so low that this difference is just as likely to be caused by the differences in the meteorological data.²⁶
 - For all air contaminants, the comparison confirms that this study's inclusion of a background concentration to account for natural background plus the regional sources (that were not explicitly modelled as existing industrial sources) is appropriate.
- The Base Scenario model results are *lower* than the background concentrations that were added to model results for all scenarios and air contaminants. This comparison confirms that the background concentrations adequately and conservatively represent existing industrial sources as well as regional sources and natural background.

Additionally, Base Scenario modelled concentrations plus background concentrations are similar to or higher than monitored concentrations for all air contaminants and averaging periods, with the exception of annual average NO₂. This comparison further confirms that the background concentrations adequately account for regional emission sources not included in the model.

- For 1-hour 98th percentile NO₂, Base Case modelled concentrations plus background concentration equals 32.7 µg/m³ compared to the monitored value of 30.7 µg/m³.
- For annual NO₂, Base Scenario modelled concentrations plus background concentration is equal to 6.8 µg/m³ compared to the monitored *period average* of 10.3 µg/m³. While the average Base Scenario + background NO₂ is less than that measured by the MAML, it should be noted that the MAML monitoring took place for approximately 4 months and is not representative of annual average concentrations. Adjusting the annual average background upward by 3.5 µg/m³ would not result in a change in risk category at any location in the health section.

²⁶ The modelling analyses used meteorological data in 2012 and the MAML collected the data in 2013. Base Scenario emission rates represent 2013 *annual average* emission rates from existing industrial and marine sources.



Table 2-3: Comparison of Base Scenario Results to Monitored Data for SO₂ and NO₂.

Criteria	SO ₂ Concentrations, (µg/m ³)		Criteria	NO ₂ Concentrations, (µg/m ³)	
	Modelled ^a	Monitored ^a		Modelled ^a	Monitored ^a
1-hr Maximum	6.52	16.46	1-hr Maximum	20.53	50.38
1-hr 98th%	3.26	4.70	1-hr 98th%	8.29	30.68
24-hr Maximum	1.62	2.28	24-hr Maximum	4.38	18.27
Period Average ^b	0.36	0.77	Period Average	1.18	10.25

- a. The modelled and monitored concentrations shown in this table are for the period starting April 14, 2013, 11AM and ending August 16, 2013, 4PM, for which the MAML was in place on Water Street, Prince Rupert (latitude 54.305962N, longitude 130.342344W). The modelled concentrations do not include any background concentrations.
- b. The period averages for the modelled and monitored concentrations are for the limited period with a total of 2,981 hours, and are not directly comparable to the annual average background concentrations used in PRAS.

Table 2-4: Comparison of Base Scenario Results to Background Concentrations for SO₂ and NO₂.

Criteria	SO ₂ Concentrations, (µg/m ³)		Criteria	NO ₂ Concentrations, (µg/m ³)	
	Modelled ^a	Background ^b		Modelled ^a	Background ^b
1-hr 98th%	3.26	10.67	1-hr 98th%	8.29	24.44
Annual Average ^c	0.29	4.00	Period Average	1.16	5.64

- a. The modelled concentrations shown in this table are for the period starting April 14, 2013, 11AM and ending August 16, 2013, 4PM, for which the MAML was in place on Water Street, Prince Rupert (latitude 54.305962N, longitude 130.342344W). The modelled concentrations do not include any background concentrations.
- b. The background concentrations listed here are the concentrations added to the modelled concentrations in all PRAS work. Only those averaging periods that are included in the modelling results presented in other sections are included in this table (i.e., 24-hour is not listed, because SO₂ and NO₂ results focused on 1-hour and annual average model results).
- c. The annual average is listed in this table, rather than the period averages, because the annual average was included as a background concentration and the full year of model results are available for comparison, while in the previous table, only the 2,981 hours of monitoring data were available.

Table 2-5: Comparison of Base Scenario Results and Monitored Data for PM_{2.5}.

Criteria	PM _{2.5} Concentrations (µg/m ³)	
	Modelled ^a	Monitored ^a
1-hr Max.	10.66	37.40
24-hr Max.	2.53	8.05
24-hr 98 th %	2.27	6.86
Period Avg.	0.53	3.00

- a. The modelled and monitored concentrations shown in this table are for period starting April 14, 2013 11AM and ending August 16, 2013, 4PM, for which the MAML was in place on Water Street, Prince Rupert (latitude 54.305962N, longitude 130.342344W). The modelled concentrations do not include any background concentrations.
- b. The period averages for the modelled and monitored concentrations are for the limited period with a total of 2981 hours, and are not comparable to the annual average background concentrations used in PRAS.



Table 2-6: Comparison of Base Scenario Results and Background Concentrations for PM_{2.5}.

Criteria	PM _{2.5} Concentrations (µg/m ³)	
	Modelled ^a	Background ^b
24-hr 98 th %	2.27	7.00
Annual Avg.	0.27	3.50

- The modelled and monitored concentrations shown in this table are for period starting April 14, 2013 11AM and ending August 16, 2013, 4PM, for which the MAML was in place on Water Street, Prince Rupert (latitude 54.305962N, longitude 130.342344W). The modelled concentrations do not include any background concentrations.
- The background concentrations listed here are the concentrations added to the modelled concentrations in all PRAS work. Only those averaging periods that are included in the modelling results presented in other sections are included in this table (i.e., 1-hour is not listed, because PM_{2.5} results focused on 21-hour and annual average model results).
- The annual average is listed in this table, rather than the period averages, because the annual average was included as a background concentration and the full year of model results are available for comparison, while in the previous table, only the 2,981 hours of monitoring data were available.

Appendix 3 includes Q-Q plots for daily maximums for the period of April 14 to August 16, showing comparisons between modelled hourly concentrations and monitored hourly concentrations. Overall, the modelled concentrations are within the expected range in comparison to the monitored data.



3 Human Health

3.1 Revised Assumptions for Health Modelling

The processes of converting the results of the dispersion modelling into health risk categorizations in this Supplementary report are identical to the process applied in the PRAS report. Any changes between scenarios are the direct result of changes in the outputs of the dispersion model.

3.2 Overall Conclusions

The updated emission information incorporated into Scenario F_R_U resulted in predictions of lower concentrations of the six pollutant concentration values at the locations with elevated modelled concentrations. When considered across all of the six combinations of pollutants and averaging periods, there were eight instances of a change from the Red category to the Orange category and four instances of a change from Red to Yellow. There were no instances of a new Red categorization for any pollutant or averaging period at any location under Scenario F_R_U.

For PM_{2.5}, the updated emission rates yielded lower estimates, that, for the most part, generated lower concentrations at areas with high modelled concentrations for both the annual average and the 24-hour averaging period. For SO₂, there was a general pattern of reduced concentrations for both the annual average and 1-hour average daily peak. For the location with the highest concentrations, predicted concentrations were substantially lower for both SO₂ averaging periods. When considering the annual averaged NO₂ concentrations, most of the locations are categorized as Yellow under both scenarios. However, predicted concentrations were also substantially lower in the location with the highest concentration; up to approximately 80% lower with respect to the annual average. For the six locations with highest concentration, predicted concentrations ranged from approximately 71% to 92% lower with respect to the 1-hour averaged concentrations of NO₂. For this averaging period, among the six locations that are categorized as Red under Scenario F_R, four of the locations transitioned from Red to Orange, one location transitioned from Red to Yellow, and one remained narrowly above the Red threshold in Scenario F_R_U.

It is possible to draw some limited inferences with respect to the impact of the results of Scenario F_R_U on conclusions for other scenarios previously modelled in the PRAS report. The revised Scenario F_R_U, to the extent that it represents a reasonable worst-case future scenario, can be used as a plausible upper bound estimate with respect to expected concentrations and colour categories. Further attention to ensure that the best estimates for emissions of PM_{2.5} are applied (specifically, as opposed to all particulate matter including the coarser fractions that are considered to be less harmful to human health) would seem to be the most important consideration in future refinements of any scenarios.



3.3 Details Supporting Overall Conclusions

As described in Section 2, the overall dispersion modelling was repeated under altered assumptions with respect to the amounts, locations and other important properties of the emissions in a new scenario labelled F_R_U. The results of the dispersion modelling were processed using the same approach as for the previous health risk characterization, which included Scenario F_R. See the PRAS report for details on the approach to risk characterization, including the basis for the four-colour scheme which is applied in an identical fashion in this Supplementary Report. As with the previous analysis, there are six combinations of pollutant and averaging period, which are computed for each of 34 locations in the study area. The sections below describe the concentration statistics, and the resulting colour category for each location, pollutant and averaging period. For convenience, the colour categorization scheme and associated thresholds from the primary report are reproduced in Table 3-1.

Table 3-1: Adaptation of the CCME Air Management Categorization Scheme to apply BC Air Quality Objectives for PM_{2.5} and Interim Air Quality Objectives for SO₂ and NO₂.

PM _{2.5} Annual Average	PM _{2.5} 24h Average (98 th %ile)	SO ₂ Annual Average	SO ₂ Hourly (99 th %ile)	NO ₂ Annual Average	NO ₂ Hourly (98 th %ile)
8 µg/m ³	25 µg/m ³	30 µg/m ³	200 µg/m ³	60 µg/m ³	188 µg/m ³
6 µg/m ³	17 µg/m ³	15 µg/m ³	100 µg/m ³	32 µg/m ³	105 µg/m ³
4 µg/m ³	10 µg/m ³	1 µg/m ³	5 µg/m ³	5 µg/m ³	22 µg/m ³

3.3.1 Categorization of Annual Average Concentrations of PM_{2.5}

The results for the annual average concentration of PM_{2.5} are presented in Table 3-2. Overall, average predicted concentrations were lower at many locations, with two locations resulting in a lower colour category (two from Red to Orange; five from Orange to Yellow). The results show considerably smaller averages in the two areas with the highest concentrations (Outer Harbour Industrial and Southern Prince Rupert Industrial) with decreases by more than 50% in both cases. The lower PM_{2.5} concentrations near Outer Harbour Industrial align with model input changes of accurate representation of nearby Prince Rupert Grain PM_{2.5} emissions coming from each individual baghouse versus conservatively assumed to emit from a single location. Similarly, the decreased PM_{2.5} concentrations near Southern Prince Rupert Industrial align with model input changes of more accurate representation of nearby Fairview rail yard emissions that take into account the buoyancy of the locomotive engine plumes.



Table 3-2: The maximum annual average concentration of PM_{2.5} among the grid points assigned to each location for Scenarios F_R and F_R_U.

Concentrations in µg/m ³	Scenario	
Background = 3.50 µg/m³		
Human Health Receptor Location	F_R	F_R_U
Residential		
Dodge Cove	6.8	5.6
Future Residential Expansion	5.2	5.1
Kitkatla	3.6	3.6
Lax Kw'alaams	4.2	4.2
Metlakatla	5.3	4.9
Port Edward Proposed Hotel	5.2	4.9
Port Edward Residential	5.7	5.3
Prince Rupert Residential	6.5	5.2
Rainbow Lake	4.4	4.3
Prudhomme Lake	4.7	4.4
Kloiya Bay	5	4.6
North Pacific Cannery	4.8	4.7
Cassiar Cannery	4.7	4.6
Osland	4.4	4.3
Hunts Inlet	3.8	3.8
Oona River	3.8	3.8
Crippen Cove	6.5	5.2
Cultural & Recreational		
Prince Rupert Golf Course	5.4	4.8
Mount Oldfield Trail	5.8	5.3
Mount Hayes Trail	8.7	6.4
Butze Rapids Trail	5	4.7
Metlakatla Sandbar	4.7	4.6
Pike Island	4.7	4.6
Sandbar North of Casey Point	7.9	5.6
Oliver Lake	5.2	4.8
Kitson Island	4.4	4.4



Concentrations in $\mu\text{g}/\text{m}^3$	Scenario	
Background = $3.50 \mu\text{g}/\text{m}^3$		
Human Health Receptor Location	F_R	F_R_U
Industrial		
Canoxy North Industrial	5.6	5.1
Outer Harbour Industrial	27	9.6
Inverness Passage Commercial	5.6	5.5
Prince Rupert NE Industrial	5	5
Southern Prince Rupert Industrial	21.9	8
Stapleton Island Industrial	4.7	4.6
Watson Island Industrial	6.5	6
Prince Rupert Airport	4.7	4.5

3.3.2 Categorization of 98th Percentile of 24-Hour Averaged Concentrations of $\text{PM}_{2.5}$

Due to the changes in the locations of emissions and other emission characteristics, there is a mixed pattern of results with respect to the 98th percentile of 24-hour averaged concentrations of $\text{PM}_{2.5}$. The results are shown in Table 3-3. The original Scenario F_R had four locations in the Red category, while Scenario F_R_U had one remaining Red (Outer Harbour Industrial), with one transition from Red to Yellow, and two transitions from Red to Orange. The estimated values are between approximately 34% and 74 % lower. Across the other locations, there were also small decreases, including nine transitions from Orange to Yellow.

The same air dispersion model input changes noted for the most pronounced decreases in annual $\text{PM}_{2.5}$ concentrations at the areas of highest concentration also account for the most pronounced decreases in 24-hour averaged $\text{PM}_{2.5}$ concentrations (more accurate characterization of existing port sources).

Table 3-3: The maximum of the 98th percentile of the 24-hour averaged concentrations of $\text{PM}_{2.5}$ among the grid points assigned to each location for Future Case F_R_U.

Concentrations in $\mu\text{g}/\text{m}^3$	Scenario	
Background = $7.00 \mu\text{g}/\text{m}^3$		
Human Health Receptor Location	F_R	F_R_U
Residential		
Dodge Cove	21.2	13.1
Future Residential Expansion	15.6	15.1
Kitkatla	8.7	8.6
Lax Kw'alaams	10.6	10



Concentrations in $\mu\text{g}/\text{m}^3$	Scenario	
Background = $7.00 \mu\text{g}/\text{m}^3$		
Human Health Receptor Location	F_R	F_R_U
Metlakatla	13.4	11.6
Port Edward Proposed Hotel	17	14.3
Port Edward Residential	20.2	15.2
Prince Rupert Residential	21.4	14.4
Rainbow Lake	13.3	11.9
Prudhomme Lake	15.1	13.4
Kloiya Bay	16.8	14
North Pacific Cannery	14.4	13.6
Cassiar Cannery	14.4	14.3
Osland	13.3	12.6
Hunts Inlet	9.6	9.5
Oona River	9.7	9.5
Crippen Cove	19.4	12.9
Cultural & Recreational		
Prince Rupert Golf Course	18.7	14.1
Mount Oldfield Trail	20.7	17.7
Mount Hayes Trail	31.3	20.5
Butze Rapids Trail	16.9	13.7
Metlakatla Sandbar	10.6	10.2
Pike Island	10.7	10.4
Sandbar North of Casey Point	28.2	12.6
Oliver Lake	17.8	14.5
Kitson Island	13.5	12.7
Industrial		
Canoxy North Industrial	20.6	15.7
Outer Harbour Industrial	117.5	30.4
Inverness Passage Commercial	19.5	18.4
Prince Rupert NE Industrial	16.2	13.8
Southern Prince Rupert Industrial	67.2	17.4
Stapleton Island Industrial	14.7	14.2
Watson Island Industrial	20.5	15.7



Concentrations in $\mu\text{g}/\text{m}^3$	Scenario	
Background = 7.00 $\mu\text{g}/\text{m}^3$		
Human Health Receptor Location	F_R	F_R_U
Prince Rupert Airport	11.2	10.4

3.3.3 Categorization of Annual Average Concentrations of SO_2

The overall pattern of the maximum annual average concentration values in each location showed lower values for a majority of locations, as seen in Table 3-4. In two of the 34 locations, there were relatively small increased values, and these locations are categorized as Yellow under both scenarios. The most notable change was at the Southern Prince Rupert Industrial location with a decrease of over 80% (and transition from Orange to Yellow). The next most notable change was a decrease of approximately 56% at the Mount Hayes Trail location (Yellow in both scenarios). In Scenario F_R_U, all locations are categorized as Yellow.

The most pronounced decreases in SO_2 concentrations at Southern Prince Rupert Industrial and Mount Hayes Trail align with model input changes of more accurate representation of nearby Fairview rail yard emissions that take into account the buoyancy of the locomotive engine plumes. Additionally, decreases in marine SO_2 emission rates accounting for the new marine fuel standard (0.1% sulphur limit for North American ECA) likely further decreased concentrations in these areas.

Table 3-4: The maximum annual average concentration of SO_2 among the grid points assigned to each location for Scenarios F_R and F_R_U.

Concentrations in $\mu\text{g}/\text{m}^3$	Scenario	
Background = 4.00 $\mu\text{g}/\text{m}^3$		
Human Health Receptor Location	F_R	F_R_U
Residential		
Dodge Cove	7.9	5.3
Future Residential Expansion	5	4.7
Kitkatla	4	4
Lax Kw'alaams	4.2	4.5
Metlakatla	4.9	4.4
Port Edward Proposed Hotel	4.7	4.4
Port Edward Residential	5.3	4.7
Prince Rupert Residential	6	6.7
Rainbow Lake	4.1	4.1
Prudhomme Lake	4.2	4.1



Concentrations in $\mu\text{g}/\text{m}^3$ Background = 4.00 $\mu\text{g}/\text{m}^3$	Scenario	
	F_R	F_R_U
Human Health Receptor Location		
Kloiya Bay	4.3	4.2
North Pacific Cannery	4.6	4.5
Cassiar Cannery	4.4	4.3
Osland	4.2	4.2
Hunts Inlet	4.1	4.1
Oona River	4.1	4.1
Crippen Cove	6.8	4.6
Cultural & Recreational		
Prince Rupert Golf Course	4.8	4.3
Mount Oldfield Trail	4.9	4.5
Mount Hayes Trail	12.4	5.5
Butze Rapids Trail	4.4	4.2
Metlakatla Sandbar	4.5	4.3
Pike Island	4.6	4.4
Sandbar North of Casey Point	7.2	4.9
Oliver Lake	4.5	4.3
Kitson Island	4.6	4.4
Industrial		
Canoxy North Industrial	5.6	4.8
Outer Harbour Industrial	7.5	6.3
Inverness Passage Commercial	5.4	5.1
Prince Rupert NE Industrial	4.5	4.3
Southern Prince Rupert Industrial	26.7	4.7
Stapleton Island Industrial	4.9	4.7
Watson Island Industrial	7.7	5.6
Prince Rupert Airport	5	4.4



3.3.4 Categorization of 99th Percentile of 1-Hour Average Daily Peak Concentrations of SO₂

The results for the maximum of 99th percentile of 1-hour average daily peak concentrations of SO₂ among grid points within each location are shown in Table 3-5. While the pattern when considered across all 34 locations was mixed, predicted concentrations were substantially lower in a number of locations with elevated concentrations (Dodge Cove, Southern Prince Rupert Industrial, Watson Island Industrial, Mount Hayes Trail, and Sandbar North of Casey Point). There were four transitions from Orange to Yellow, and one transition from Red to Yellow. All but four of the remaining locations experienced a range of small to large percentage decreases while staying within the Yellow category. Of these four exceptions, a notable location was Lax Kw'alaams, at which there was an approximate doubling in this value (but it was still categorized as Yellow). In Scenario F_R_U, there was one remaining Orange location (Future Residential Expansion exceeds the Yellow/Orange threshold by approximately 10%), while all others were categorized as Yellow. The same air dispersion model input changes noted for the decrease in annual SO₂ concentrations at the areas of highest concentration also account for the most pronounced decreases in 1-hour average daily peak SO₂ concentrations: the more accurate characterization of existing port sources and decreases in marine SO₂ emission rates accounting for the new marine fuel standard.

Table 3-5: The maximum of the 99th percentile of the 1-hour average daily peak concentrations of SO₂ among the grid points assigned to each location for Scenarios F_R and F_R_U.

Concentrations in µg/m ³ Background = 10.67 µg/m ³	Scenario	
	F_R	F_R_U
Residential		
Dodge Cove	103.6	34.9
Future Residential Expansion	112.7	111.6
Kitkatla	12.3	12.2
Lax Kw'alaams	20.9	40.8
Metlakatla	44.3	27.9
Port Edward Proposed Hotel	39.5	28.6
Port Edward Residential	80	68.8
Prince Rupert Residential	92.8	57.1
Rainbow Lake	17.1	14.9
Prudhomme Lake	18.5	16.6
Kloiya Bay	23.4	19.6
North Pacific Cannery	27.9	30.3
Cassiar Cannery	21.9	22.7



Concentrations in $\mu\text{g}/\text{m}^3$ Background = 10.67 $\mu\text{g}/\text{m}^3$	Scenario	
	F_R	F_R_U
Human Health Receptor Location		
Osland	19.3	18.3
Hunts Inlet	16	15.6
Oona River	14.6	14.1
Crippen Cove	69.9	23
Cultural & Recreational		
Prince Rupert Golf Course	45.5	19.4
Mount Oldfield Trail	49.8	33
Mount Hayes Trail	181.9	67.1
Butze Rapids Trail	33.6	20.6
Metlakatla Sandbar	29.4	22.7
Pike Island	29.2	23.3
Sandbar North of Casey Point	136.9	27.3
Oliver Lake	30	23.8
Kitson Island	60.6	59.6
Industrial		
Canoxy North Industrial	68.5	38.4
Outer Harbour Industrial	67	86.1
Inverness Passage Commercial	86.9	52.2
Prince Rupert NE Industrial	32.9	21.5
Southern Prince Rupert Industrial	505.3	30.5
Stapleton Island Industrial	93.6	93.2
Watson Island Industrial	124.1	57.4
Prince Rupert Airport	43.4	19.2

3.3.5 Categorization of Annual Average Concentrations of NO₂

The results for the maximum annual averaged concentrations of NO₂ among grid points within each location are shown in Table 3-6. The results show a substantial decrease of close to 80% at one location (Southern Prince Rupert Industrial) which corresponds to a category change from Red to Yellow. One other location had a category change from Orange to Yellow (Mount Hayes Trail). The remaining locations are Yellow under both scenarios and represent a mixture of small increases and small decreases, with the exception of one substantial decrease of approximately 50% at one location (Sandbar North of Casey Point). The most pronounced decreases in NO₂ concentrations at Southern Prince Rupert Industrial and Mount Hayes Trail align with model input changes of more accurate representation of nearby Fairview rail yard



emissions that take into account the buoyancy of the locomotive engine plumes. Additionally, decreases in marine NO_x emission rates by using more representative engine load and emission factor data also likely result in decreased concentrations in the higher concentration areas.

Table 3-6: The maximum annual average concentration of NO₂ among the grid points assigned to each location for Scenarios F_R and F_R_U.

Concentrations in µg/m ³ Background = 5.64 µg/m ³	Scenario	
	F_R	F_R_U
Residential		
Dodge Cove	27.5	17.8
Future Residential Expansion	12.7	11.9
Kitkatla	6	5.9
Lax Kw'alaams	8.3	8.7
Metlakatla	12.5	11.1
Port Edward Proposed Hotel	9.4	9.3
Port Edward Residential	12.8	12.3
Prince Rupert Residential	19.5	13.2
Rainbow Lake	7.2	6.9
Prudhomme Lake	7.6	7.3
Kloiya Bay	8.2	7.9
North Pacific Cannery	11.4	10.2
Cassiar Cannery	11	9.7
Osland	8.2	7.7
Hunts Inlet	6.4	6.4
Oona River	6.4	6.3
Crippen Cove	19.9	13.4
Cultural & Recreational		
Prince Rupert Golf Course	11.1	9.7
Mount Oldfield Trail	12.4	11.2
Mount Hayes Trail	36.2	20.6
Butze Rapids Trail	8.8	8.8
Metlakatla Sandbar	10.3	10
Pike Island	10.8	10.5



Concentrations in $\mu\text{g}/\text{m}^3$ Background = 5.64 $\mu\text{g}/\text{m}^3$	Scenario	
	F_R	F_R_U
Human Health Receptor Location		
Sandbar North of Casey Point	31.6	15.9
Oliver Lake	9.1	8.8
Kitson Island	9.1	9.5
Industrial		
Canoxy North Industrial	10.4	10.4
Outer Harbour Industrial	19.1	23.8
Inverness Passage Commercial	15	13.3
Prince Rupert NE Industrial	9.7	9.8
Southern Prince Rupert Industrial	107	23.9
Stapleton Island Industrial	10.4	10.3
Watson Island Industrial	14.2	13.5
Prince Rupert Airport	11.6	11

3.3.6 Categorization of 98th Percentile of 1-Hour Average Daily Peak Concentrations of NO₂

The results for the maximum of the 98th percentile of 1-hour average daily peak concentrations of NO₂ among grid points within each location are shown in Table 3-7. The most substantive differences between the two scenarios were in the locations with the highest predicted concentrations under Scenario F_R. Four of the six locations that were categorized as Red under Scenario F_R were re-categorized as Orange under Scenario F_R_U, and one of the six locations categorized as Red under Scenario F_R was categorized as Yellow under F_R_U. The one other location previously categorized as Red under Scenario F_R remained narrowly above the Red threshold (Mount Hayes Trail). In all six locations, decreases were substantial (ranging from over 70% to approximately 92%). Most of the locations maintained their colour categories between the two scenarios with comparably smaller slight increases and decreases. The exceptions were three transitions from Orange to Yellow (Metlakatla, Prince Rupert Golf Course, and Watson Island Industrial). The same air dispersion model input changes noted for the decrease in annual NO₂ concentrations at the areas of highest concentration also account for the most pronounced decreases in 1-hour NO₂ concentrations: the more accurate characterization of existing port sources and decreases in marine NO_x emission rates.



Table 3-7: The maximum of the 98th percentile of the 1-hour average daily peak concentrations of NO₂ among the grid points assigned to each location for Future Case F_R_U.

Concentrations in µg/m ³	Scenario	
Background = 24.44 µg/m ³		
Human Health Receptor Location	F_R	F_R_U
Residential		
Dodge Cove	620.4	133.5
Future Residential Expansion	151.3	144
Kitkatla	38	35.7
Lax Kw'alaams	133.8	140.2
Metlakatla	109.7	82.4
Port Edward Proposed Hotel	88.5	84.7
Port Edward Residential	123.7	107.2
Prince Rupert Residential	485.5	116.9
Rainbow Lake	50	47.7
Prudhomme Lake	61.5	60.4
Kloiya Bay	75.5	67.8
North Pacific Cannery	90.5	87.7
Cassiar Cannery	74.3	68.4
Osland	67.5	62.3
Hunts Inlet	56.3	52.4
Oona River	50.6	47.3
Crippen Cove	374.6	92.7
Cultural & Recreational		
Prince Rupert Golf Course	127.2	86.4
Mount Oldfield Trail	127.2	121.5
Mount Hayes Trail	712.6	205.2
Butze Rapids Trail	76	71.8
Metlakatla Sandbar	72.7	70.5
Pike Island	82.1	79.8
Sandbar North of Casey Point	802.9	111.9
Oliver Lake	83.5	78.8
Kitson Island	150.3	162.2



Concentrations in $\mu\text{g}/\text{m}^3$	Scenario	
Background = $24.44 \mu\text{g}/\text{m}^3$		
Human Health Receptor Location	F_R	F_R_U
Industrial		
Canoxy North Industrial	100.4	92.2
Outer Harbour Industrial	144.3	156
Inverness Passage Commercial	157	125.7
Prince Rupert NE Industrial	133.7	117.5
Southern Prince Rupert Industrial	1795	150
Stapleton Island Industrial	129.8	134.4
Watson Island Industrial	114.3	104.6
Prince Rupert Airport	86.4	71.9

3.3.7 Summary Comparison of Results for Scenarios F_R and F_R_U

The results are summarized in Figure 3-1. The number of receptors categorized as Green did not change between the two scenarios. However under Scenario F_R_U there were fewer receptor locations categorized as Orange or Red and more receptor locations categorized as Yellow level compared with Scenario F_R for all three pollutants in all of the averaging periods.

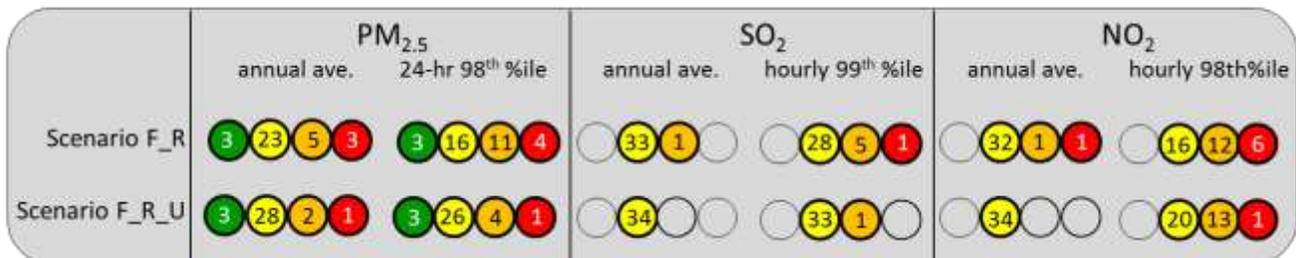


Figure 3-1: Summary of risk management levels (as defined by CCME) for human health, by scenario. Circles are coloured only if the assessment found that colour categorization result for any of the 34 human health receptor locations. Numbers in the circles convey how many of the 34 locations were in each colour category for each scenario.



4 Vegetation

4.1 Revised Assumptions for Vegetation Modelling

There were no changes in assumptions or methods with regard to vegetation from the previous analysis. The description of the vegetation of the area applies to this supplementary analysis as well. The only changes relate to the changed inputs to CALPUFF and resulting model outputs. The uncertainties and limitations of the analysis remain unchanged from the PRAS.

4.2 Overall Conclusions

Under Scenario F_R_U, modelled projected maximum and mean concentrations for both SO₂ and NO₂ decreased substantially from those projected under the original Scenario F_R.

Peak concentrations of SO₂ did not reach levels sufficient to raise concerns for the health of vegetation in Scenario F_R and that remained the case under Scenario F_R_U (Table 4-1). In Scenario F_R_U, maximum 1-hour concentrations did not exceed the BC Interim Air Quality Guideline. Annual mean concentrations that exceeded the European and WHO critical levels of 20 and 10 µg/m³, respectively, did not exceed those thresholds under Scenario F_R_U (Table 4-2). The growing season daylight mean of 12 µg/m³ did exceed the 10 µg/m³ threshold, however, that level is not of concern for higher vegetation. The annual mean concentration intended to protect lichens (all hours versus daylight hours) was not exceeded.

Peak concentrations of NO₂ in Scenario F_R_U were less than one-quarter of those projected to occur in the Scenario F_R and were well below those that would be expected to cause visible injury to higher vegetation (Table 4-3). Exceedances of thresholds of interest dropped substantially as well, with a change from 1,262 to 37 for the 1-hour BC guideline. Exceedances of the WHO guideline decreased from 1,115 to 31 under Scenario F_R_U (Table 4-4). Over 81 million receptor hours were modelled. All exceedances were projected to occur within or very near to the industrialized areas. The European critical level for NO₂ was not exceeded. A total of 60 receptors (out of 9,243 modelled) had NO₂ annual means between 25 and 28 µg/m³, just below the European critical level. All of the 60 receptors were within the industrialized area.

The spatial extents of projected elevated concentrations of SO₂ and NO₂ under Scenario F_R_U were also reduced substantially (Figure 4-1 and Figure 4-2) and pose little or no concern to the health of both vascular and non-vascular plants. Exceedance of the 1-hour BC guideline were concentrated in area of about 10 x 10 km in each of the two industrial areas, although scattered exceedances of the 1-hour guideline occurred within a 20 x 20 km area in each case. As a result, for both SO₂ and NO₂, the Risk Assessment Framework would be modified to reflect a low risk categorization due to Very Unlikely occurrence and Minor consequence. If proportional decreases in emissions occur in other scenarios, similar decreases in impacts would be expected. Since F_R_U represents a new bookend, and since the results of modelling indicate a low potential impact on vegetation, other scenarios would be expected to have a similar low probability of any impact of consequence on vegetation, including non-vascular vegetation.



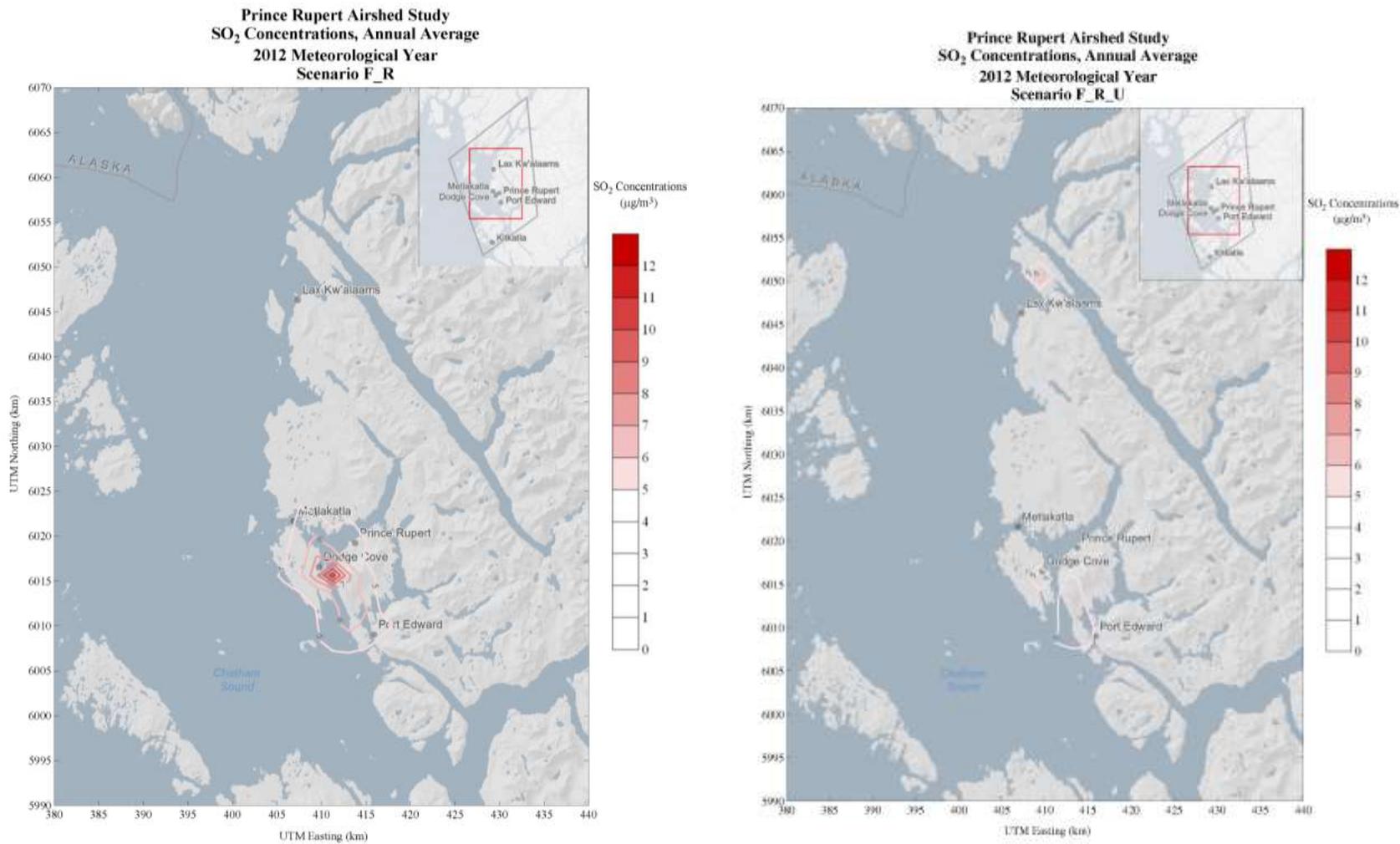


Figure 4-1: Spatial distribution of annual mean SO₂ concentrations under Scenarios F_R and F_R_U.



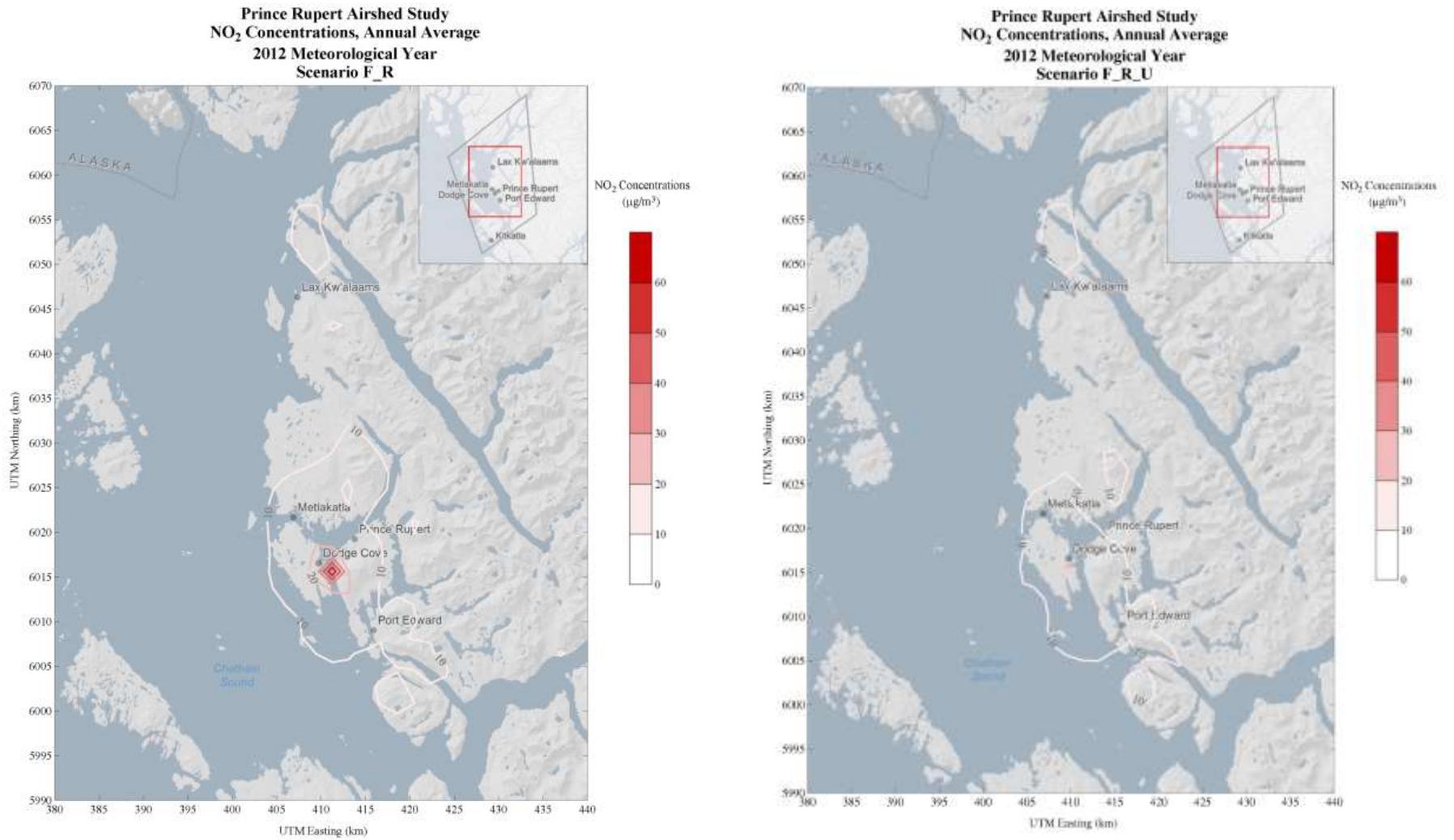


Figure 4-2: Spatial distribution of annual mean NO₂ concentrations under Scenarios F_R and F_R_U.



4.3 Details Supporting Overall Conclusions

Table 4-1: Comparison of modelled concentrations of SO₂ under scenarios F_R and F_R_U.

Scenario	Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	BC Interim Air Quality Objective ^b (µg/m ³)	US EPA Secondary Standards ^c (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location - All Receptors (UTM, NAD 83, km)	
							Julian Day	Time	East	North
F_R	1-hour	1 st	547	547			103	2300	411.543	6016.220
	1-hour	2 nd		547			232	0100	411.543	6016.220
	1-hour	4 th		505	200		231	2000	411.543	6016.220
	3-hour	1 st	413				232	0100	411.543	6016.220
	3-hour	2 nd	315			1300	197	2200	411.543	6016.220
	Annual	Mean	27						411.543	6016.020
	Annual Growing Season ^d	Mean	32						411.543	6016.020
	Annual Growing Season Daylight ^d	Mean	23						411.543	6016.020
F_R_U	1-hour	1 st	185	185			041	0500	414.176	6007.600
	1-hour	2 nd		156			227	1400	416.058	6007.818
	1-hour	4 th		112	200		264	1300	416.058	6007.818
	3-hour	1 st	95				227	1300	416.058	6007.818
	3-hour	2 nd	72			1300	099	1300	416.058	6007.818
	Annual	Mean	8						409.176	6050.600
	Annual Growing Season ^d	Mean	9						409.176	6050.600
	Annual Growing Season Daylight ^d	Mean	12						412.043	6017.520

a Modelled concentrations of 3-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include a background concentrations corresponding to the appropriate to the averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e. the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations are provided by MOE on 3/6/2015, and converted from ppb to µg/m³ based on the values in BC AQOs table:

4.0 ppb 10.7 µg/m³ for 1 hour and 3 hour averaging period
 1.5 ppb 4.0 µg/m³ for Annual averaging period

b The BC Interim Air Quality Objective is based on annual 99th percentile of daily 1-hour maximum over one year. Therefore, the 4th highest modelled daily maximum 1-hour concentration is compared to the objective.

c Secondary National Ambient Air Quality Standard (NAAQS) define the levels that protect the public welfare from any known or anticipated adverse effects of a pollutant. The secondary standard for the 3-hour averaging period is not to be exceeded more than once per calendar year. Therefore, results are compared to the second high.

d Growing Season is from April 15 through September 15 and Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.



Table 4-2: Comparison of modelled numbers of exceedances of SO₂ thresholds under scenarios F_R and F_R_U.

Scenario	Averaging Period	BC Air Quality Objective ^a	# of Exceedances ^b	Maximum Location (UTM, NAD 83, km)	
		(µg/m ³)		East	North
F_R	1-hour during All Hours	200	64	411.543	6016.220
	1-hour during Growing Season	200	46	411.543	6016.220
F_R_U	1-hour during All Hours	200	0		
	1-hour during Growing Season	200	0		

a The BC Air Quality Objective for the 1-hour averaging period is achieved based on annual 99th percentile of daily 1-hour maximum over one year, which allows the objective to be exceeded by 3 days. The number of exceedances shown here are the total number of hours in the year that the objective is exceeded for the receptor presented in Table 4-1.

b The value for each scenario location is the greatest number of exceedances at a single receptor for the given year. Receptors on water are excluded from the analysis. Growing Season is from April 15 through September 15.



Table 4-3: Comparison of modelled concentrations of NO₂ under scenarios F_R and F_R_U.

Scenario	Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	BC Interim Air Quality Objective ^b (µg/m ³)	WHO Guideline ^c (µg/m ³)	European Critical Level ^c (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location - All Receptors (UTM, NAD 83, km)	
								Julian Day	Time	East	North
F_R	1-hour	1 st	2,482	2,482		200		140	2300	411.543	6016.220
	1-hour	2 nd		2,311				200	2100	411.543	6016.220
	1-hour	8 th		1,795	188			173	2300	411.543	6016.220
	Annual	Mean	107		60		30			411.643	6015.720
	Annual Growing Season ^d	Mean	130				30			411.543	6016.020
	Annual Growing Season Daylight ^d	Mean	95							411.543	6016.020
F_R_U	1-hour	1 st	576	576		200		284	1200	410.176	6049.600
	1-hour	2 nd		559				261	1300	410.176	6049.600
	1-hour	8 th		301	188			261	1500	410.176	6050.600
	Annual	Mean	25		60		30			409.176	6050.600
	Annual Growing Season ^d	Mean	28				30			411.543	6016.220
	Annual Growing Season Daylight ^d	Mean	31							411.543	6016.220

a Modelled concentrations of the 1-hour and annual averaging period represent the maximum of the 2012 meteorological year modelled, and include a background concentration corresponding to the appropriate to the averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e. the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations are provided by MOE on 3/6/2015, and converted from ppb to µg/m³ based on the values in BC AQOs table:

13.0 ppb 24.44 µg/m³ for 1 hour averaging period
 3.0 ppb 5.64 µg/m³ for annual averaging period

b The BC Interim Air Quality Objective is based on annual 98th percentile of daily 1-hour maximum over one year. Therefore, the 8th highest modelled daily maximum 1-hour concentration is compared to the objective.

c Comparison to the WHO Guideline is not intended do not provide conclusions related to impacts on the environment. The European Critical Level is intended for protection of vegetation.

d Growing Season is from April 15 through September 15 and Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.



Table 4-4: Comparison of modelled numbers of exceedances of NO₂ thresholds under scenarios F_R and F_R_U.

Scenario	Averaging Period	Threshold (µg/m ³)	# of Exceedances ^a	Maximum Location ^b (UTM, NAD 83, km)	
				East	North
F_R	BC Air Quality Objectives ^c				
	1-hour during All Hours	188	1262	411.543	6016.020
	Annual during All Hours ^b	60	1	411.643	6015.720
	1-hour during Growing Season	188	769	411.543	6016.020
	Annual during Growing Season ^b	60	1	411.543	6016.020
	WHO Guideline				
	1-hour during All Hours	200	1115	411.543	6016.020
	1-hour during Growing Season	200	690	411.543	6016.020
	European Critical Level				
	Annual during All Hours ^b	30	1	411.643	6015.720
Annual during Growing Season ^b	30	1	411.543	6016.020	
F_R_U	BC Air Quality Objectives ^c				
	1-hour during All Hours	188	37	417.176	6002.600
	Annual during All Hours	60	0		
	1-hour during Growing Season	188	26	417.176	6002.600
	Annual during Growing Season	60	0		
	WHO Guideline				
	1-hour during All Hours	200	31	417.176	6002.600
	1-hour during Growing Season	200	24	417.176	6002.600
	European Critical Level				
	Annual during All Hours	30	0		
Annual during Growing Season	30	0			

a The value for each scenario location is the greatest number of exceedances at a single receptor for the given year. Receptors on water are excluded from the analysis. Growing Season is from April 15 through September 15.

b There are multiple receptors that show a single exceedance of the threshold level. The receptor listed in this table corresponds to the receptor with the highest concentration listed in Table 4-3.

c The BC Air Quality Objective for the 1-hour averaging period is achieved based on annual 98th percentile of daily 1-hour maximum over one year, which allows the objective to be exceeded by 7 days. The number of exceedances shown here are the total number of hours in the year that the objective is exceeded for the receptor presented in the table.



5 Soils and Terrestrial Ecosystems

5.1 Revised Assumptions for Soils Modelling

The potential risk of acidification and eutrophication from sulphur (S) and nitrogen (N) deposition to forest, shrubland and wetland (receptor) ecosystems in the Prince Rupert study domain was re-assessed based on revised atmospheric dispersion modelling (see Section 2.1) under the Scenario F_R_U. Following the same methodology as in the PRAS report (see ESSA et al. 2015), the assessment of risk was based on the area and magnitude of critical load exceedance, i.e., where deposition under Scenario F_R_U is in excess of the critical load. Mass balance critical loads of acidity (S and N) and nutrient N were determined for natural terrestrial habitats covering 82% of the terrestrial study area. Further, empirical critical loads of nutrient N deposition were evaluated following Bobbink and Hettelingh (2010).

Average total (wet and dry) S and N deposition across the study domain in Scenario F_R_U was lower than the Scenario F_R. Average S deposition decreased from 2.68 meq/m²/yr under Scenario F_R to 2.56 meq/m²/yr under F_R_U; average N decreased from 4.55 meq/m²/yr to 4.34 meq/m²/yr. However, overall there was an increase in deposition north of Lax Kw'alaams, and a decrease around Prince Rupert (Figure 5-1).

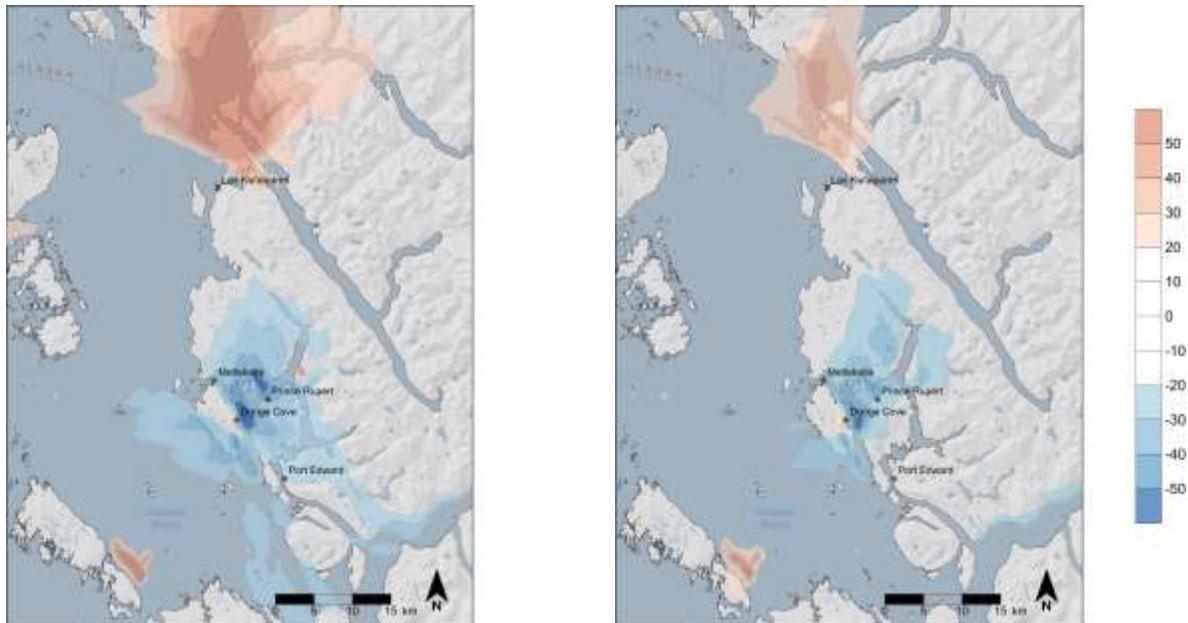


Figure 5-1: Percent (%) change in S deposition (right) and N deposition (left) between Scenarios F_R and F_R_U. The colour scale indicates the percent increase (yellow-orange) and decrease (blue) in Scenario F_R_U relative to F_R. See Figure 2-25 and Figure 2-28 for total N and S deposition under Scenario F_R_U. Note that predicted changes in deposition near Dundas and Prescott Islands represent small magnitude changes to low deposition areas (see Figure 2-25 and Figure 2-28).



Average accumulated exceedance of critical loads was determined under Scenario F_R_U for receptor ecosystems in every 1 km × 1 km grid across the study domain. The areal proportion of exceedance was estimated with reference to an 'effects domain', defined as the receptor ecosystem area enclosed by the 15 meq/m²/yr modelled anthropogenic S and N deposition isopleth under the revised Scenario F_R_U. Note that the area of the effects domain for acidification decreased from 586 km² under Scenario F_R to 536 km² under Scenario F_R_U (Figure 5-2).



Figure 5-2: Location of receptor ecosystems with predicted exceedance of critical loads of acidity (white-filled 1 km × 1 km grid squares; n = 11) under emissions Scenario F_R_U. Grey-filled squares indicate additional 1 km × 1 km grids with exceedance of acidity under emissions Scenario F_R. The effects domain under Scenario F_R_U (black line, covering an area of 536 km²) and Scenario F_R (grey-dashed line, covering an area of 586 km²) area also shown.

5.2 Overall Conclusions

The revised atmospheric modelling under Scenario F_R_U did not affect the risk categorization for terrestrial ecosystems compared with Scenario F_R, as presented in the PRAS report (ESSA et al. 2015). The areal exceedance of acidity was 6.9 km² under F_R_U compared with 10.3 km² under F_R (see Figure 5-2 and Table 5-1). Areal exceedance of nutrient N similarly decreased (Table 5-2); however, the magnitude of exceedance slightly increased for eutrophication, e.g., exceedance of nutrient N increased from 19.0 meq/m²/yr under F_R to 21.6 meq/m²/yr under F_R_U. Overall, the risk ranking did not change between F_R and F_R_U.

Predicted exceedance under the emissions Scenario F_R_U is considered to be Moderate to Critical, i.e., the scenario is expected to have an impact of a magnitude or spatial extent that is considered potentially extremely unacceptable. This risk categorization is consistent with the Scenario F_R and was primarily based on nutrient N impacts. It is important to note that a critical risk categorization indicates unacceptable areal exceedance (>5% of the effects domain) based on the chosen critical load (Table 5-4, ESSA et al. 2015). In this study, exceedance with respect to empirical nutrient N indicates an increased risk for change in epiphytic macro-lichen species composition. However, this does not preclude an increased risk for composition shifts in N-sensitive vascular plants.

Despite decreased average deposition of S and N across the study domain under Scenario F_R_U compared with F_U (about 5% decrease for both S and N), and the associated reduced areal exceedance, the proportion of the effects domain with predicted exceedance did not change greatly owing to the smaller effects domain size under scenario F_R_U. If proportional decreases in emissions occur across all other scenarios, it would lead to reduced impacts, i.e., lower magnitude and spatial extent of exceedance (but may not change the proportional exceedance of the effects domain). In general, the changes are likely to be small and will not greatly influence the overall risk ranking.

5.3 Details Supporting Overall Conclusions

Exceedance of critical loads of acidity (Table 5-1) and nutrient N (Table 5-2) was estimated under Scenario F_R_U. The areal exceedance under Scenario F_R_U was estimated with respect to the new effects domain and the F_R effects domain (see Table 5-1 and Table 5-2). Areal exceedance under Scenario F_R_U ranged from 6.88 km² for critical loads of acidity (Table 5-1) to 17.78 km² and 65.31 km² for critical loads of nutrient and empirical nitrogen (Table 5-2). The risk categorization did not change from Scenario F_R.



Table 5-1: Exceedance of the Critical Load Function for acidification (defined by $CL_{max}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$) of forest, shrubland and wetland ecosystems in the study area. Note that exceeded area (%) is given as a percent of the F_R 'effects domain' area, except for F_R_U which is given as a percent of the revised F_R_U 'effects domain' [and the F_R 'effect domain'].

Scenario	F_R	F_R_U
Risk category ^a		
Average exceedance (meq/m ² /yr)	24.44	16.03
Average exceedance S (meq/m ² /yr)	15.66	9.72
Average exceedance N (meq/m ² /yr)	8.78	6.32
Exceeded area (%) ^b	1.75	1.29 [1.17]
Exceeded area (km ²)	10.27	6.88
Exceeded area >10 meq/m ² /yr (km ²)	7.26	3.78
Exceeded area >20 meq/m ² /yr (km ²)	6.34	2.55

^a Risk category based on exceedance area (%).

^b Exceeded area presented as a proportion (%) of the effects domain, which is defined as the receptor ecosystem area enclosed by a 15.0 meq/m²/yr modelled sulphur and nitrogen deposition isopleth under Scenario F_R (586 km²) and Scenario F_R_U (536 km²).

Table 5-2: Exceedance of critical load of nutrient nitrogen ($CL_{nut}(N)$) for forest ecosystems on mineral soil and empirical nutrient nitrogen ($CL_{emp}(N)$) for terrestrial habitats, respectively in the study area. Note that exceeded area (%) is given as a percent of the F_R 'effects domain' area, except for F_R_U which is given as a percent of the revised F_R_U 'effects domain' [and the F_R 'effect domain'].

Scenario	F_R	F_R_U
Risk category ^a		
$CL_{nut}(N)$ exceedance (meq/m ² /yr)	19.03	21.58
$CL_{nut}(N)$ exceeded area (%) ^b	4.02	3.72 [3.47]
$CL_{nut}(N)$ exceeded area (km ²)	23.54	17.78
Risk category ^a		
$CL_{emp}(N)$ exceedance (meq/m ² /yr)	16.07	16.76
$CL_{emp}(N)$ exceeded area (%) ^b	15.44	11.8 [10.7]
$CL_{emp}(N)$ exceeded area (km ²)	93.82	65.31

^a Risk category based on $CL_{nut}(N)$ and $CL_{emp}(N)$ exceeded area (%).

^b Exceeded area presented as a proportion (%) of the effects domain, which is defined as the receptor ecosystem area enclosed by the 15.0 meq/m²/yr modelled sulphur and nitrogen deposition isopleth under Scenario F_R ($CL_{nut}(N)$: 513 km²; $CL_{emp}(N)$: 608 km²) and Scenario F_R_U ($CL_{nut}(N)$: 478 km²; $CL_{emp}(N)$: 554 km²).



6 Aquatic Ecosystems

6.1 Revised Assumptions for Water Modelling

6.1.1 Changes in deposition inputs

The potential for acidification for each of the 35 lakes in the study area was re-assessed based on the revised assumptions for atmospheric modelling (described in Section 2.1) under Scenario F_R_U. Applying the same methodology used in the PRAS report (Section 6.1 of Volume 1 and Section 4 of Volume 2 in ESSA et al. 2015), the potential of the studied lakes to exceed the critical loads (CLs) was estimated using both the Steady State Water Chemistry (SSWC) (Henriksen et al. 2002) and the First-order Acidity Balance (FAB) models (Henriksen and Posch 2001; Aherne et al. 2004; UNECE 2004; Posch et al. 2012). Additionally, the expected change in pH under the new deposition Scenario F_R_U was calculated using a modification of the ESSA-DFO model (Marmorek et al. 1990; ESSA et al. 2013, pg. 247-249) and the risk of eutrophication for the lakes in the study area using empirical critical loads for nutrient-N.

Deposition results (total N and SO₄) from the revised Scenario F_R_U were area-averaged for the watersheds of each of the 35 lakes. These deposition data were then used as inputs to the existing SSWC, FAB and ESSA-DFO models. The revised assumptions for atmospheric modelling (Scenario F_R_U) involved a decrease in the watershed-averaged deposition of both SO₄ and N, for 26 of the 35 studied lakes (see Figure 6-1), as compared to Scenario F_R.

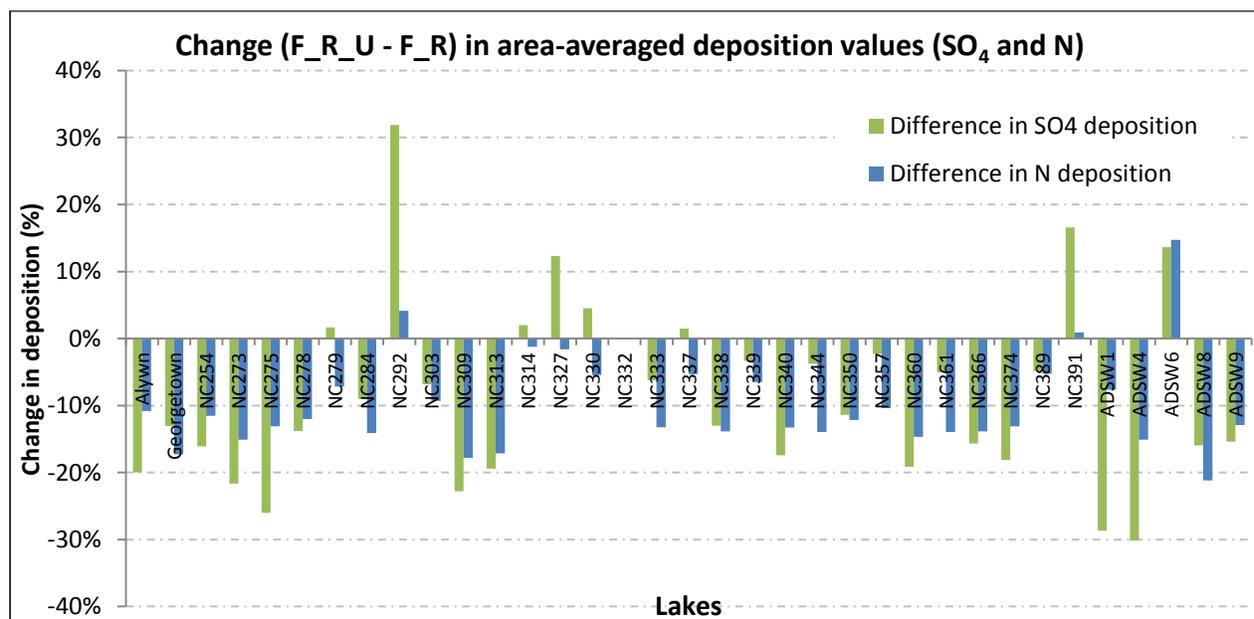


Figure 6-1: Change in area-averaged deposition values for the watersheds of the 35 lakes in the study area. Changes are expressed as percentages of the difference in deposition (F_R_U – F_R) for both SO₄ and N (meq/ha/year), with respect to the original deposition values for Scenario F_R.



Nine watersheds showed an increase in either SO₄ or N deposition values under Scenario F_R_U:

- Four watersheds showed an increase in both SO₄ and N deposition (lakes NC391 and NC292, located in the north of the study area; and lakes ADSW6 and NC332, located in the west of the study area).
- Five watersheds, located in the north (NC327 and NC337) and southwest (NC314, NC330, and NC279), would experience an increase only in watershed-averaged deposition of SO₄.

6.1.2 Analysis of new lake samples

The PRAS aquatic assessment included two sets of lake samples:

- Data set 1 (DS1) comprising of 30 lakes sampled by Environment Canada (EC) in September 2014.
- Data set 2 (DS2) including seven lakes sampled in August 2014 by AECOM for the Prince Rupert LNG (PRLNG) project.

After analyzing the water chemistry data of these 37 lakes and discarding duplicate samples and those with a charge imbalance indicative of analytical/sampling errors, the final sample of analyzed lakes was reduced to 35 lakes. The 35 sampled lakes tended to be larger (median lake area of 12.45 ha) than the overall population of 859 lakes >1 ha in the study area (median lake area of 2.65 ha). The combined data set could not be considered a statistically representative sample because of the mix of sampling criteria used for the two data sets, the gaps in coverage (especially for lakes to the north of Port Edward in the predicted plume of acidic deposition), and the bias towards larger lakes.

One of the recommendations of the PRAS report was to close the gaps in lake coverage with additional lake samples. EC conducted a sampling campaign in the PRAS area in September 2015 and 20 new lake samples (**Data set 3: DS3**) were added to the original sample of 35 lakes. Figure 6-2 shows the location of the old and new lakes.



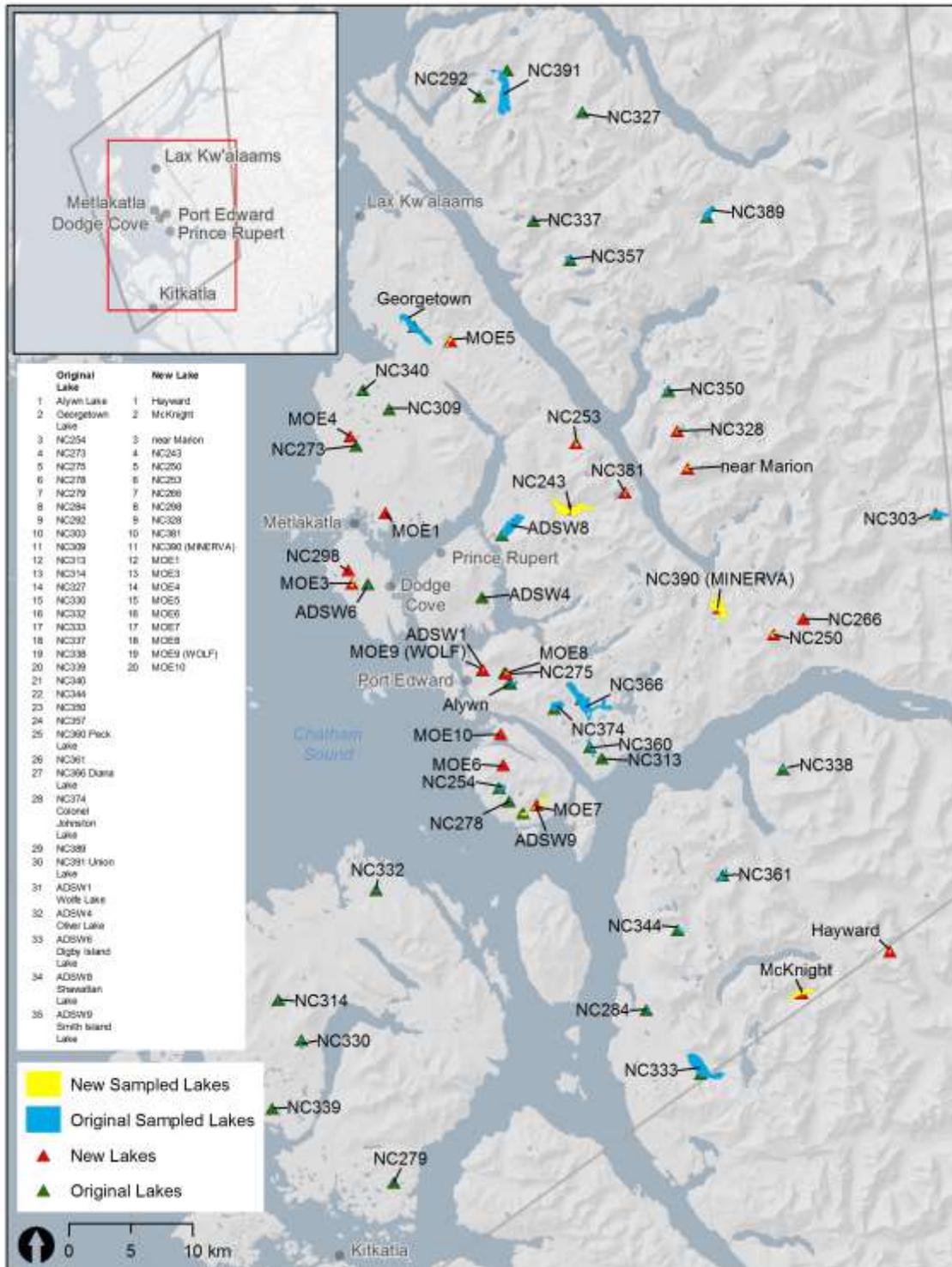


Figure 6-2: Map of the study area showing the 35 original lake samples and the 20 new lakes included in the analysis.

Out of the 20 new lakes, one sample (near Marion) was discarded because of its poor charge balance (20.65% off correct charge balance of anions and cations) and a difference between estimated and measured conductivity of 60.8%. In addition, three lakes in DS3 were identified as duplicates of lakes sampled in either DS1 or DS2 and were therefore discarded from further analysis. The duplicate lakes were:

- MOE7 (DS3), the same lake as AD-SW9 from DS2;
- MOE8 (DS3), the same lake as NC275 from DS1; and
- MOE9 (DS3), the same lake as AD-SW1 (Wolf Lake) from DS2.

Based on these considerations, the total sample size, including the new lakes, was limited to 51 lakes (30 lakes from DS1, 5 lakes from DS2 and 16 from the new data set DS3). The median lake area for the new lakes (DS3) was smaller (8.13 ha) than for the original sample (DS1 and DS2; 12.45 ha). Half of the 16 new lakes have a current pH lower than 6. The overall chemical profile of lakes in DS3, further discussed in the following sections, is similar to the lakes in DS1. Gran ANC values were not measured but were estimated using a regression equation between Gran ANC and Total Alkalinity (equation 6.1 in Section 6.1.1.2 of the PRAS report, originally developed in the Kitimat Airshed Assessment (ESSA et al. 2013, pg. 276).

Data quality

As was done in the PRAS report, an analysis of charge balance and conductivity of the new lake samples was conducted to assess the quality of the data and integrate all of the cumulative analytical errors in all measured parameters. The three data sets show charge balances close to 1:1, with an average percentage difference of -1.95% (Figure 6-3). The concentration of anions is higher than the concentration of cations in most of the samples. Lake samples in DS2 showed greater deviation from charge balance (-2.52%) compared to lakes in DS1 (-2.43%) and DS3 (-1.12%).



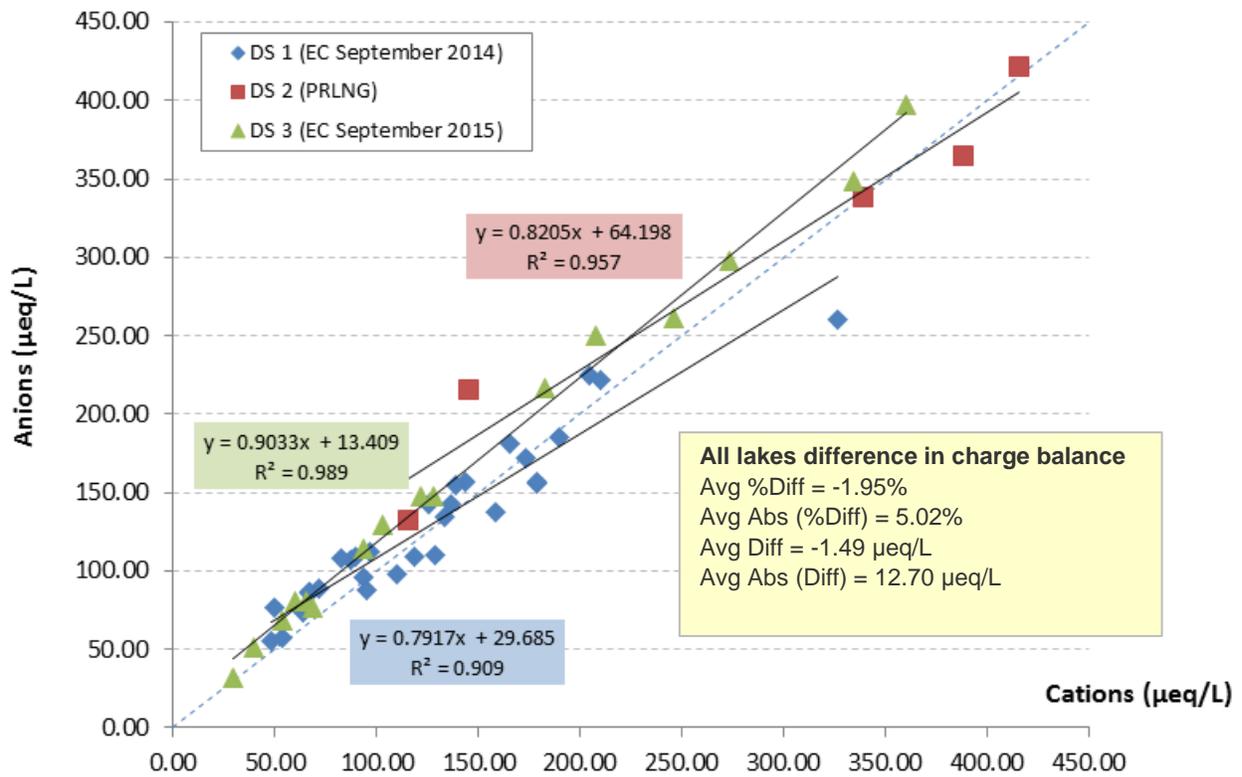


Figure 6-3: Charge balance of the sampled lakes (DS1= EC September 2014, DS2=PRLNG lakes, and DS3=EC September 2015). The Y-axis is the sum of all major anions (negatively charged ions); the X-axis the sum of all major cations (positively charged ions). Both the 1:1 line (dashed) and the regression lines (solid) are shown for each data set.

Organic anions have variable charge depending on which organic acids are present and the pH of the solution. As was done with DS1 and DS2 in the PRAS report, a sensitivity analysis was completed to assess how the overall charge balance was affected by the assumed charge density (i.e., µeq or organic anion per mg of dissolved organic carbon, DOC). For DS3 lakes, the deviation from charge balance was minimized with an assumed charge density of 5.0 µeq per mg of DOC (Table 6-1). Therefore a charge density of 5.0 µeq per mg of DOC was assumed for the analysis (similar to the assumption of 5.5 µeq per mg of DOC for DS1 and DS2).



Table 6-1: Effect of DOC charge density (μeq of organic anion per mg of DOC) on the charge balance of lakes in DS3. Mean %DIFF = mean % charge balance (negative values have higher anions; positive values have higher cations). Mean ABS % is the mean of the absolute value of deviations from perfect charge balance. Mean Diff is the mean deviation from charge balance in $\mu\text{eq/L}$. Mean AbsDiff is the mean of the absolute value of deviations from charge balance in $\mu\text{eq/L}$. Yellow highlight indicates the selected charge density value (5.0 μeq of organic anion per mg of DOC).

Charge density	Mean %diff	Mean ABS%	Mean diff	Mean Abs Diff	#lakes>10% off balance
7.50	-8.08	8.08	-20.85	20.85	5
7.00	-6.88	6.88	-16.50	16.50	4
6.50	-5.64	5.79	-12.15	13.15	4
6.00	-4.36	4.73	-7.80	10.21	2
5.50	-3.05	3.95	-3.45	8.93	2
5.00	-1.68	3.81	0.90	9.62	1
4.00	1.18	5.01	9.59	14.93	2

Conductivity data were available for both DS1 and DS3 data sets. These measured values were compared against the estimated conductivity using the US EPA’s CONCAL method for calculated conductance as shown in Figure 6-4 (refer to Section 6.2.1 of the PRAS report for further details on the methods used for data quality analysis).

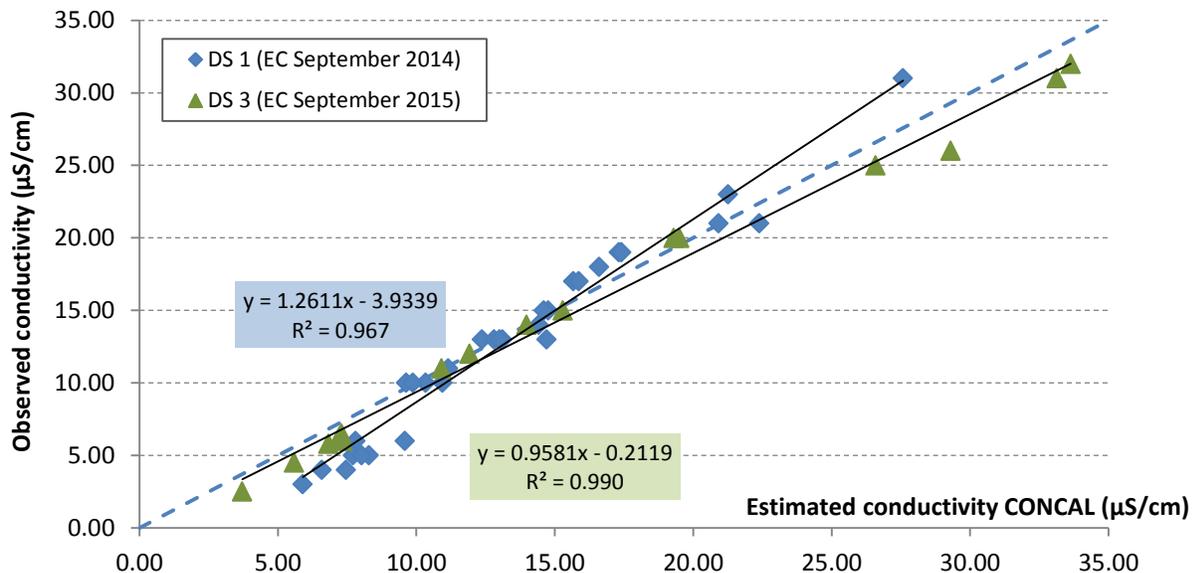


Figure 6-4: Analysis of estimated conductivity versus observed conductivity for the lakes in DS1 and DS3. Both 1:1 line (dashed) and the regression lines (solid) are shown.

Based on the results of these charge balance and conductivity tests, the overall level of data quality for the DS3 data set is acceptable.



Characteristics and Composition of Lakes

This section presents a summary of the analyses of alkalinity, pH and anion composition for the new lakes (data set DS3), including the results from the previously used data sets (DS1 and DS2) for comparison purposes.

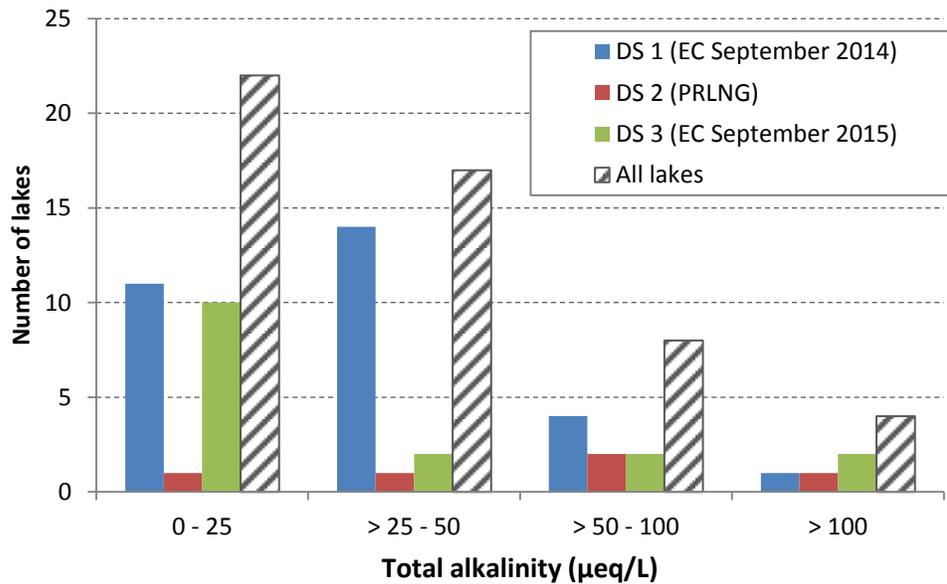


Figure 6-5: Distribution of total alkalinity among sampled lakes, showing alkalinity categories for all lakes and stratified by data set.

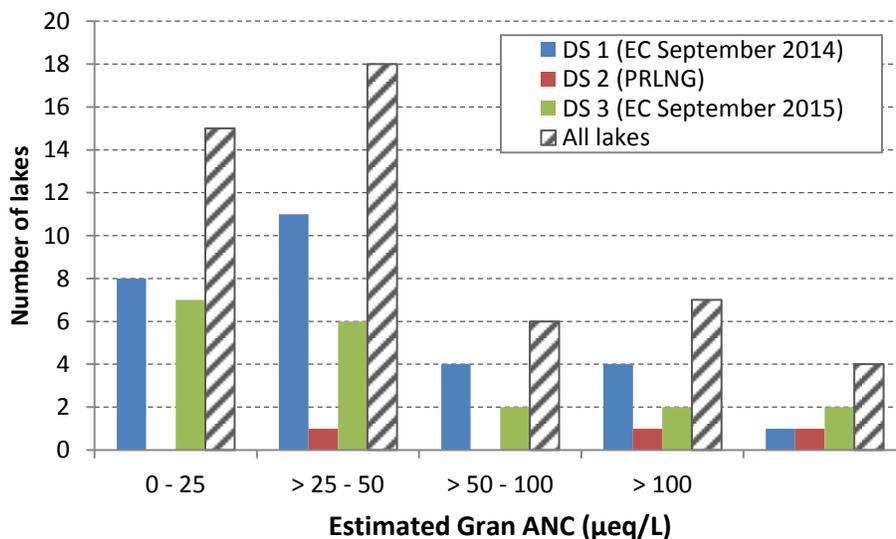


Figure 6-6: Distribution of estimated Gran Acid Neutralizing Capacity (ANC) for all lakes and stratified by data set.



Figure 6-5 shows that a higher proportion of the DS3 lakes were in the lowest alkalinity category (10 out of 16 lakes had a total alkalinity of 0-20 $\mu\text{eq/L}$), as compared to DS1 (11 out of 30 lakes). DS3 includes six acidic lakes (estimated Gran ANC <0), which amounts to 38% of the 16 lakes in DS3 (Figure 6-6). About 81% of the DS3 lakes have an estimated Gran ANC <50 $\mu\text{eq/L}$ and therefore could potentially experience acidic episodes during storm and snowmelt events (Driscoll et al. 2001). Overall, the DS3 lakes are more acidic than those in DS1 and DS2, indicating a higher risk of acidification.

Figure 6-7 shows the frequency distribution of lake pH (as measured in the laboratory) of the three data sets. Half of the lakes in DS3 (8 of 16) have a pH lower than 6.0 (the pH threshold used to determine critical loads), as compared to 40% of the lakes in DS 1 and DS 2.

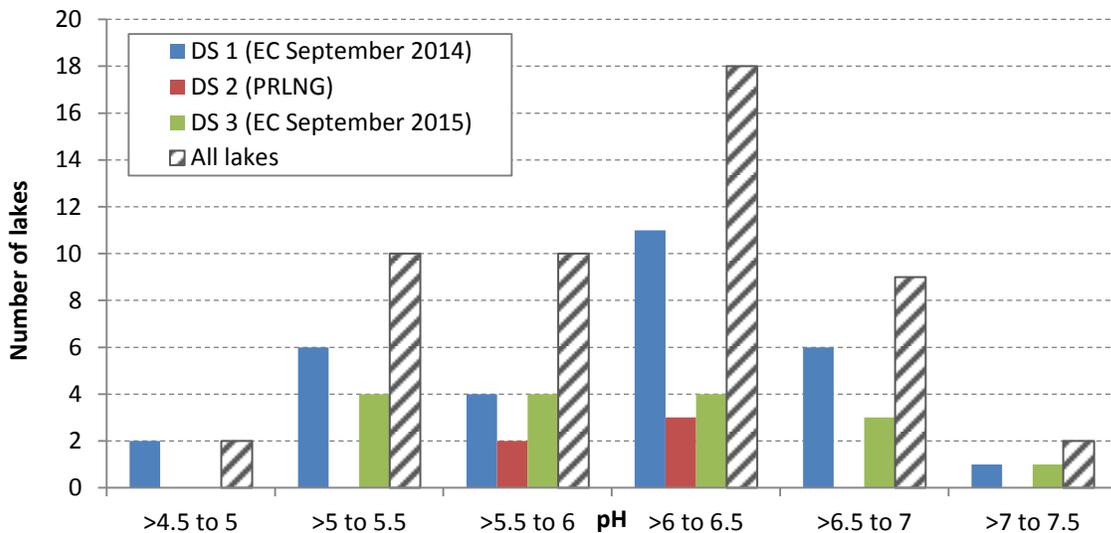


Figure 6-7: Distribution of pH (measured in the laboratory), for all lakes and stratified by data set.

Figure 6-8 shows the overall anion composition for all 51 lakes (i.e., all three data sets) as well as the anion composition for the lakes in DS3. The DS3 lakes have a higher proportion of organic-influenced lakes (organic anions constitute more than 25% of the total anions, light green shade in Figure 6-8) and organic-dominated lakes (organic anions constitute more than 50% of the total anions, dark green shade in Figure 6-8), as compared to the relative proportions for the overall data set. The chemistry of the DS3 lakes in general shows more influence of organic anions, and less influence of chloride and carbonate anions.



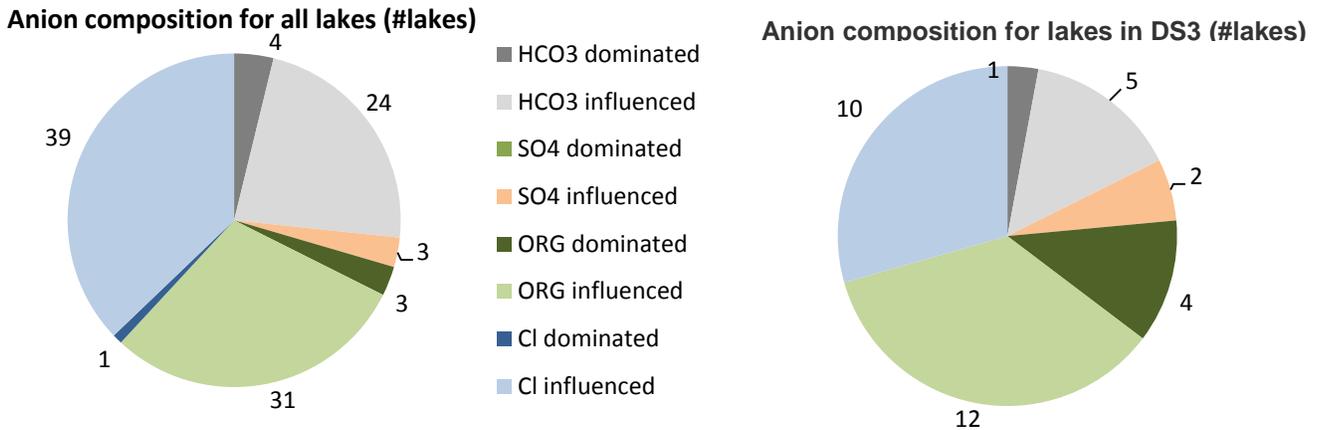


Figure 6-8: Overall anion composition of the total sample of 51 sampled lakes (left) and of the 16 lakes in DS3 (right). A lake can be in more than one category (e.g., both chloride influenced and organic influenced), so the sum exceeds 51 and 16, respectively.

DS3 lakes are generally located in the Hecate Lowlands Ecoregion (HEL), which is part of the Coastal Gap Ecoregion and of the larger Coast and Mountain Ecoprovince of British Columbia. The HEL region is a low-lying area where extensive peatlands have formed due to the poor drainage conditions and the extreme amount of moisture characteristic of the hypermaritime environment (Banner et al. 2005). The location of DS3 lakes in predominantly peatland areas could explain their higher content of organic acids and anions compared to the other lakes sampled in the PRAS area.

Out of the 16 new lakes, eight (50%) have a pH lower than 6.0. Table 6-3 shows the anion composition of these eight lakes, as well as the estimated preindustrial, original pH (pH_o), based on the modified ESSA-DFO model. All the lakes in DS3 with current pH < 6 (i.e., 88%) are estimated to have also had a pre-industrial, original pH_o lower than 6, and are thus considered to be naturally acidic lakes. The DS3 lakes with current pH < 6.0 are all either influenced or dominated by organic anions, and are all influenced by chloride anions (Table 6-3). Six of the eight lakes with pH < 6.0 have high DOC levels (from 11 to 27 mg/L). Thus it appears that the low pH of lakes in DS3 was caused primarily by organic acids and sea salt, which was also the case for the naturally acidic lakes in DS1 and DS2. Hayward Lake (in the southeastern part of the study area) shows evidence of sulphate influence.



Table 6-2: Analysis of the anion composition of eight lakes with current pH <6. Shaded values indicate anion influence or dominance ($\geq 25\%$). Bolded numbers indicate anion dominance ($\geq 50\%$). DOC = dissolved organic carbon (mg/L), HCO_3^- = bicarbonate (grey shading), Cl = chloride (blue shading), SO_4^{2-} = sulphate, ORG = organic anions (green shading). Last column shows estimated pre-industrial pH_0 based on modified ESSA-DFO model (ESSA et al. 2013).

LAKE	DOC	pH (lab)	% HCO_3^-	% Cl	% SO_4^{2-}	% ORG	pH_0	ΔpH
Hayward	3.40	5.79	7%	31%	26%	33%	5.90	-0.112
MOE3	16.20	5.74	9%	37%	17%	36%	5.75	-0.007
MOE4	19.60	5.97	18%	25%	3%	54%	5.97	-0.003
MOE6	12.70	5.14	3%	38%	6%	51%	5.29	-0.147
MOE10	12.90	5.01	3%	39%	6%	50%	5.10	-0.090
NC266	11.10	5.12	4%	29%	8%	58%	5.23	-0.105
NC298	27.10	5.35	6%	29%	16%	48%	5.35	0.000
NC390 (MINERVA)	5.00	5.84	7%	34%	14%	44%	5.97	-0.132

6.2 Overall Conclusions

The revisions to the atmospheric modelling assumptions (i.e. Scenario F_R_U) do not affect the results for aquatic ecosystems of the 35 lakes that were analyzed and discussed in the PRAS report. Under the new Scenario F_R_U, the overall risk for lake acidification is Low since there are no CL exceedances for either SSWC or FAB models and the estimated pH changes are under the biologically significant threshold of change (i.e. $\Delta\text{pH} \geq 0.3$) for all lakes. Considering that F_R_U represents an updated and more accurate version of the worst case scenarios, it is reasonable to assume that equivalent changes to the other deposition scenarios would not result in any significant change and the low risk category would be maintained for these 35 lakes. The risk category changes to Moderate when the new lakes in DS3 are included, due to a CL exceedance in one lake.

Only one of the new lakes in DS3 would be expected to exceed its critical load, according to both the SSWC and FAB models. This lake, NC250, is located on the east of the study area and has a current pH of 6.10. This lake has low base cations ($11.3 \mu\text{eq/L}$), perhaps due to the high runoff in its watershed (i.e., $4.6 \text{ m}^3/\text{m}^2/\text{yr}$). Although this lake is located in a watershed where the acid sensitivity class of the bedrock would imply a high potential to neutralize acidity ($\text{ASC} = 4$), maps of bedrock geology are too coarse to precisely determine the geology of small watersheds. The low concentration of base cations measured in the lake are a more direct indicator, and show that lake NC250 is highly sensitive to acidic deposition.

The risk for eutrophication was assessed based on the, potential for exceedance of the N-nutrient threshold of the 859 lakes in the PRAS area with a surface larger than one hectare. Under both F_R and F_R_U, 3% of the lakes would exceed the threshold assuming a dystrophic condition in the lakes and 1% would exceed the threshold for oligotrophic lakes. As oligotrophic lakes are expected to be the predominant lake type in the study area, the threshold of 5 kg N/ha/yr is likely to be more generally applicable and the Moderate categorization is a



more appropriate characterization of the risk from eutrophication, consistent with the criteria defined in section 6.1.4 of the PRAS report (ESSA et al. 2015).

6.3 Details Supporting Overall Conclusions

6.3.1 Exceedances of Critical Loads and Predicted Changes in Lake pH

Exceedance of critical loads was assessed for both Scenarios F_R and F_R_U for the original 35 lakes and for the new 16 lakes using the SSWC and FAB models (for a detailed description of the analysis methods see Section 6.1 of Volume 1 and Section 4 of Volume 2 of the PRAS report: ESSA et al. 2015).

A summary of the exceedance results for SSWC is presented in Table 6-3. For the original sample of 35 lakes, no exceedances were detected under either the original highest deposition (F_R) or the revised (F_R_U) scenario. In both cases SO₄ and N deposition values are predicted to be lower than the critical loads in all of the analyzed lakes. In the case of the new lakes (DS 3), one exceedance was obtained under both scenarios for Lake NC250.

Table 6-3: Comparison of the results for CL exceedance (SSWC model) for Scenarios F_R and F_R_U, across data sets. Results are shaded according to exceedance class: red > 0 meq/m²/yr, yellow = -10 to 0 meq/m²/yr (near to CL), blue = -20 to -10 meq/ m²/yr (below the CL), and green ≤-20 meq/m²/yr (well below the CL)

Lakes	Data sets	Exceedances (meq/m ² /yr) - SSWC model	
		Scenario F_R	Scenario F_R_U
Alywn	DS 1	-193.36	-194.59
Georgetown	DS 1	-354.22	-354.96
NC254	DS 1	-63.80	-64.30
NC273	DS 1	-59.84	-63.63
NC275	DS 1	-781.71	-783.83
NC278	DS 1	-105.90	-106.29
NC279	DS 1	-116.36	-116.36
NC284	DS 1	-325.49	-325.54
NC292	DS 1	-53.70	-52.94
NC303	DS 1	-141.09	-141.14
NC309	DS 1	-17.92	-20.54
NC313	DS 1	-71.51	-71.97
NC314	DS 1	-107.84	-107.83
NC327	DS 1	-14.26	-14.08
NC330	DS 1	-106.08	-106.07
NC332	DS 1	-163.62	-163.62
NC333	DS 1	-97.45	-97.47
NC337	DS 1	-64.46	-64.43
NC338	DS 1	-9.48	-9.60
NC339	DS 1	-125.70	-125.71
NC340	DS 1	-147.64	-149.57



Lakes	Data sets	Exceedances (meq/m ² /yr) - SSWC model	
		Scenario F_R	Scenario F_R_U
NC344	DS 1	-109.99	-110.01
NC350	DS 1	-81.21	-81.42
NC357	DS 1	-69.56	-69.60
NC360	DS 1	-55.02	-55.52
NC361	DS 1	-111.26	-111.29
NC366(Diana)	DS 1	-74.87	-75.22
NC374	DS 1	-186.27	-187.02
NC389	DS 1	-427.24	-427.29
NC391	DS 1	-106.01	-105.69
AD-SW1	DS 2	-478.86	-483.26
AD-SW4	DS 2	-550.47	-554.21
AD-SW6	DS 2	-315.78	-310.80
AD-SW8	DS 2	-135.73	-136.57
AD-SW9	DS 2	-54.53	-54.85
Hayward	DS 3	-38.81	-38.84
McKnight	DS 3	-70.38	-70.40
MOE1	DS 3	-408.45	-420.07
MOE3	DS 3	-180.75	-181.77
MOE4	DS 3	-175.45	-178.43
MOE5	DS 3	-287.44	-288.12
MOE6	DS 3	-35.46	-35.98
MOE10	DS 3	-45.21	-46.01
NC243	DS 3	-623.30	-623.61
NC250	DS 3	10.20	10.10
NC253	DS 3	-179.98	-180.49
NC266	DS 3	-49.44	-49.53
NC298	DS 3	-243.59	-232.93
NC328	DS 3	-53.02	-53.13
NC381	DS 3	-39.59	-39.65
NC390 (MINERVA)	DS 3	-41.09	-41.23

With the inputs of land use data, runoff and harvestable area, the FAB model was re-run for Scenarios F_R and F_R_U. Table 6-4 summarizes the exceedance results obtained using this modelling method. As discussed for SSWC, the updated deposition assumptions did not result in any exceedances for the lakes in DS1 and DS2, consistent with the prior analysis. In the case of the new lakes in DS3, an exceedance is predicted for Lake 250 for both scenarios F_R and F_R_U.



Table 6-4: Comparison of the results for CL exceedance (FAB model) for Scenarios F_R and F_R_U, across data sets. Results are shaded according to exceedance class: red > 0 meq/m²/yr, yellow = -10 to 0 meq/m²/yr (near to CL), blue = -20 to -10 meq/ m²/yr (below the CL), and green ≤-20 meq/m²/yr (well below the CL).

Lakes	Data sets	Exceedances (meq/m ² /yr) – FAB model	
		Scenario F_R	Scenario F_R_U
Alywn	DS 1	-204.09	-193.07
Georgetown	DS 1	-383.13	-354.87
NC254	DS 1	-70.11	-63.53
NC273	DS 1	-65.20	-62.83
NC275	DS 1	-844.83	-785.46
NC278	DS 1	-114.45	-107.74
NC279	DS 1	-148.11	-117.76
NC284	DS 1	-379.94	-328.54
NC292	DS 1	-57.20	-50.62
NC303	DS 1	-156.99	-142.59
NC309	DS 1	-16.51	-20.69
NC313	DS 1	-87.58	-73.00
NC314	DS 1	-129.63	-109.57
NC327	DS 1	-9.13	-8.34
NC330	DS 1	-130.87	-107.39
NC332	DS 1	-196.26	-165.78
NC333	DS 1	-117.92	-97.70
NC337	DS 1	-69.30	-61.34
NC338	DS 1	-10.34	-9.08
NC339	DS 1	-147.43	-127.34
NC340	DS 1	-165.03	-150.18
NC344	DS 1	-126.66	-110.78
NC350	DS 1	-83.84	-77.32
NC357	DS 1	-74.55	-66.95
NC360	DS 1	-64.38	-56.47
NC361	DS 1	-121.20	-111.90
NC366	DS 1	-87.92	-75.44
NC374	DS 1	-218.08	-186.30
NC389	DS 1	-469.44	-434.50
NC391	DS 1	-114.86	-104.40
ADSW1	DS 2	-534.49	-484.91
ADSW4	DS 2	-588.06	-557.53
ADSW6	DS 2	-337.59	-310.70
ADSW8	DS 2	-158.18	-145.25
ADSW9	DS 2	-78.88	-67.48
Hayward	DS 3	-41.14	-41.35
McKnight	DS 3	-87.75	-87.94
MOE1	DS 3	-435.13	-459.32
MOE3	DS 3	-256.32	-255.83
MOE4	DS 3	-205.55	-213.75



Lakes	Data sets	Exceedances (meq/m ² /yr) – FAB model	
		Scenario F_R	Scenario F_R_U
MOE5	DS 3	-321.02	-324.64
MOE6	DS 3	-36.08	-36.22
MOE10	DS 3	-50.38	-51.12
NC243	DS 3	-706.38	-708.42
NC250	DS 3	8.4	8.3
NC253	DS 3	-214.09	-216.30
NC266	DS 3	-58.24	-58.52
NC298	DS 3	-272.20	-255.14
NC328	DS 3	-53.22	-53.78
NC381	DS 3	-45.60	-46.10
NC390 (MINERVA)	DS 3	-50.34	-50.68

As was done for the PRAS analysis, changes lake pH were estimated using the modified ESSA-DFO model; considering the incremental SO₄ and N deposition under the revised Scenario F_R_U and the new lakes. For the original 35 lakes, none of the lakes showed more than a 0.3 unit decline in pH under the revised highest emission scenario. This was also the case when the additional 16 lakes from DS3 were included in the analysis. Table 6-5 summarizes the results of the modified ESSA-DFO model for all of the analyzed scenarios.

Table 6-5: Changes in pH and ANC for Scenarios F_R and F_R_U across data sets, according to the ESSA-DFO model. Green highlight indicates decreases in pH; yellow highlight indicates ΔpH <-0.1; orange highlight indicates ΔpH <-0.3 and red highlight indicates current pH <6.0.

Lakes	Changes in pH (ΔpH) and ANC (ΔANC) – ESSA-DFO model				
	Current pH _t	Scenario F_R		Scenario F_R_U	
		Predicted ΔpH	ΔANC	Predicted ΔpH	ΔANC
Alywn	6.32	-0.002	-0.232	-0.002	-0.186
Georgetown	6.78	0.000	0.000	0.000	0.000
NC254	5.26	-0.098	-1.840	-0.084	-1.599
NC273	6.05	-0.067	-4.179	-0.052	-3.302
NC275	7.03	0.000	0.000	0.000	0.000
NC278	5.07	-0.032	-0.621	-0.028	-0.541
NC279	5.30	-0.002	-0.034	-0.002	-0.034
NC284	6.55	0.000	0.000	0.000	0.000
NC292	6.17	-0.027	-1.537	-0.030	-1.715
NC303	6.51	-0.001	-0.040	-0.001	-0.036
NC309	5.12	-0.292	-5.345	-0.231	-4.245
NC313	4.84	-0.021	-0.409	-0.017	-0.330
NC314	5.97	-0.002	-0.105	-0.002	-0.105
NC327	6.33	-0.019	-0.926	-0.019	-0.942
NC330	6.24	-0.001	-0.073	-0.001	-0.073
NC332	5.64	-0.001	-0.034	-0.001	-0.034



Lakes	Changes in pH (Δ pH) and ANC (Δ ANC) – ESSA-DFO model				
	Current pH _t	Scenario F_R		Scenario F_R_U	
		Predicted Δ pH	Δ ANC	Predicted Δ pH	Δ ANC
NC333	6.40	-0.001	-0.089	-0.001	-0.079
NC337	6.60	-0.012	-1.077	-0.011	-1.042
NC338	5.89	-0.038	-0.730	-0.033	-0.630
NC339	5.41	-0.001	-0.042	-0.001	-0.040
NC340	5.81	-0.011	-0.823	-0.009	-0.680
NC344	6.34	-0.001	-0.089	-0.001	-0.081
NC350	6.21	-0.015	-0.655	-0.013	-0.577
NC357	6.24	-0.013	-0.819	-0.012	-0.754
NC360	4.91	-0.076	-1.452	-0.064	-1.214
NC361	6.09	-0.003	-0.169	-0.003	-0.149
NC366(Diana)	5.49	-0.044	-0.848	-0.038	-0.724
NC374	6.73	-0.002	-0.279	-0.002	-0.229
NC389	6.82	0.000	0.000	0.000	0.000
NC391	6.49	-0.006	-0.566	-0.007	-0.602
AD-SW1	6.13	0.000	0.000	0.000	0.000
AD-SW4	6.47	0.000	0.000	0.000	0.000
AD-SW6	6.26	0.000	0.000	0.000	0.000
AD-SW8	5.98	-0.006	-0.388	-0.005	-0.326
AD-SW9	5.51	-0.009	-0.490	-0.008	-0.418
Hayward	5.79	-0.016	-0.315	-0.014	-0.280
McKnight	6.01	-0.003	-0.129	-0.003	-0.117
MOE1	6.59	0.000	0.000	0.000	0.000
MOE3	5.74	-0.017	-1.015	-0.016	-0.973
MOE4	5.97	-0.005	-0.541	-0.004	-0.440
MOE5	6.61	0.000	-0.006	0.000	-0.005
MOE6	5.14	-0.139	-2.599	-0.139	-2.598
MOE10	5.01	-0.043	-0.824	-0.036	-0.696
NC243	7.09	0.000	0.000	0.000	0.000
NC250	6.10	-0.053	-1.019	-0.045	-0.815
NC253	6.70	-0.001	-0.200	-0.001	-0.173
NC266	5.12	-0.024	-0.459	-0.021	-0.401
NC298	5.35	0.000	0.000	0.000	0.000
NC328	6.21	-0.025	-0.821	-0.023	-0.748
NC381	6.15	-0.032	-1.416	-0.030	-1.308
NC390 (MINERVA)	5.84	-0.040	-0.767	-0.035	-0.673

6.3.2 Analysis of Lake Eutrophication

The risk of eutrophication under the new deposition scenario and for the new lakes was also assessed by comparing empirical thresholds for critical loads for nutrient-N with the expected deposition values for N (kg/ha/yr). As discussed in Section 6.2.4 of the PRAS report, the new lake samples were classified as dystrophic or oligotrophic depending on their pH and the



prevalence of their organic anions (i.e., dystrophic lakes have a pH lower than 6.0 and their organic anions constitute more than 50% of their total anion composition). The new lake samples are all oligotrophic.

Table 6-6 summarizes the exceedance results obtained for new lakes considering their lower bound CL threshold (i.e. 5 kg N/ha/yr for oligotrophic lakes), which represents the worst-case scenario and the only situation for which positive exceedances were predicted for lake MOE1 (Scenario F_R) and NC298 (F_R_U).

Table 6-6: Selected results of the analysis of eutrophication risk for the 35 sampled lakes. Occurrence of exceedance has been highlighted in red; negative exceedance values are highlighted in green. Results are provided for the LB = Lower bound nutrient-N critical load (i.e., 5 N kg/ha/yr for oligotrophic lakes. All the lakes in DS3 are oligotrophic).

Lake	pH	Organic anions (%)	Exceedance of nutrient N-CLs (Kg N/ha/yr)	
			F_R	F_R_U
Hayward	5.79	25%	-4.74	-4.78
McKnight	6.01	27%	-4.75	-4.77
MOE1	6.59	33%	0.16	-1.63
MOE3	5.74	27%	-1.19	-0.61
MOE4	5.97	44%	-1.56	-2.40
MOE5	6.61	23%	-3.12	-3.55
MOE6	5.14	41%	-3.22	-3.09
MOE10	5.01	40%	-3.75	-3.55
NC243	7.09	10%	-3.52	-3.79
NC250	6.1	11%	-4.42	-4.51
NC253	6.7	13%	-3.55	-3.83
NC266	5.12	48%	-4.51	-4.58
NC298	5.35	38%	-0.56	0.29
NC328	6.21	7%	-4.32	-4.40
NC381	6.15	22%	-3.91	-4.03
NC390 (MINERVA)	5.84	34%	-4.31	-4.41

The analysis of the risk of eutrophication was extended to all the lakes in the PRAS area with a surface of more than 1 ha (i.e., 859 lakes in total). Since water chemistry data are not available for all these lakes, and their trophic status is therefore unknown, the N deposition values for these lakes (based on their centroids) were compared with two CL conservative thresholds: 3 kg N/ha/yr to assess potential damage to dystrophic lakes; and 5 kg N/ha/yr for oligotrophic lakes, (for further details on the selection of the N-nutrient thresholds please see Section 6.1.4 of the PRAS report).

The exceedances under the revised Scenario F_R_U were consistent with previous results (Figure 6-9) and the overall risk is still considered High (Table 6-7) for dystrophic lakes and



Moderate for oligotrophic lakes. As oligotrophic lakes are the predominant lake type in the study area, the threshold of 5 kg N/ha/yr is likely to be more generally applicable and the Moderate categorization is more consistent with the criteria described in section 6.1.4 of the PRAS report.

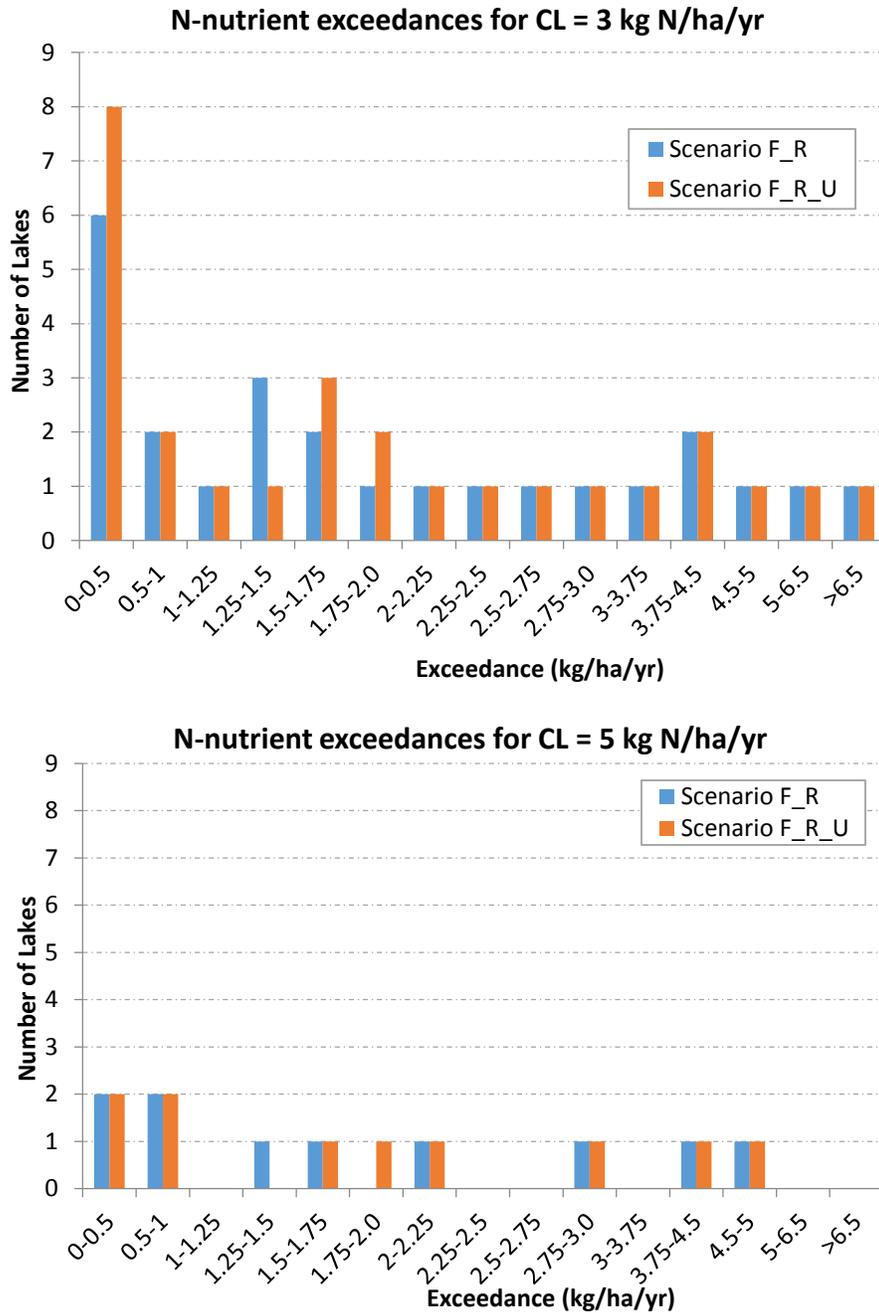


Figure 6-9: Frequency distribution of total exceedances of nutrient-N Critical Loads across scenarios for all of the 859 lakes in the PRAS area. Upper panel represents exceedances for a CL threshold of 3 N kg/ha/yr (applicable to dystrophic lakes) and lower panel shows exceedances for a CL threshold of 5 N kg/ha/yr (applicable to oligotrophic lakes).



Table 6-7: Exceedance results for nutrient-N Critical Loads for all lakes (with a surface area greater than 1 ha) in the PRAS area. Yellow highlight indicates a moderate level of risk (i.e., 1.3-3.6% of the total lakes show exceedance) and green highlight indicates a low level of risk (i.e., less than 1.3% of lakes result in exceedance), according to the risk framework introduced in Section 6.1.3.

N-nutrient CL thresholds	Exceedance	
	F_R	F_R_U
CL = 3 N kg/ha/yr		
# lakes with exceedance	25	27
%lakes	3%	3%
Median exc. (kg/ha/yr)	1.69	1.53
CL = 5 N kg/ha/yr		
# lakes with exceedance	10	10
%lakes	1%	1%
Median exc. (kg/ha/yr)	1.67	1.74

6.3.3 Overall Risk Assessment

Table 6-8 summarizes the results presented in the previous sections and which have been obtained for the new modelling assumptions (i.e., changes in deposition and consideration of new lake samples).

The revised air dispersion modelling assumptions under Scenario F_R_U do not alter the results presented in the PRAS report for the 35 lakes. With respect to the risk of acidification, no CL exceedances are predicted under either SSWC or FAB model, and none of the lakes is expected to experience a change in its pH that would go beyond the biologically significant threshold of $\Delta\text{pH} = -0.3$. The risk of acidification for the 35 sampled lakes under the revised Scenario F_R_U is therefore considered Low (i.e. less than 1 lake, or 2.5% of the receptors, with a $\Delta\text{pH} \geq 0.3$). According to the risk criteria in Table 6-3 of the main report, the risk moves to Moderate when the additional lakes in DS3 are included, as there is one lake (NC250) which shows exceedance of its critical load for acidity under both the SSWC and FAB model, though none of the lakes in DS3 is predicted to show a decrease of more than 0.3 pH units.

With respect to eutrophication, overall risk under both F_R and F_R_U is considered High (Table 6-7) for dystrophic lakes and Moderate for oligotrophic lakes. As oligotrophic lakes are expected to be the predominant lake type in the study area, the threshold of 5 kg N/ha/yr is likely to be more generally applicable and the Moderate categorization is a more appropriate characterization of the risk from eutrophication, consistent with the criteria described in section 6.1.4 of the PRAS report.



Table 6-8: Exceedances, pH changes, eutrophication risk and overall risk category for the 51 sampled lakes and under Scenarios F_R and F_R_U.

Lakes	Data sets	Exceedances (meq/m ² /yr)				Changes in pH - ESSA-DFPO model			Eutrophication risk		Risk category	
		SSWC model		FAB model		Current pH	Predicted ΔpH		Nutrient-N exceedance (kga N/ha/yr)		CL exceedance?/ ΔpH > -0.3	
		F_R	F_R_U	F_R	F_R_U		F_R	F_R_U	F_R	F_R_U	F_R	F_R_U
Alywn	DS 1	-193.36	-194.59	-204.09	-193.07	6.32	-0.002	-0.002	-2.72	-2.76	No	No
Georgetown	DS 1	-354.22	-354.96	-383.13	-354.87	6.78	0.000	0.000	-3.33	-3.51	No	No
NC254	DS 1	-63.80	-64.30	-70.11	-63.53	5.26	-0.098	-0.084	-3.45	-3.38	No	No
NC273	DS 1	-59.84	-63.63	-65.20	-62.83	6.05	-0.067	-0.052	-1.75	-2.19	No	No
NC275	DS 1	-781.71	-783.83	-844.83	-785.46	7.03	0.000	0.000	-2.51	-2.46	No	No
NC278	DS 1	-105.90	-106.29	-114.45	-107.74	5.07	-0.032	-0.028	-1.87	-1.61	No	No
NC279	DS 1	-116.36	-116.36	-148.11	-117.76	5.30	-0.002	-0.002	-4.88	-4.88	No	No
NC284	DS 1	-325.49	-325.54	-379.94	-328.54	6.55	0.000	0.000	-4.66	-4.67	No	No
NC292	DS 1	-53.70	-52.94	-57.20	-50.62	6.17	-0.027	-0.030	-3.67	-3.60	No	No
NC303	DS 1	-141.09	-141.14	-156.99	-142.59	6.51	-0.001	-0.001	-4.72	-4.75	No	No
NC309	DS 1	-17.92	-20.54	-16.51	-20.69	5.12	-0.292	-0.231	-2.60	-3.03	No	No
NC313	DS 1	-71.51	-71.97	-87.58	-73.00	4.84	-0.021	-0.017	-1.73	-1.90	No	No
NC314	DS 1	-107.84	-107.83	-129.63	-109.57	5.97	-0.002	-0.002	-4.86	-4.85	No	No
NC327	DS 1	-14.26	-14.08	-9.13	-8.34	6.33	-0.019	-0.019	-4.31	-4.31	No	No
NC330	DS 1	-106.08	-106.07	-130.87	-107.39	6.24	-0.001	-0.001	-4.85	-4.84	No	No
NC332	DS 1	-163.62	-163.62	-196.26	-165.78	5.64	-0.001	-0.001	-4.77	-4.74	No	No
NC333	DS 1	-97.45	-97.47	-117.92	-97.70	6.40	-0.001	-0.001	-4.73	-4.75	No	No
NC337	DS 1	-64.46	-64.43	-69.30	-61.34	6.60	-0.012	-0.011	-4.01	-4.07	No	No
NC338	DS 1	-9.48	-9.60	-10.34	-9.08	5.89	-0.038	-0.033	-4.46	-4.54	No	No
NC339	DS 1	-125.70	-125.71	-147.43	-127.34	5.41	-0.001	-0.001	-4.90	-4.90	No	No
NC340	DS 1	-147.64	-149.57	-165.03	-150.18	5.81	-0.011	-0.009	-2.90	-3.09	No	No
NC344	DS 1	-109.99	-110.01	-126.66	-110.78	6.34	-0.001	-0.001	-4.55	-4.61	No	No
NC350	DS 1	-81.21	-81.42	-83.84	-77.32	6.21	-0.015	-0.013	-4.27	-4.39	No	No
NC357	DS 1	-69.56	-69.60	-74.55	-66.95	6.24	-0.013	-0.012	-4.16	-4.25	No	No
NC360	DS 1	-55.02	-55.52	-64.38	-56.47	4.91	-0.076	-0.064	-1.75	-1.79	No	No



Lakes	Data sets	Exceedances (meq/m ² /yr)				Changes in pH - ESSA-DFPO model			Eutrophication risk		Risk category	
		SSWC model		FAB model		Current pH	Predicted ΔpH		Nutrient-N exceedance (kga N/ha/yr)		CL exceedance?/ ΔpH > -0.3	
		F_R	F_R_U	F_R	F_R_U		F_R	F_R_U	F_R	F_R_U	F_R	F_R_U
NC361	DS 1	-111.26	-111.29	-121.20	-111.90	6.09	-0.003	-0.003	-4.56	-4.62	No/No	
NC366(Diana)	DS 1	-74.87	-75.22	-87.92	-75.44	5.49	-0.044	-0.038	-3.76	-4.03	No/No	
NC374	DS 1	-186.27	-187.02	-218.08	-186.30	6.73	-0.002	-0.002	-3.10	-3.17	No/No	
NC389	DS 1	-427.24	-427.29	-469.44	-434.50	6.82	0.000	0.000	-4.55	-4.56	No/No	
NC391	DS 1	-106.01	-105.69	-114.86	-104.40	6.49	-0.006	-0.007	-4.06	-4.03	No/No	
AD-SW1	DS 2	-478.86	-483.26	-534.49	-484.91	6.13	0.000	0.000	-1.46	-1.69	No/No	
AD-SW4	DS 2	-550.47	-554.21	-588.06	-557.53	6.47	0.000	0.000	-2.10	-2.23	No/No	
AD-SW6	DS 2	-315.78	-310.80	-337.59	-310.70	6.26	0.000	0.000	1.56	2.42	No/No	
AD-SW8	DS 2	-135.73	-136.57	-158.18	-145.25	5.98	-0.006	-0.005	-2.59	-3.54	No/No	
AD-SW9	DS 2	-54.53	-54.85	-78.88	-67.48	5.51	-0.009	-0.008	-2.09	-2.02	No/No	
Hayward	DS 3	-38.81	-38.84	-41.14	-41.35	5.79	-0.016	-0.014	-4.74	-4.78	No/No	
McKnight	DS 3	-70.38	-70.40	-87.75	-87.94	6.01	-0.003	-0.003	-4.75	-4.77	No/No	
MOE1	DS 3	-408.45	-420.07	-435.13	-459.32	6.59	0.000	0.000	0.16	-1.63	No/No	
MOE3	DS 3	-180.75	-181.77	-256.32	-255.83	5.74	-0.017	-0.016	-1.19	-0.61	No/No	
MOE4	DS 3	-175.45	-178.43	-205.55	-213.75	5.97	-0.005	-0.004	-1.56	-2.40	No/No	
MOE5	DS 3	-287.44	-288.12	-321.02	-324.64	6.61	0.000	0.000	-3.12	-3.55	No/No	
MOE6	DS 3	-35.46	-35.98	-36.08	-36.22	5.14	-0.139	-0.139	-3.22	-3.09	No/No	
MOE10	DS 3	-45.21	-46.01	-50.38	-51.12	5.01	-0.043	-0.036	-3.75	-3.55	No/No	
NC243	DS 3	-623.30	-623.61	-706.38	-708.42	7.09	0.000	0.000	-3.52	-3.79	No/No	
NC250	DS 3	10.20	10.10	8.40	8.30	6.10	-0.053	-0.045	-4.42	-4.51	Yes/No	
NC253	DS 3	-179.98	-180.49	-214.09	-216.30	6.70	-0.001	-0.001	-3.55	-3.83	No/No	
NC266	DS 3	-49.44	-49.53	-58.24	-58.52	5.12	-0.024	-0.021	-4.51	-4.58	No/No	
NC298	DS 3	-243.59	-232.93	-272.20	-255.14	5.35	0.000	0.000	-0.56	0.29	No/No	
NC328	DS 3	-53.02	-53.13	-53.22	-53.78	6.21	-0.025	-0.023	-4.32	-4.40	No/No	
NC381	DS 3	-39.59	-39.65	-45.60	-46.10	6.15	-0.032	-0.030	-3.91	-4.03	No/No	
NC390 (MINERVA)	DS 3	-41.09	-41.23	-50.34	-50.68	5.84	-0.040	-0.035	-4.31	-4.41	No/No	



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Appendix 1: Modelled Port Facility Emission Rates and Source Parameters for the Base Scenario

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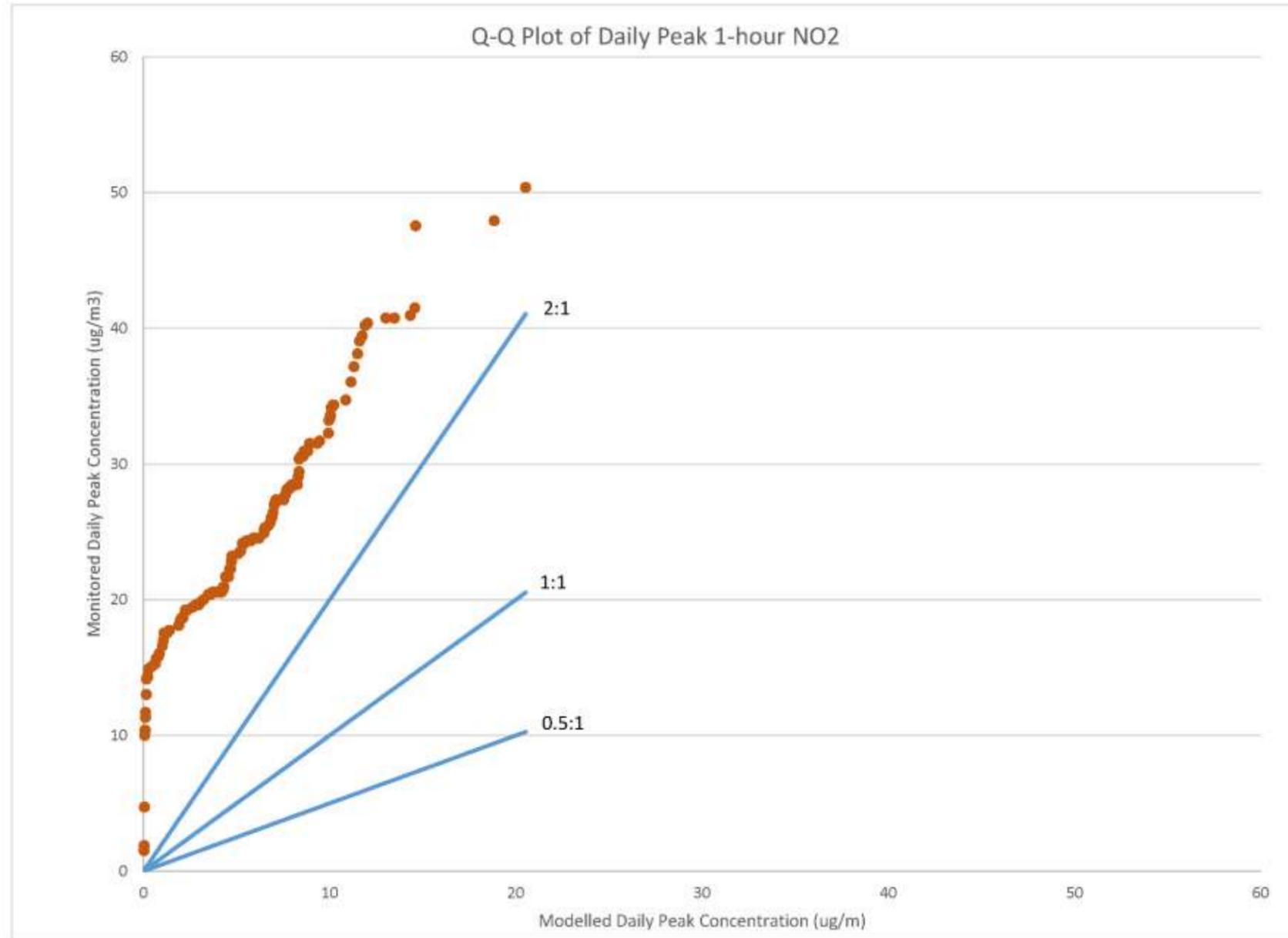


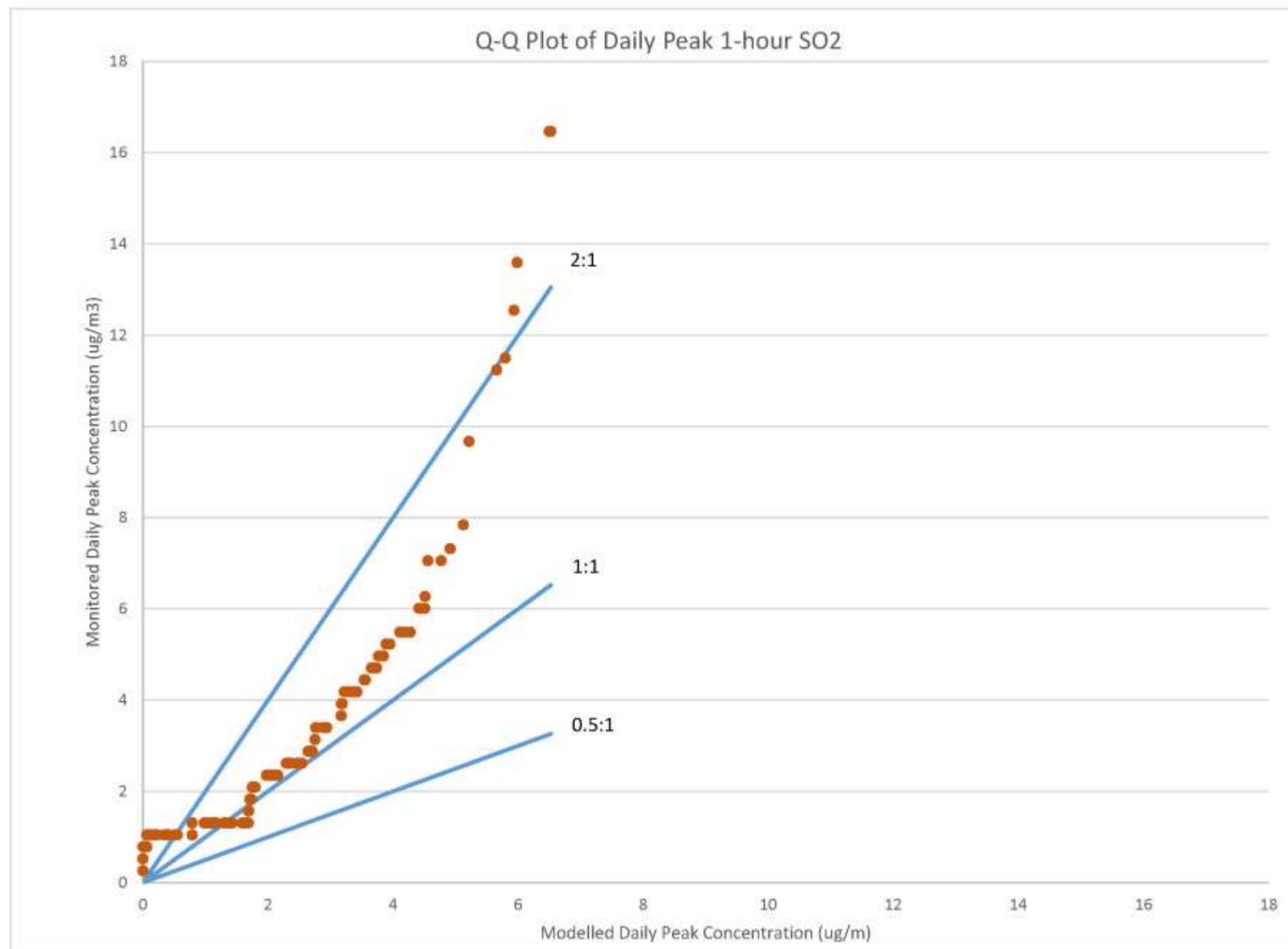
Appendix 2: Inputs for Scenario F_R_U

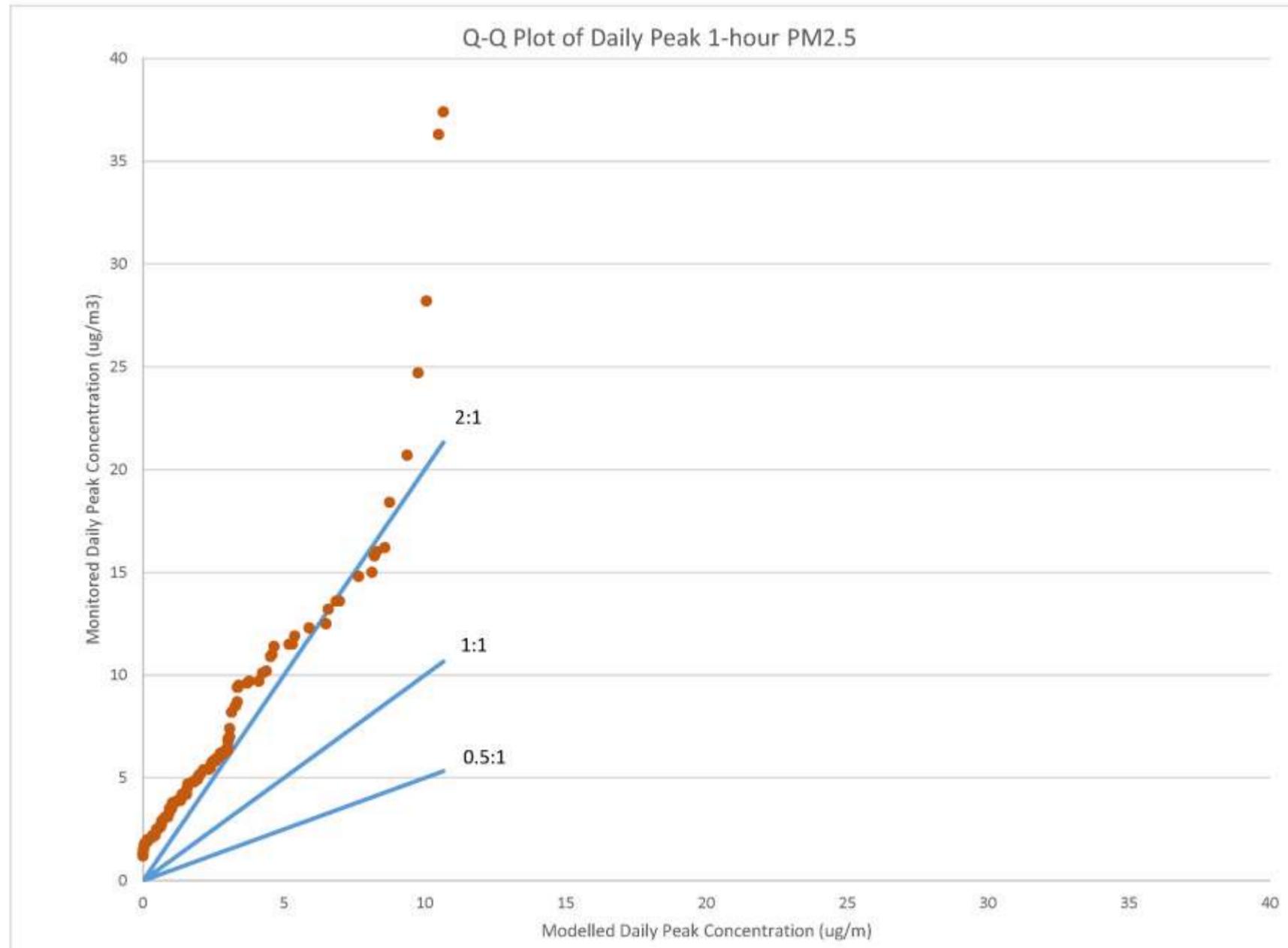
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Appendix 3: Comparison of Modelled Concentrations with Monitoring Data for the Base Scenario







Supplementary Report



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Environmental & Cumulative
Effects Assessment



Climate Change Adaptation &
Risk Reduction



Aquatic Species at Risk &
Water Resource Management



Terrestrial Ecology &
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Final Report



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Prince Rupert Airshed Study

Volume 1: Technical Report

Note: A Supplementary Report of the Prince Rupert Airshed Study has been completed and should be referred to when reviewing study results. The Supplementary Report to the study represents a refined data set based on facility design improvements, an updated emissions inventory, additional receiving environment information, and the addition of a base scenario.



Prepared for the Government of British Columbia, Ministry of Environment

Prince Rupert Airshed Study

Final Report

Volume 1: Technical Report

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Venn Pass, from Mount Hays looking to Metlakatla village (credit: Gary Robinson, used by permission).

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List of Abbreviations and Terms

Symbols and Abbreviations

Δ	delta, meaning quantitative change (e.g., Δ ANC or Δ pH)
<	is less than what follows
\leq	is less than or equal to what follows
>	is greater than what follows
\geq	is greater than or equal to what follows
AAC	Annual Allowable Cut
Al	aluminum
ANC	acid neutralizing capacity
ANN	Annette Island upper air station
AQO	air quality objectives
AQTDR	Air Quality Technical Data Report
ASC	acid sensitivity class
BC	British Columbia
BCH	BC Hydro
BMT	British Columbia Baseline Thematic Mapping
CAAQS	Canadian Ambient Air Quality Standards
CALMET	a diagnostic 3-dimensional meteorological model that forms a component of the CALPUFF system
CALPOST	a post-processing package that forms a component of the CALPUFF system
CALPUFF	an air quality dispersion model that forms part of an advanced non-steady state meteorological and air quality modelling system of the same name
CAPMON	Canadian Air and Precipitation Monitoring Network
CCME	Canadian Council of Ministers for the Environment
CGIAR	Consultative Group on International Agricultural Research
COPD	Chronic Obstructive Pulmonary Disease
CL	critical load
CLF	critical load function
CO ₂	carbon dioxide
DEM	digital elevation model
DFO	Fisheries and Oceans Canada
DIN	dissolved inorganic nitrogen



DLE	dry low emissions
DOC	dissolved organic carbon
DS1, DS2	Data set 1, data set 2 (sampled lakes)
EA	environmental assessment
EMEP	European Monitoring and Evaluation Programme
ESRL	Earth System Research Laboratory
FAB	First-order Acidity Balance model
GAQM	Guideline on Air Quality Models
GIS	geographic information system
GSHHG	Global Self-consistent, Hierarchical, High-resolution Geography
HNO ₃	nitric acid
ISHD	Integrated Surface Hourly Database
KAA	Kitimat Airshed Assessment study
KMP	Kitimat Modernization Project
LNG	liquefied natural gas
MAML	Mobile Air Monitoring Laboratory
MCHEM	chemical transformation scheme
MDISP	dispersion coefficients switch setting
MESOPUFF II	A chemical transformation scheme (used in this study only for Scenario F_M)
MM5	5 th generation mesoscale model (data from this model used in sensitivity analyses of CALPUFF model output)
MODIS	Moderate Resolution Imaging Spectroradiometer program
MOE	British Columbia Ministry of Environment
n	number (sample size, e.g., “n=6”)
N	nitrogen
NAAQS	US EPA National Ambient Air Quality Standards
NADP	National Atmospheric Deposition Program
NCDC	National Climatic Data Center
NDBC	National Data Buoy Center
(NH ₃) ₂ SO ₄	ammonium sulphate
NH ₃ NO ₃	ammonium nitrate
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NO ₂	nitrogen dioxide



NO ₃	nitrate
NO _x	nitrogen oxides
PM	particulate matter
PM _{2.5}	particulate matter up to 2.5 micrometers in diameter
PNW	Pacific NorthWest (LNG)
PR	Prince Rupert (LNG)
PRAS	Prince Rupert Airshed Study
PRLNG	Prince Rupert LNG
QA/QC	quality assurance/quality control
QP	qualified professional
RFP	Request for Proposals
RIVAD	A chemical transformation scheme (with ISORROPIA equilibrium)
S	sulphur
SCR	selective catalytic reduction
SGTIBL	Sub-grid scale thermal internal boundary layers
SO ₂	sulphur dioxide
SO ₄	sulphate, a salt of sulphuric acid
SRP	soluble reactive phosphorus
SRTM	Shuttle Radar Topographic Mission
SSMB	steady state mass balance model
SSWC	steady state water chemistry (model)
STAR	SO ₂ Technical Assessment Report for the Kitimat Modernization Project
TFL	tree farm license
US	United States (of America)
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WRF	Weather Research and Forecasting

Measurement Units

ha	hectares
km	kilometre
kg/ha	kilograms per hectare



kg/ha/yr	kilograms per hectare per year (units of deposition flux)
mg/l	milligrams per litre
meq/m ² /yr	milliequivalents per square metre per year
mtpa	million (metric) tons per annum
ppb	parts per billion
ppm	parts per million
t/d	(metric) tons per day
µeq/L	microequivalents per litre (µ can also be shown as u)
µg/m ³	micrograms per cubic metre (µ can also be shown as u)

Glossary of Terms

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
acidic episode	An event in a water body in which acidification of surface waters results in an acid neutralizing capacity of less than or equal to 0
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
alkalinity	Measures the ability of a solution to neutralize acids; the terms acid neutralizing capacity and alkalinity are sometimes used interchangeably
ambient	Of the surrounding area or environment
anion	An ion with more electrons than protons, giving it a negative charge, e.g., SO ₄ ²⁻
anthropogenic	Of, relating to, derived from, or caused by humans or related to human activities or actions
base cations	An alkali or alkaline earth metal (Ca ²⁺ , Mg ²⁺ , K ⁺ , Na ⁺)
base saturation	The proportion of total soil cation exchange capacity that is occupied by exchangeable base cations (i.e., by Ca ²⁺ , Mg ²⁺ , K ⁺ , Na ⁺)
catchment	See “watershed”
cation	An ion with fewer electrons than protons, giving it a positive charge, e.g., Ca ²⁺
climate	The average weather of a location over a long period of time



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
empirical	Derived from or guided by experience or experiment
eutrophication	The enrichment of an ecosystem with chemical nutrients, typically compounds containing nitrogen, phosphorus, or both
Gran ANC	The capacity of a solution to neutralize strong acids, determined by titration to the inflection point of the pH-alkalinity titration curve
higher vegetation	Vascular plants, i.e., those with conducting tissue such as angiosperms, gymnosperms, ferns (plants other than lichens and mosses)
hydrology / hydrologic ion	Pertaining to the movement, distribution, and quality of water An atom or molecule in which the total number of electrons is not equal to the total number of protons, giving it a positive or negative electrical charge
isopleth	Contour line on a map connecting places with the same value of some parameter, e.g., total sulphate deposition
leaching	The extraction of materials from a carrier into a liquid
morbidity	A diseased state or symptom
organic acids	Acids possessing a carboxyl (-COOH) group or phenolic (C-OH) group; includes fulvic and humic acids
percentile	A measure used in statistics indicating the value below which a given percentage of observations in a group of observations fall
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
saturation	The point at which a solution of a substance can dissolve no more of that substance
sea salt effect	The process by which hydrogen ions are displaced from the soil exchange complex by base cations (from neutral salts); the result is a short-term increase in the acidity of associated water; also referred to as the “sea salt effect”



strong acids	Acids having a high tendency to donate protons or to completely dissociate in natural waters (e.g., H ₂ SO ₄ , HNO ₃ , HCl, and some organic acids)
turbidity	The cloudiness of a fluid caused by suspended particles
watershed	The geographic area from which surface water drains into a particular lake or point along a stream
wet deposition	Transfer of substances from the atmosphere to terrestrial and aquatic environments via precipitation (e.g., rain, snow, sleet, hail, and cloud droplets); droplet deposition is sometimes referred to as occult deposition



1 Introduction

1.1 Background

There is considerable interest in the Prince Rupert area of British Columbia (BC) from the oil and gas industry seeking a marine terminal along BC's Pacific Coast from which to export oil and natural gas extracted from northeastern BC and Alberta. Numerous liquid natural gas (LNG) export terminals, port facilities and an oil refinery have been proposed for the area, placing urgent demands on government regulators. Provincial agencies making Environmental Assessment (EA) Certificate decisions under the *BC Environmental Assessment Act* and permitting decisions under the *BC Environmental Management Act* (including the BC Environmental Assessment Office, BC Oil and Gas Commission, and BC Ministry of Environment (MOE)) require an understanding of the potential combined impacts from existing and proposed industrial facilities. The ESSA team was contracted by MOE to conduct a high-level scoping study of the potential combined effects of nitrogen dioxide (NO₂), sulphur dioxide (SO₂), and particulate matter less than 2.5 microns (µm) in diameter (PM_{2.5}) emissions on human health, vegetation, soil (representing terrestrial ecosystems) and lakes (representing aquatic ecosystems) in the Prince Rupert area. The study was based on seven scenarios, representing different combinations of existing and proposed stationary and mobile emissions sources and emission treatment levels. The objective was to provide information that would help decision-makers understand and compare the potential effects of NO₂, SO₂, and PM_{2.5} on human health and the environment in an airshed context, given the proposed clusters of LNG and other industrial discharges. Other pollutants, such as volatile organic compounds and ozone, are not addressed in the scope of this study because the levels of these pollutants are expected to remain low and will not vary substantially based on the number of LNG facilities and the NO_x control employed by the facilities.

The Prince Rupert Airshed Study (PRAS) study area is shown in Figure 1-1 and comprises an area of 10,956 km². The industrial facilities explored in this study include existing and proposed port facilities (Canpotex, Fairview, Ridley Island Coal and Prince Rupert Grain), an existing BC Hydro (BCH) gas fired turbine, and six proposed LNG facilities and export terminals:

- Grassy Point LNG, emission capacity 20 mtpa
- Pacific NorthWest (PNW) LNG, emission capacity 19.2 mtpa
- WCC LNG, emission capacity 30 mtpa
- Prince Rupert (PR) LNG, emission capacity 21 mtpa
- Aurora LNG, emission capacity 24 mtpa
- Watson Island LNG, emission capacity 2 mtpa

The location of these facilities is shown in Figure 1-2. In addition to these stationary emissions sources of NO₂, SO₂, and PM_{2.5}, the study also included rail and marine transportation sources of these contaminants in the study area (Figure 1-3). Figure 1-3 also shows the names of many of the islands in the study area.



The human health assessment within the study includes many communities (Prince Rupert, Port Edward, Lax Kw'alaams, Metlakatla, Kitkatla, Crippen Cove, Oona River, Osland, Hunts Inlet, North Pacific Cannery, Dodge Cove, Cassiar Cannery, Rainbow Lake, Kloiya Bay and Prudhomme Lake) as well as recreational and cultural areas.

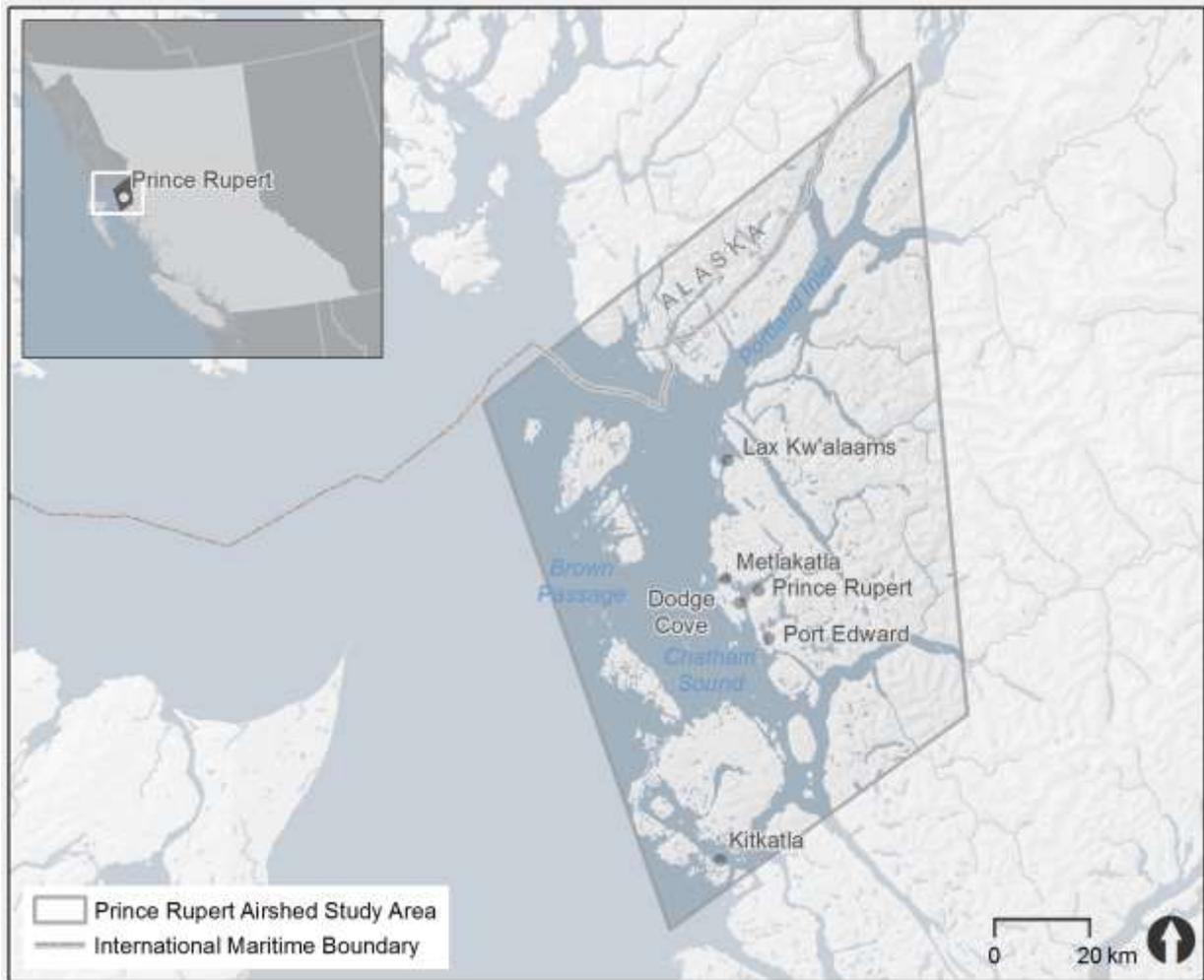


Figure 1-1: Map showing the study area.

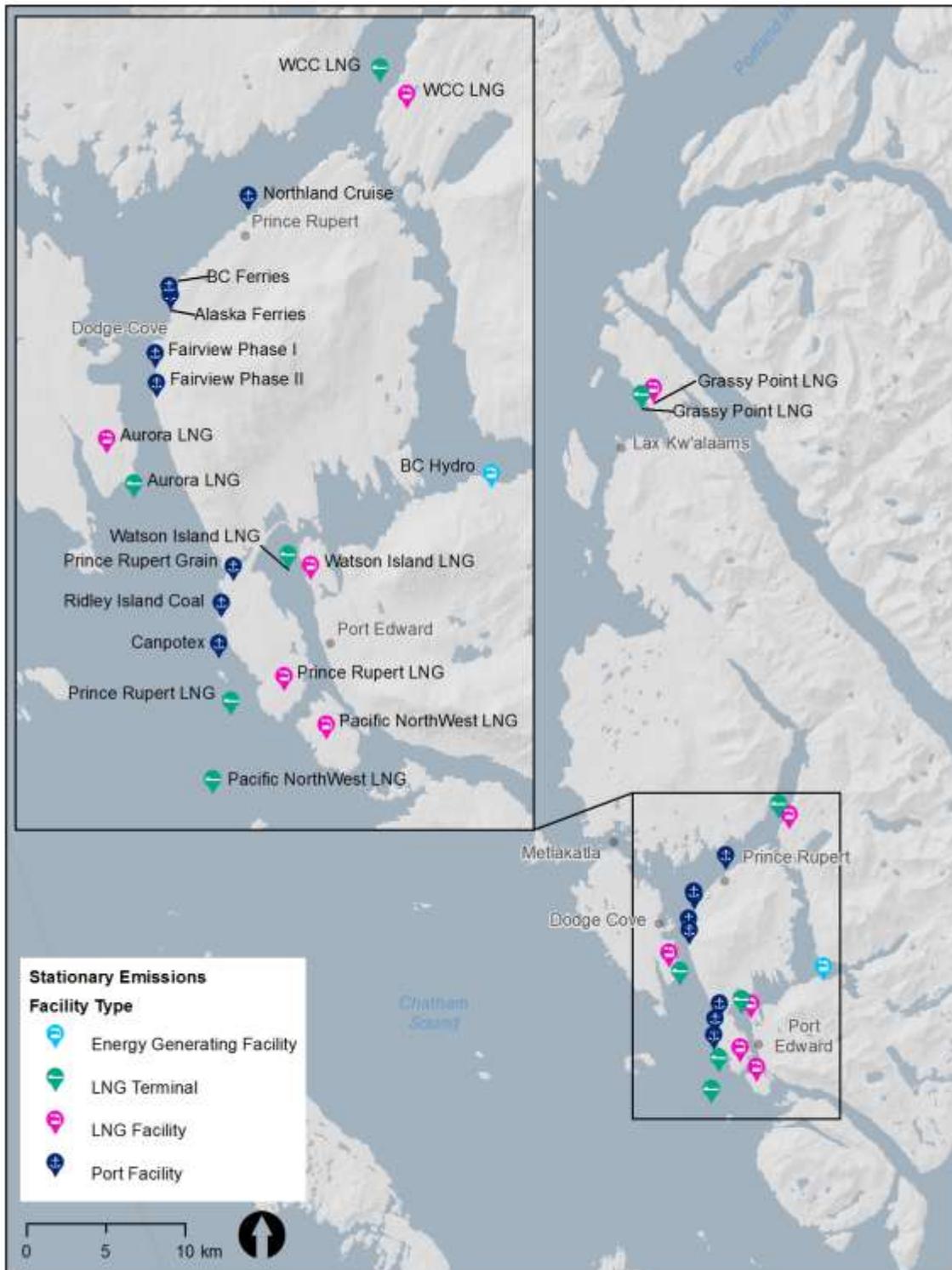


Figure 1-2: Map showing the stationary emission sources included in this study.



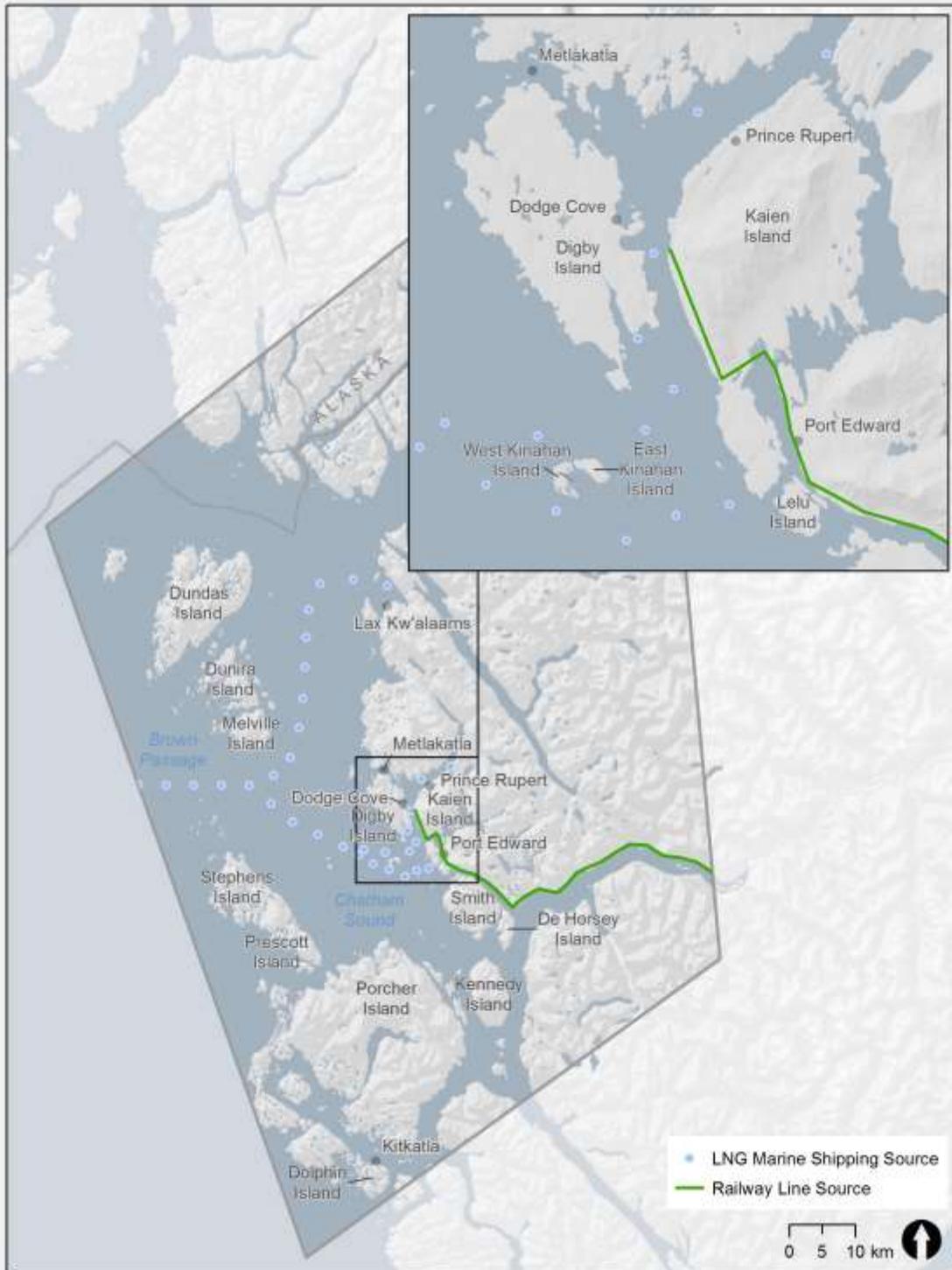


Figure 1-3: Map showing the transportation emission sources included in this study as well as island names.

1.2 Approach

This high-level scoping study was designed using the source-pathway-receptor framework illustrated in Figure 1-4. MOE was interested in learning about the potential effects on human health from direct exposure to SO₂, NO₂, and PM_{2.5} concentrations and the potential effects on vegetation from direct exposure to SO₂ and NO₂ in the air, as well as the potential effects on vegetation, soils and lakes from deposition of sulphur (S) and nitrogen (N).

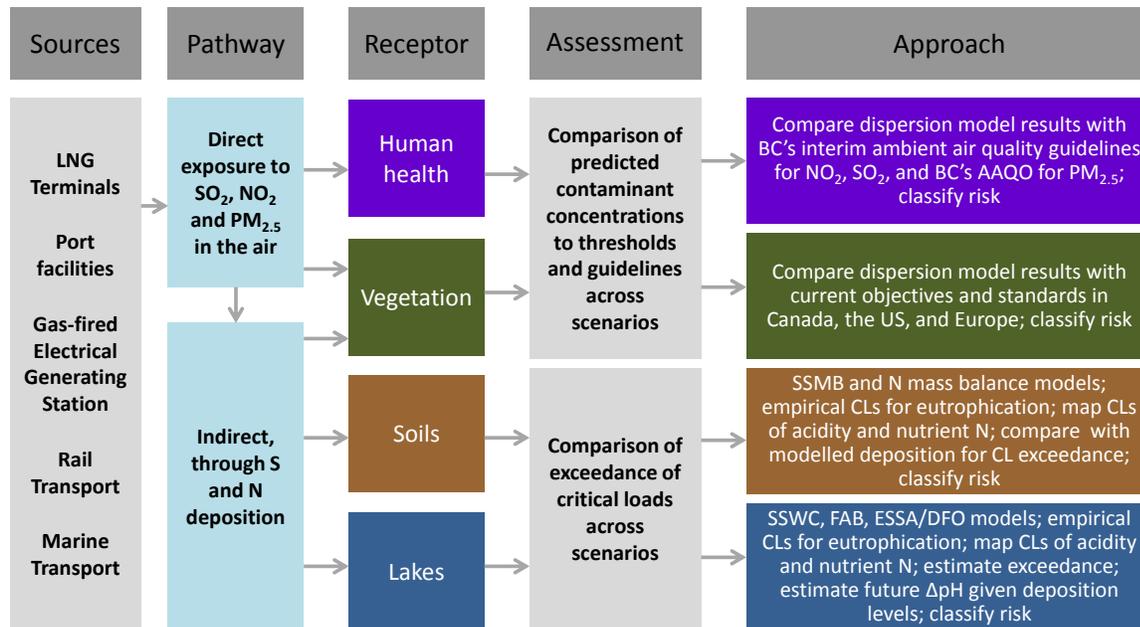


Figure 1-4: High-level summary of our study design.

The work for each pathway and receptor was undertaken by qualified professionals (QPs) in each field:

- Air Dispersion and Deposition – Trinity Consultants Inc.
- Human Health – Risk Sciences International Inc.
- Vegetation – Dr. John Laurence
- Terrestrial Ecosystems (acidification and eutrophication) – Trent University
- Aquatic Ecosystems (acidification and eutrophication) – ESSA Technologies Ltd.

The methods used for the Prince Rupert study built on similar work completed recently for the KMP SO₂ Technical Assessment (STAR) for Rio Tinto Alcan (ESSA et al. 2013) and the Kitimat Airshed Emissions Effects Assessment (KAA) for MOE (ESSA et al. 2014), with modifications as necessary for the differences in the PRAS landscape, emissions (the addition of PM_{2.5}), data availability, and scenarios. The approach used in this study was consistent with the General Guidance for Air Emissions Impact Assessment published by the BC Ministry of Environment on November 21, 2014 (BC MOE, 2014).



The methodology for the PRAS was designed so that results would be comparable to those of the KAA to provide a regional perspective on impacts. Consequently, this study has many important similarities to the KAA, including:

- Examination of alternative emission scenarios representing different levels of emissions treatment across multiple facilities, informing decision-makers about the *relative* risks of different scenarios (and how far apart they are from each other in terms of expected risks), as well as about the *magnitude* of potential changes from current conditions (i.e., how many facilities the area can accommodate without unacceptable risks to human health and/or environmental receptors).
- Modelling of emissions of SO₂ and NO_x, their transformations into different chemical forms including sulfates and nitrates which make up secondary PM_{2.5}, and deposition as sulphuric and nitric acids.
- Consideration of emissions from mobile and stationary sources (including LNG terminals and a BC Hydro gas-fired turbine).
- Assessment of impacts on four receptors: human health, vegetation, soils and lakes.
- Assessment of acidification and eutrophication based on critical load methodology.

Also as for the KAA, the PRAS study results have been organized into four colour-coded risk categories: green, yellow, orange and red. Table 1-1 defines these categories for the environmental receptors (vegetation, soils and lakes). The risk categories for human health have different meanings and interpretation, and are further explained in Section 3.

Detailed descriptions of the methods and results for each of the pathways and receptors shown in Figure 1-4 are presented in Section 2 through Section 6 of this report.

Table 1-1: Risk categories and definitions for the environmental receptors: vegetation, soils and lakes.

Low	Scenarios expected to have no, or negligible, impact
Moderate	Scenarios expected to have an impact, but of a magnitude, frequency, and spatial distribution considered to be acceptable ^a
High	Scenarios expected to have an impact of a magnitude, frequency or spatial extent, or spatial distribution, considered to be unacceptable ^a ; further investigation is needed into the implications of the assumptions in this study to determine if reducing uncertainties and refining assessment inputs lowers the risk category
Critical	Scenarios expected to have an impact of a magnitude, frequency or spatial distribution, considered to be extremely unacceptable ^a ; further investigation could be made into the implications of the assumptions in this study to determine if reducing uncertainties and refining assessment inputs lowers the risk category, but would be unlikely to reduce the risk rating sufficiently to be considered acceptable

^a The quantitative boundaries of these categories used for the assessments of vegetation, soils and lakes are presented in Sections 4, 5 and 6 respectively. It is important to note that “acceptability” of impacts depends on one’s values, and is ultimately a policy decision that will be *informed* by this study.



1.3 Scenarios

Total emissions of SO₂, NO_x and PM_{2.5} from the seven scenarios are listed in Table 1-2. The scenarios were designed to represent a range of six potential emission sources and treatments. Scenario A serves as a “low-emission bookend” with the lowest NO_x emissions and lowest total emissions when considering all sources (“full build”), and Scenario F_R serves as a “high-emission bookend” with the highest emissions of NO_x and total emissions of all three contaminants with all sources considered. The remaining scenarios comprise different combinations of treatments and number of sources. The cumulative emissions of each contaminant for each scenario are depicted in Figure 1-5.

Scenario F_M assumes the same facility characteristics as Scenario F_R, but uses a different chemical transformation scheme for the dispersion modelling. The KAA used the MESOPUFF chemical transformation scheme. For this study, all scenarios except Scenario F_M applied the RIVAD with ISORROPIA chemical transformation scheme. These two chemical transformation schemes are discussed further in Section 2.1.3. The purpose of including Scenario F_M was to better understand the effects of the change to RIVAD for this study, in order to facilitate comparisons of study results for the other scenarios with the results from the KAA. In recognition of this difference between Scenario F_M and the other scenarios, receptor Sections 3, 4, 5 and 6 present study results for the six RIVAD scenarios, and the study results for Scenario F_M are provided in Appendix 1 (see Volume 2 of this report).

Table 1-2: Emissions from the seven scenarios assessed in the study. Emission numbers are estimates based on available design information for these sources.

Scenario Name	Description	Total SO ₂ t/d	Total NO _x t/d	Total PM _{2.5} t/d
Scenario A	Full Build, all facilities employ e-drive	7.5	34	1.4
Scenario B	Partial Build (PNW, Aurora, BCH), all built facilities employ DLE	3.3	34	2.1
Scenario C	Full Build, all facilities employ SCR	7.8	42	5.4
Scenario D	Partial Build (Grassy Point, Aurora, Watson Island), all built facilities employ DLE	4.2	44	2.2
Scenario E	Partial Build (PNW, WCC, PR, BCH), all built facilities employ DLE	5.7	50	3.0
Scenario F_R	Full Build, all facilities employ DLE	7.8	90	5.4
Scenario F_M	Full Build, all facilities employ DLE_Mesopuff	7.8	90	5.4
Variation in emissions across all scenarios (highest : lowest)		2.4X	2.6X	3.9X

'Full Build e-drive': this scenario assumes 100% electric power for combustion sources (engines, heaters, turbines).

'Partial Build DLE': these scenarios assume the listed facilities use dry low NO_x emission combustion systems and the rest are not constructed.

'Full Build DLE': these scenarios assume all of the LNG facilities use dry low NO_x emission combustion systems.

'Full Build SCR': this scenario assumes all of the LNG facilities use selective catalytic reduction combustion systems.

'Full Build DLE_Mesopuff': this scenario assumes the same as F_R (that all facilities are built and all use dry low NO_x emission combustion systems), but uses the MESOPUFF II chemistry model. All other scenarios use RIVAD with ISORROPIA atmospheric chemistry model.



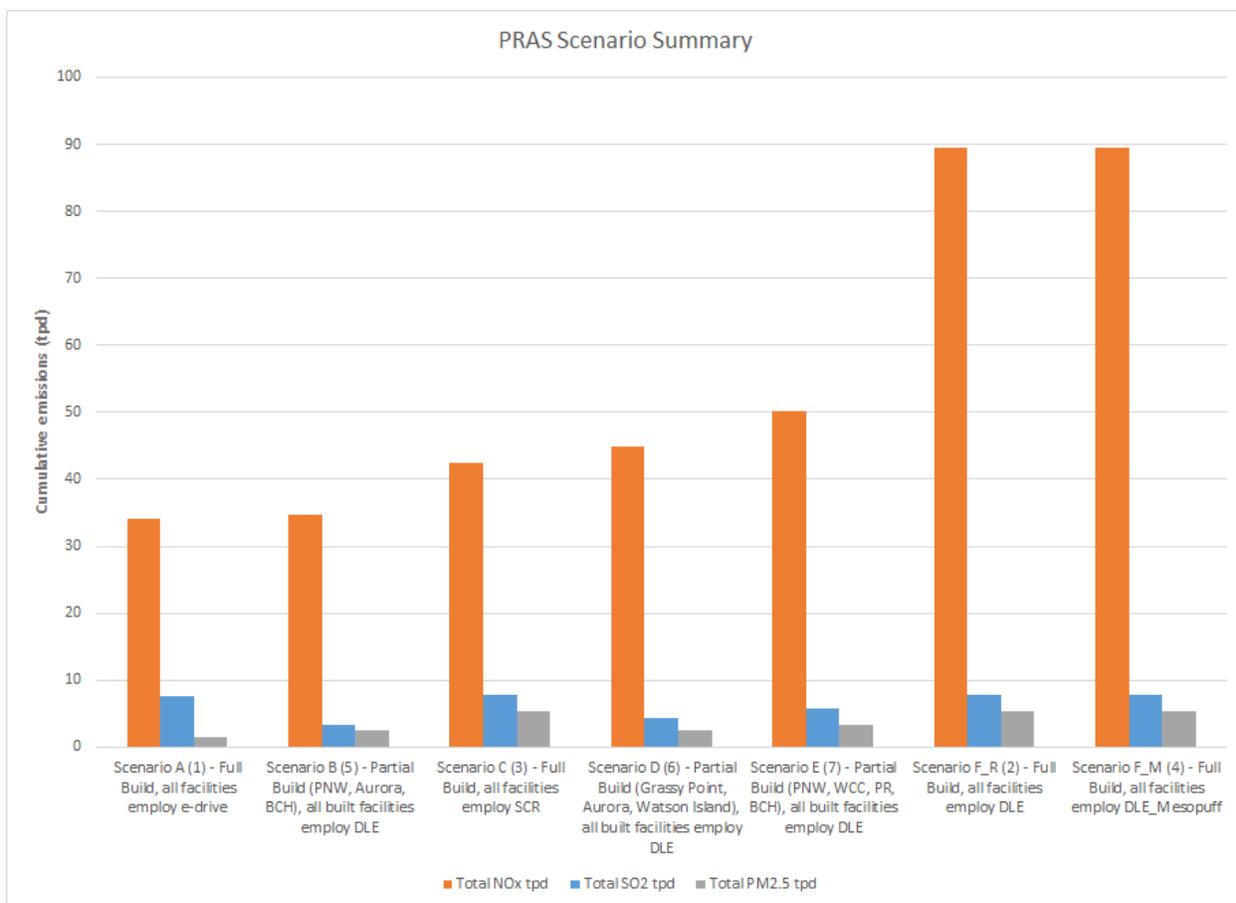


Figure 1-5: Bar chart illustrating cumulative emissions by scenario.

Figure 1-6, Figure 1-7, and Figure 1-8 provide greater detail for each of the bars in Figure 1-5 by showing the contributions of each modelled facility or transportation category to the total cumulative emissions of NO_x, SO₂ and PM_{2.5}, respectively. Please note that the y-axis of Figure 1-6 is 10 times that of Figure 1-7 and Figure 1-8. Some key points from these figures:

- Figure 1-6.** The four largest sources of NO_x are LNG terminals (up to 20.0 t/d), Grassy Point LNG (up to 18.8 t/d), Prince Rupert LNG (up to 12.2 t/d), and Aurora LNG (up to 9.4 t/d). Emissions of NO_x from LNG terminals and LNG shipping depend on the total production of LNG, and are therefore higher for the full-build scenarios (A, C, F_R, F_M) than for the partial-build scenarios (B, D, E).
- Figure 1-7.** The four largest sources of SO₂ are the Port Facilities terminals (up to 2.2 t/d), Prince Rupert LNG (up to 2 t/d), Watson Island LNG (up to 0.7 t/d) and LNG terminals (up to 0.7 t/d). Emissions of SO₂ from Port Facilities terminals are constant across all scenarios. Emissions of SO₂ from LNG terminals and LNG shipping are also higher for the full-build scenarios (A, C, F_R, F_M) than for the partial-build scenarios (B, D, E).
- Figure 1-8.** The four largest sources of PM_{2.5} are Prince Rupert LNG (up to 1.0 t/d), Grassy Point LNG (up to 1.0 t/d), Aurora LNG (up to 0.75 t/d), and Pacific NorthWest LNG (up to 0.75 t/d).



As was done in the KAA, the characteristics for each facility have been modelled as separate “layers”, explained further in Section 2.1. This allows MOE the flexibility to later explore additional scenarios through different layer combinations without having to re-do the air dispersion and deposition modelling. MOE will retain ownership of all of the model results and outputs.

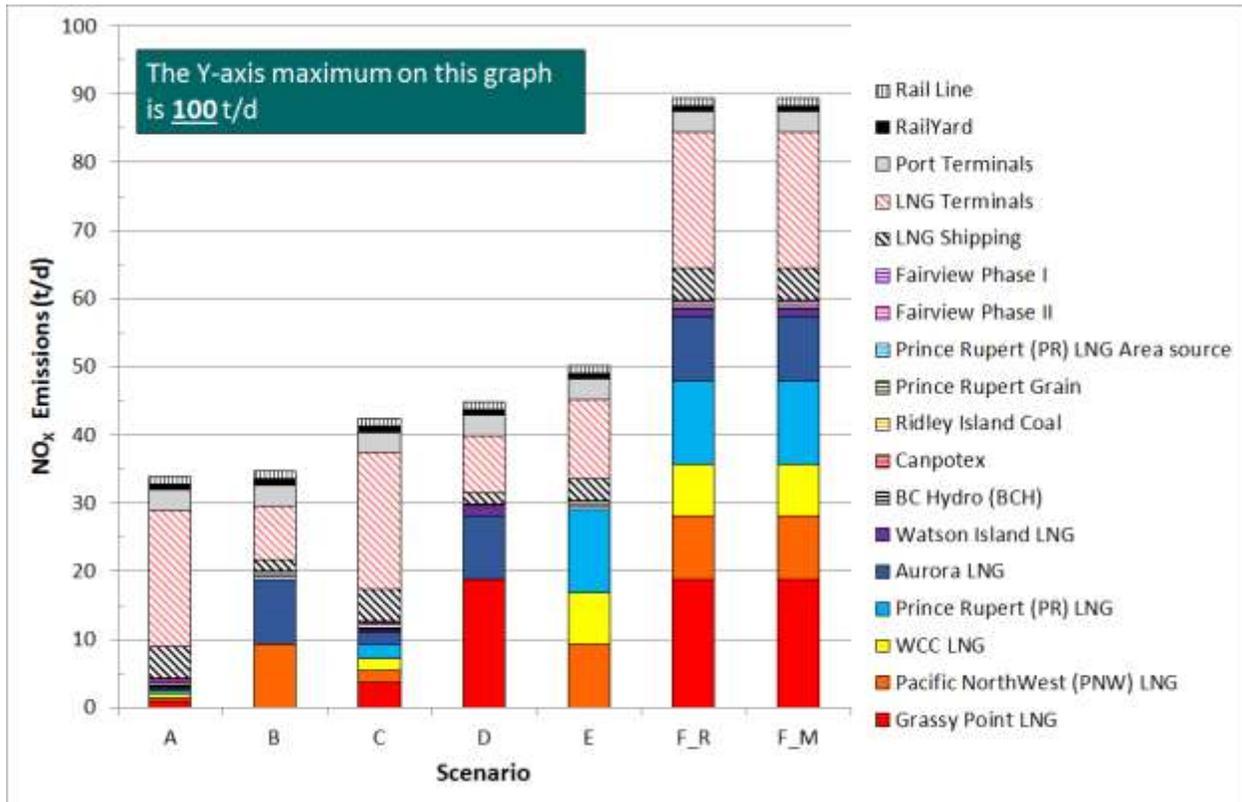


Figure 1-6: Cumulative contributions of NO_x from different sources in each emission scenario.



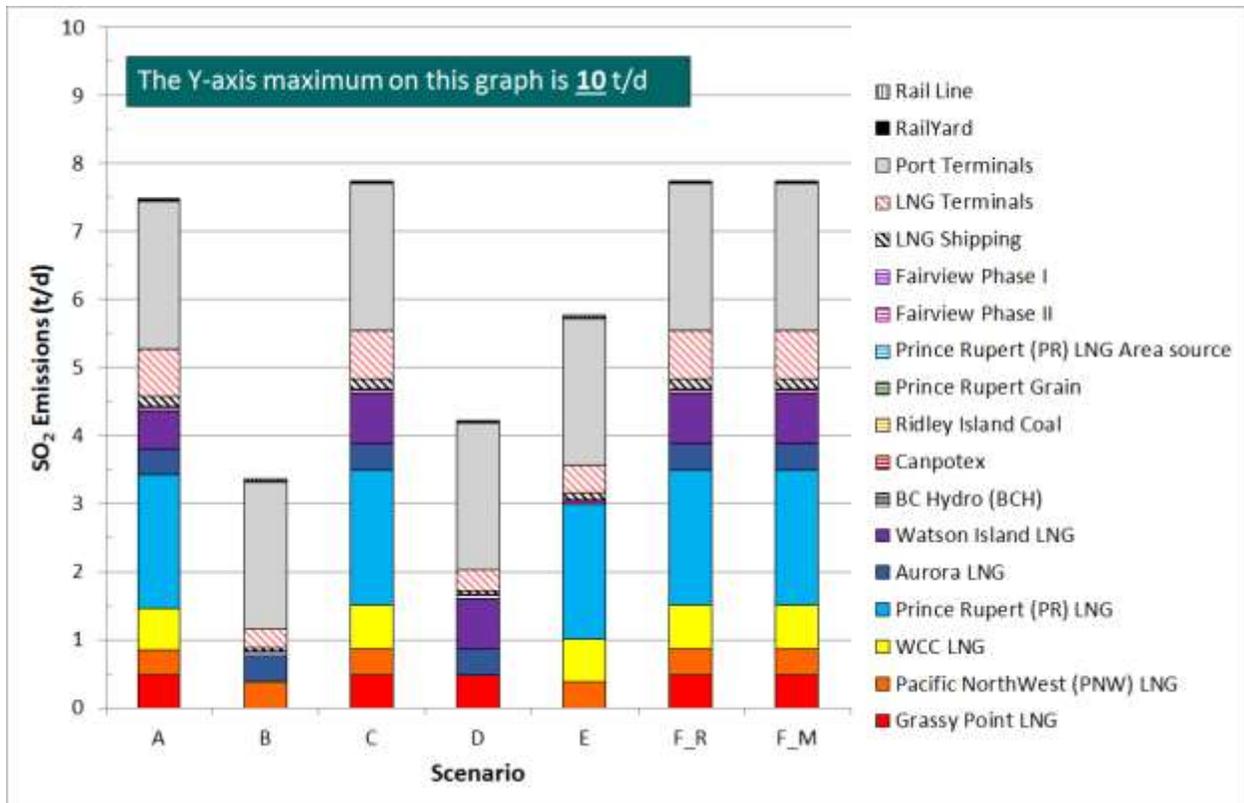


Figure 1-7: Cumulative contributions of SO₂ from different sources in each emission scenario.



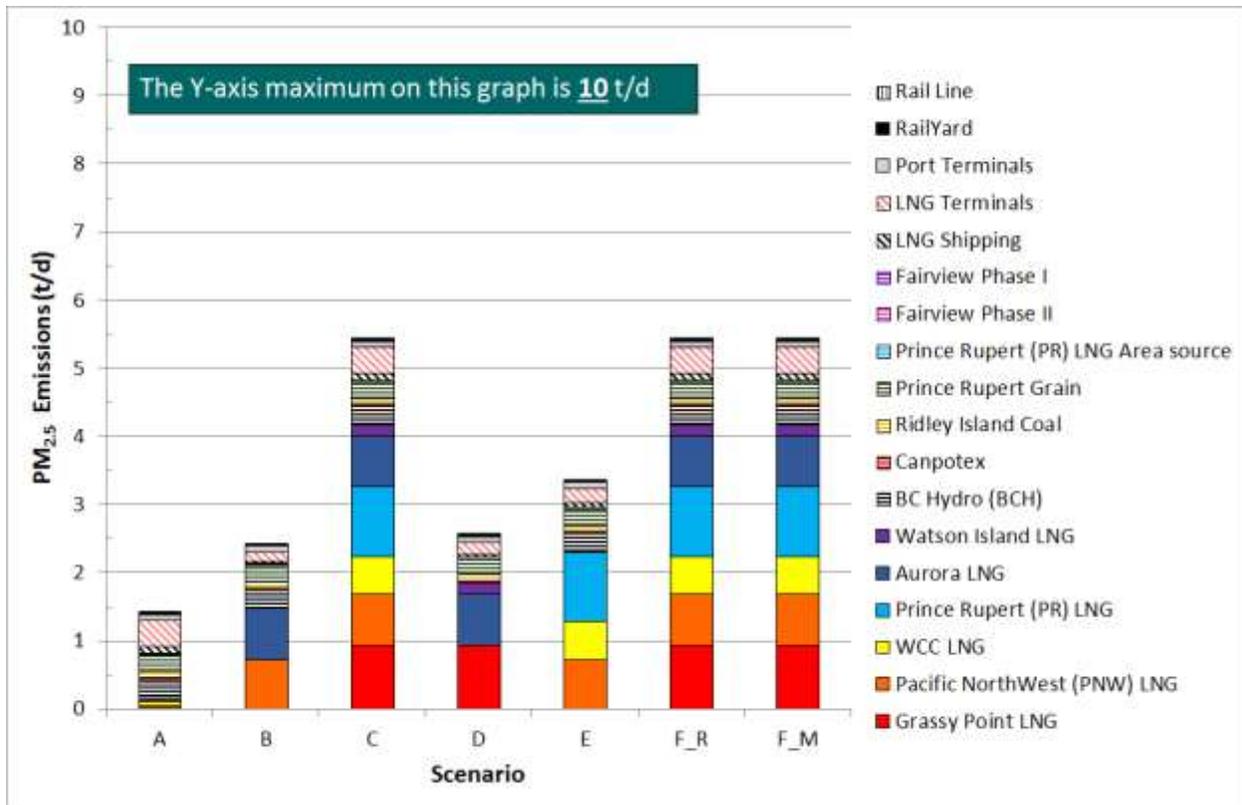


Figure 1-8: Cumulative contributions of PM_{2.5} from different sources in each emission scenario.

1.3.1 Comparison of Provided and Modelled Emission Rate Intensities

As further discussed in Section 2.1.4, Grassy Point LNG, Pacific NorthWest LNG, Prince Rupert LNG and WCC LNG modelled emission rates were provided directly by proponents, except for the thermal oxidizers at Grassy Point LNG and WCC LNG, which use Pacific NorthWest LNG data as proxies. Emissions from Aurora LNG use Pacific NorthWest LNG emissions as proxies for all land emission sources, and emissions from Watson Island LNG use Triton LNG (a LNG facility modelled in KAA) as a proxy. Table 1-3 presents the emission intensity of each facility representing the total modelled emission rate from each facility for Scenario F_R with respect to each facility’s production rate.

Table 1-3: Emission Intensities of Stationary Sources at LNG Facilities for Scenario F_R

LNG Facility	Production Rate (mtpa)	Scenario F_R_U Emission Intensity for Stationary Sources ¹ (t/d per mtpa)		
		Total SO ₂	Total NO _x	Total PM _{2.5}
Grassy Point LNG	20	0.025	0.942	0.048
Pacific NorthWest LNG	19.2	0.021	0.490	0.039
WCC LNG	30	0.021	0.250	0.018
Prince Rupert LNG	21	0.094	0.583	0.049
Aurora LNG	24	0.016	0.392	0.031
Watson Island LNG	2	0.367	0.574	0.082

¹ As discussed in Section 2.1.4, the emission rates for thermal oxidizers at Grassy Point LNG and WCC LNG use Pacific NorthWest LNG thermal oxidizers as proxies. The emissions from Watson Island LNG use Triton LNG as proxy; therefore, the emission intensities for this facility are not discussed below.



Figure 1-6 and Table 1-3 show that the NO_x emission intensities vary considerably among LNG facilities, with the emission intensity ranging from 0.250 t/d per mtpa up to 0.942 t/d per mtpa. The highest intensity is 0.942 t/d per mtpa, while the next highest is 0.583 t/d per mtpa (approximately 40% lower). While the reason for this disparity is unknown, this variation may be due to the facility with highest emission intensity using more conservative NO_x emission factors in estimating the emission rates.

Figure 1-7 and Table 1-3 show that the SO₂ emission intensities also vary substantially among LNG facilities. The thermal oxidizer, which combusts the sulphur removed from the feed gas, makes up the vast majority of SO₂ from the LNG facilities. The intensity of SO₂ emission rates from only the thermal oxidizers based on *provided* proponent data ranges from 0.019 t/d per mtpa up to 1.00 t/d per mtpa.¹ The wide variation in SO₂ intensity indicates a wide variety of assumptions made by proponents about the sulphur and H₂S content in the feed gas and the fraction of that sulphur that must be removed in the acid gas removal unit. According to the background information provided by proponents, the assumptions used to develop the SO₂ emission rates from thermal oxidizers are based on inlet total sulphur concentration of 2 milligram per standard cubic metre (mg/Nm³) up to 115 mg/Nm³.² Some differences in sulphur feed gas assumptions are expected, because different proponents will be drawing their feed gas from different gas fields. However, the extent of the variation also indicates differences in other assumptions such as what species of sulphur and the level to which sulphur is required to be removed to meet the requirements of downstream equipment or end-market specifications.

Figure 1-8 and Table 1-3 show that the PM_{2.5} emission intensity ranges from 0.018 t/d per mtpa to 0.049 t/d per mtpa (not considering Watson Island LNG). The variation also indicates different assumptions applied to the provided emission rates for PM_{2.5}. WCC LNG has the lowest PM_{2.5} emission intensity while being the largest proposed LNG facility of 30 mtpa. PM_{2.5} emission calculations are typically based on the fuel gas composition and sulphur content of the gas, assumptions for which likely varied from site to site.

¹ The 0.019 t/d per mtpa to 1.00 t/d mtpa does not match Table 1-3 because these emission intensities are calculated based on proponent provided data for thermal oxidizers at the LNG facilities, not all the stationary sources at these facilities. Thermal oxidizer emissions that are considered outliers are replaced with an estimate representative of the remaining facilities.

² One proponent provided an emissions estimate for thermal oxidation that was more than 10 times greater than the next highest estimate (based on 115 mg/Nm³ sulphur content of the feed gas). As the proponent stated that actual Sulphur values would be significantly lower than this unusually high estimate, it was considered an outlier and was replaced with an estimate representative of the remaining facilities.



2 Air Dispersion and Deposition Modelling

2.1 Methods

The CALPUFF dispersion modelling analysis followed the *Guidelines for Air Quality Dispersion Modelling in British Columbia* (BC MOE 2008) methods and procedures, as detailed in Appendix 2.1 (Modelling Protocol) in Volume 2 of this report. All decisions regarding modelling methods requiring expert judgement were made in consultation with MOE. Dennis Fudge, BC MOE Air Pollution Meteorologist, provided formal approval of the CALMET protocol on February 6, 2015 and the CALPUFF modelling methodology on February 19, 2015 to Trinity. Both protocols included all CALMET and CALPUFF procedures and were developed through many discussions between Trinity and MOE. All subsequent decisions were also made in consultation with MOE, as extensively referenced throughout this report.

2.1.1 Layering Method

As discussed in Section 1.3, modelling outputs were developed for seven separate scenarios for the analysis of potential impacts on human health, vegetation, soils, and lakes. Rather than preparing a scenario-specific CALPUFF input file and conducting the associated model run, each facility was modelled individually for one to four cases which each facility may operate:

- LNG Facilities – four options modelled:
 - Base case using emissions provided by proponents or proxy data which represent dry low NO_x emissions (DLE)
 - Selective Catalytic Reduction (SCR) on turbines
 - 100% electric for combustion sources (engines, heaters, turbines)
 - Base Case running in an alternate chemical transformation mode (MESOPUFF II scheme option in lieu of RIVAD scheme with ISORROPIA equilibrium)
- Port Facilities – two options modelled:
 - Base Case
 - Base Case running in an alternate chemical transformation mode (MESOPUFF II scheme option in lieu of RIVAD scheme with ISORROPIA equilibrium)
- Rail Line – two options modelled:
 - Base Case
 - Base Case running in an alternate chemical transformation mode (MESOPUFF II scheme option in lieu of RIVAD scheme with ISORROPIA equilibrium)
- Shipping – two options modelled:
 - Base Case
 - Base Case running in an alternate chemical transformation mode (MESOPUFF II scheme option in lieu of RIVAD scheme with ISORROPIA equilibrium)

Once each facility was modelled individually, results were then combined in the post-processing phase of the CALPUFF modelling analysis (i.e., using POSTUTIL for NO₂, SO₂, and PM_{2.5} concentrations and deposition). Using this summing, or “layer”, method will allow MOE to request additional combination scenarios for a fraction of the time and cost required for a scenario-specific CALPUFF run. This layering approach may result in some overestimation or



underestimation of combined results for SO₂. However, the difference is expected to be small, as detailed in Section 2.3.

2.1.2 About Dispersion Models

Dispersion models serve as a tool to predict or estimate ambient air concentrations and deposition rates due to industrial or other 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. Dispersion models are designed to be conservative, because their most common purpose is to provide a worst-case estimate of the 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).

Once a project is in operation, air monitoring programs are often implemented to verify that the ambient concentrations are below levels of concern. However, dispersion models are also increasingly being used now to estimate air pollutant concentrations from existing sources, as a reliable and more cost effective option than ambient air monitoring. Most notably, the United States Environmental Protection Agency (US EPA) has proposed using dispersion modelling to determine the attainment status of regions within each state with respect to a 1-hour SO₂ ambient air quality standard. The most commonly-used dispersion models for predicting air pollutant concentrations from industrial sources are AERSCREEN, AERMOD, and CALPUFF.

About the CALPUFF Dispersion Model and its Selection over other Models

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 km);
- represent complex terrain conditions in the Prince Rupert 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); 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.

2.1.3 CALPUFF Dispersion Modelling Methods Summary

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.

Modelling Domain

The CALPUFF modelling system utilizes three modelling grids: the meteorological grid; the computational grid; and the sampling grid (or receptor grid). The meteorological grid is the system of grids within which meteorological fields are developed with CALMET. The computational grid defines the computational area for a CALPUFF run (i.e., where the puffs are tracked), and is defined identically to the meteorological grid. The sampling grid defines the locations where the ground level concentration and/or deposition results are calculated and stored within the CALPUFF output files. The sampling grid/study area was defined by MOE. The meteorological/computational grid extends approximately 50 km beyond the sampling grid boundary in order to account for puff recirculation (emission plumes leaving the study area and then transporting back into the study area due to changing winds over time and space).

The meteorological and CALPUFF computational grid spacing is 1 km across the entire domain. This resolution strikes a balance between the finer resolutions sometimes used for local scale assessments (often set to 500 metres) and coarser resolution used for long range assessment (often set to 4 km spacing as in the KAA). The 1 km resolution provides refined meteorological patterns for the local scale while still accommodating a larger size regional-scale sampling grid (study area) in a single model. The 1 km resolution also corresponds to the resolution needed by the soil and water assessments, where long range transport plays a larger role. Figure 2-1 presents the meteorological/computational and sampling domains.



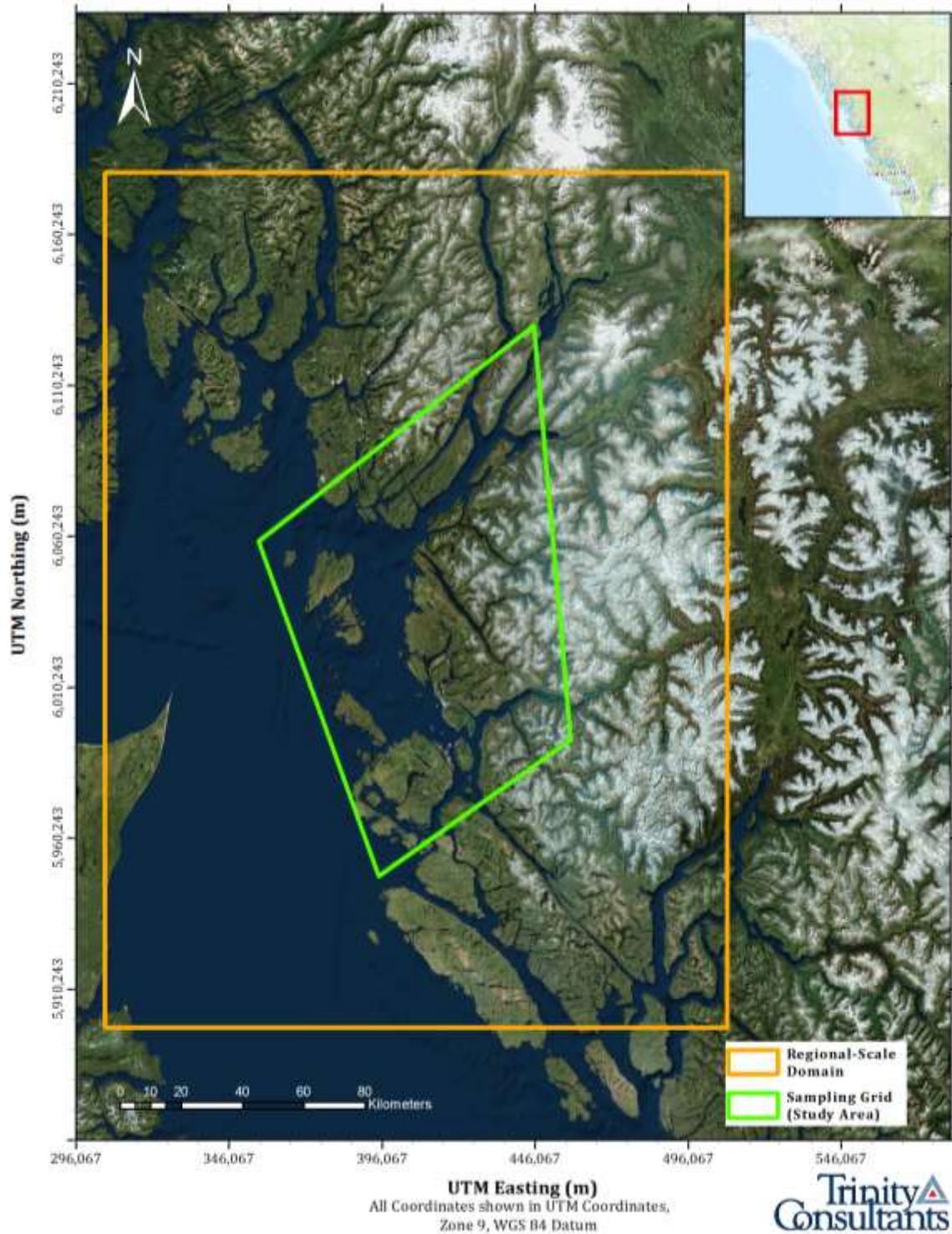


Figure 2-1: Regional scale meteorological/computational modelling domain and sampling grid (study area). The regional scale modelling domain is larger than the study area (defined by MOE) in order to account for puff recirculation (puffs moving outside the study area and circling back inside).

CALMET Meteorological Processor

Meteorology plays a major role in determining air quality changes downwind of emission sources. Both the wind and atmospheric stability greatly affect dispersion conditions. Local influences due to terrain and land-cover factors can also be important. For dispersion modelling, the CALMET meteorological model was used in conjunction with the CALPUFF air quality dispersion model. Input data for CALMET consisted of surface (over-land and over-water) and upper air data for the period January 1 - December 31, 2012.

The CALMET surface layer characterization was resolved in part with compatible data from meteorological stations available within the modelling domain. Upper air observations from the single station within the domain were also included.

All observation stations are placed near populated areas and do not provide regular and sufficient coverage across the entire modelling domain. Therefore, the Weather Research and Forecasting (WRF) numerical weather prediction system was used to produce mesoscale meteorological fields and enhance the depiction of the meteorological conditions.

Meteorological Grid Domain

The CALMET modelling domain was defined to encompass the study area defined by MOE with a minimum 50 km buffer. The CALMET domain was constructed as a rectangular Cartesian grid, which covers a 202 by 283 km area at a 1 km resolution and extends 4 km in the vertical direction. Through consultation with MOE, it was determined that the height of 4 km would be sufficient to resolve the atmospheric boundary layer, where the plume dispersion occurs. The vertical span of the domain was split into 11 layers.

The southwest corner of the CALMET grid was selected as Easting 305.6 (km), Northing 5897.6 (km) in Universal Transverse Mercator (UTM) Zone 9, World Geodesic System 1984 (WGS-84) coordinates.

The CALPUFF FAQ³ states that “[f]or applications in the middle latitudes, the distortion due to use of UTM coordinates will generally become significant for modeling domains exceeding 200 kilometers on a side.” Since Prince Rupert is at the northern edge of the “middle latitudes” belt, a smaller threshold would apply. The full CALMET and CALPUFF domain is larger than 200 km. However, the study area is 101 km east-west by 182 km north-south; therefore, results would not be expected to be significantly affected by using the UTM coordinate system. Small effects may be seen near the boundaries of the domain, but would not likely be significant in the context of 1 km spaced receptors in these regions. The advantage of using the UTM coordinate system is that the various disciplines using the results and most reviewers are familiar with UTM coordinates, and can easily map those coordinates to user-friendly programs, such as Google Earth.

³ <http://www.src.com/calpuff/FAQ-answers.htm#1.1.5>



Geophysical Data

CALMET requires geophysical data to characterize the terrain and land use parameters that potentially affect dispersion. Terrain features affect flows, create turbulence in the atmosphere, and are potentially subjected to higher concentrations of elevated puffs. Different land use types exhibit variable characteristics such as surface roughness, albedo, Bowen ratio, and leaf-area index that also affect turbulence and dispersion. The methodology for geophysical parameters is described in detail in Appendix 2.2 (CALMET Methodology) in Volume 2 of this report, and summarized in the sections below.

Terrain Elevation

Terrain elevation for the CALMET was obtained using the TERREL processor. The model was executed with terrain maps provided by the Consultative Group on International Agricultural Research (CGIAR) and the Consortium for Spatial Information (CSI) website.⁴ Data were collected as part of the Shuttle Radar Topographic Mission (SRTM) and processed by CSI into 5 x 5 degree tiles at 90-metre resolution⁵. More details are provided in Appendix 2.2 (CALMET Methodology) in Volume 2 of this report.

The SRTM data were used only for the geo-processing of the CALMET domain, because it provided the best consistency across the entire modelling domain; the elevations of the discrete receptors and emission sources were extracted from higher resolution data.

In addition to the SRTM data, high resolution coastline data were used to better outline the sea-land boundary. The coastline data were obtained from the Global Self-consistent, Hierarchical, High-resolution Geography (GSHHG) Database supported by the National Geographic Data Center at NOAA.⁶

Land Use

Land characteristics in the domain were extracted using the CALMET pre-processor CTGPROC. The input land use maps were obtained from British Columbia Geographic Data Center⁷ and from the United States Geological Survey (USGS)⁸ websites in GeoTIFF format. The British Columbia Baseline Thematic Mapping (BMT) provided 30-metre resolution land cover maps, which were used to resolve the Canadian part of the domain. The USGS maps are part of the 2001 National Land Cover Database (NLCD), have grid resolution of 30 metres and were used to resolve the Alaskan part of the modelling domain. More details of the processing procedures are provided in Appendix 2.2 (CALMET Methodology) in Volume 2 of this report.

⁴ <http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1>

⁵ Note that the SRTM elevation data used was found to represent the entire domain better than the alternative of using a mix of digital elevation data (DEM) from Canadian and US data sources, and the Version 4 Archive used has corrected the previously identified error of reporting elevations near the top of canopies.

⁶ <http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html>

⁷ <http://www.data.gov.bc.ca/dbc/geographic/index.page?WT.svl=Topnav>

⁸ <http://earthexplorer.usgs.gov/>



MAKEGEO is the final geophysical processor which reads the fractional land use and terrain elevation data and calculates the set of surface micro-meteorological parameters needed for calculation of some of the CALMET meteorological variables as well as some dispersion characteristics at CALPUFF stage; these are: surface roughness length, Bowen ratio, albedo, leaf area index, soil heat flux parameter, and anthropogenic heat flux.

In this study, the seasonal variation of the surface micro-meteorology was accounted for. After analysing a variety of maps (monthly albedo, leaf area index, etc.) provided by NASA via their Moderate Resolution Imaging Spectroradiometer (MODIS)⁹ program, it was concluded that there are two clearly distinguished seasons – winter without continuous snow cover, and summer with lush vegetation.

The process of assigning seasonal values to the albedo, Bowen ratio, and surface roughness length was based on the procedures approved by USEPA and published in the “AERSURFACE User’s Guide”, revised January 16th, 2013. The values for leaf area index, soil heat flux parameter, and anthropogenic heat flux were based on the CALMET default values, and corrected based on the MODIS images. Seasonal values used in the model are provided in Appendix 2.2 (CALMET Methodology) in Volume 2 of this report. It was established that for purposes of the Bowen ratio variations, 2012 was a year of wet moisture conditions.

Meteorological Data

CALMET was used to assimilate data for 2012 using WRF data, surface station observations, upper air station observations, and National Oceanic and Atmospheric Administration’s buoy station observations to develop the meteorological field.¹⁰ The methodology for geophysical parameters is described in detail in Appendix 2.2 (CALMET Methodology) in Volume 2 of this report, and summarized in the sections below. A map showing the observation stations is also included in Appendix 2.2 (CALMET Methodology) in Volume 2 of this report.

Weather Research & Forecast (WRF) Model

The 2012 WRF dataset for use in the CALMET processing was provided by the MOE.¹¹ The WRF dataset contains 12 files, each covering one calendar month. The beginning and ending time were shifted to accommodate the time difference between local time zone (UTC-8) and GMT, the native WRF time zone. The WRF dataset was used to generate the diagnostic meteorological fields and as a main source of precipitation data for the domain. WRF data resolution is 4 km.

⁹ http://neo.sci.gsfc.nasa.gov/view.php?datasetId=MCD43C3_M_BSA

¹⁰ Note that precipitation data are not available on an hourly scale in the meteorological domain. Therefore, the WRF dataset was used for precipitation information.

¹¹ WRF Dataset prepared by Li Huang, Air Quality Meteorologist, MOE and mailed to Trinity January 20, 2015



Over-land Surface Meteorological Station

In addition to the WRF meteorological data, surface observations from nine meteorological stations were included in the modelling. Data for the Prince Rupert stations – the airport (CYPR) and Roosevelt Park School Met_60 stations were provided by MOE.¹²

Additionally surface hourly observations in TD-3505 format were obtained from the Integrated Surface Hourly Database (ISHD) supported by the National Climatic Data Center (NCDC).¹³

Prince Rupert airport station and Roosevelt Park School Met_60 were considered as most representative for the domain, because they are nearest to the center of the study area and modelling domain, and nearest to the modelled sources. The other surface observation stations are not near any of the modelled sources. The observations for the nine surface stations were blended with the SMERGE processor.

Upper Air Meteorological Data

Twice-daily radiosonde observations from Annette Island upper air station were obtained from the NCDC Earth System Research Laboratory (ESRL) website.¹⁴ Annette Island upper air station (ANN) is located at latitude 55.03N and longitude 131.57W. The raw radiosonde observations were processed with the upper air processor READ62.

Over-water Meteorological Data

The aerodynamic and thermal properties of water surfaces require a different method for calculating the boundary layer parameters in the marine environment. A profile technique, using air-sea temperature differences, is used in CALMET to compute the micro-meteorological parameters in the marine boundary layer. The WRF dataset was used as the primary source for these over-water data, with buoy stations added to nudge the model to preserve the local weather pattern in the northern coastal area.

Three buoy stations were located within the CALMET domain, but none of them is operating within the boundaries of the study area. After analyzing the observations from the buoy stations it was determined that only two of them provide data of sufficient quality for modelling. Initially, the North Hecate buoy (HECA) was considered along with Ketchikan and Mary Island buoys but, after performing quality control testing, it was concluded that HECA should be excluded from the final modelling. For more details about the quality control testing, see Appendix 2.2.8 in Volume 2 of this report.

Over-water observations were obtained from the National Data Buoy Center (NDBC)¹⁵ and processed using the BUOY utility.

¹² <http://envistaweb.env.gov.bc.ca/>

¹³ <ftp://ftp.ncdc.noaa.gov/pub/data/noaa/>

¹⁴ <http://www.esrl.noaa.gov/raobs/>

¹⁵ <http://www.ndbc.noaa.gov/>



CALMET Processing

The latest available version of CALMET (version 6.4 level 121203) was used in the final stage of the meteorological data processing. In this final stage, CALMET combines the geophysical data (MAKEGEO output), the surface and upper air observation stations, and WRF's meteorological fields together and computes the values of these variables for each domain grid cell and each hour. The modelling period – January to December 2012 – was split into 12 periods each corresponding to a calendar month. The domain time zone was set to Pacific (UTC-8). Detailed description of the key CALMET parameters requiring expert judgment are provided in Appendix 2.2 (CALMET Methodology) in Volume 2 of this report.

CALMET QA/QC and Validation

The Quality Assurance Quality Control (QA/QC) procedures for the CALMET processing were performed as specified in Sections 10.2.1 of the BC dispersion modelling guidelines (BC MOE 2008). Further details regarding the QA/QC procedures are provided in Appendix 2.2 (CALMET Methodology) in Volume 2 of this report.

The surface station meteorological data provided by MOE were used to perform a validation step of the CALMET model output and switch settings. Preliminary CALMET models settings of different CALMET control settings (options/switch settings) were analysed. Each sample was of 24-hour length, representing different seasons and different stability conditions. The final CALMET control input and wind field output was provided to MOE and was approved before completion of the meteorological processing. Additionally, the seasonal wind roses, and temperature profiles of the Roosevelt Park School Met_60 observation stations were compared to the wind and temperatures of the closest CALMET grid point.

Sampling Grid

MOE specified the study area within which modelling receptors should be placed. Additionally, individual points were included for locations of specific interest in order to evaluate impacts on lakes, soils, and vegetation, and finely-spaced receptors were included for residential and commercial/industrial areas of interest for potential human health impacts, detailed as follows:

- Receptors were set to 1 km x 1 km across the study area to improve the project timeline while maintaining the resolution needed for the vegetation, water, and soil assessments.
- Residential and commercial/industrial area receptor spacing used 100-metre spacing (as for the KAA). The human health receptors also included discrete locations of interest.
- Receptors were also added in the centre of each lake, as this was necessary for the eutrophication assessment.
- For vegetation studies, receptors on water were excluded.

Terrain elevations for receptors were determined from digital elevation models (DEMs). Fine resolution (20-metre) Canadian Digital Elevation Datasets were used for all receptors in the near-field (within 25 km from an emission source); medium resolution (100-metre) Canadian Digital Elevation Datasets were used for receptors in the far-field in BC; and 90-metre Shuttle Radar Topographic Mission (SRTM) data were used for Alaska.



Figure 2-2 shows the receptors within the study area. A detailed map of human health receptors is provided in Section 3 (Figure 3-3).

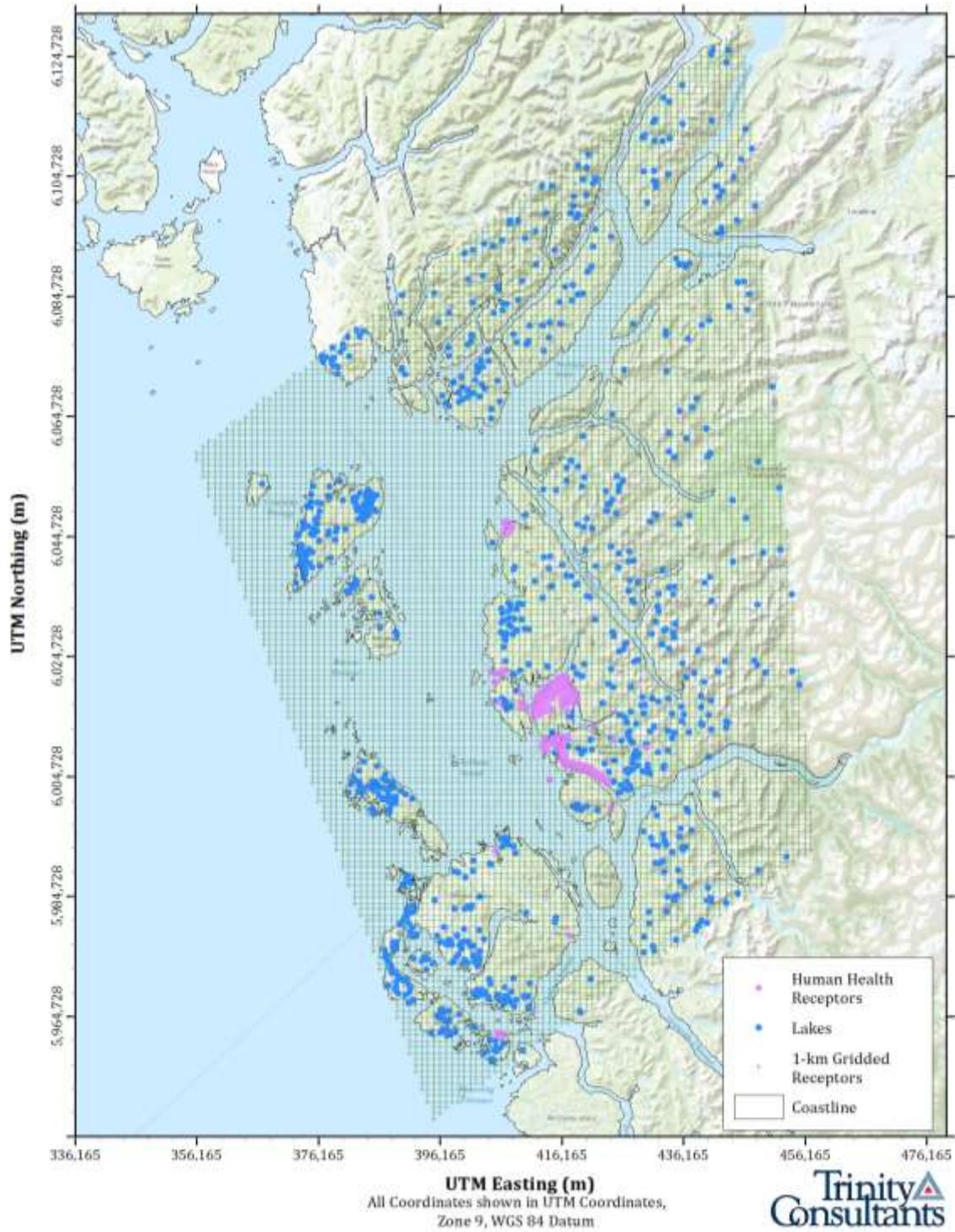


Figure 2-2: Modelled receptors within study area.

CALPUFF Dispersion Model

The CALPUFF model uses the output file from CALMET together with source, receptor, and chemical reaction information to predict hourly concentrations. A CALPUFF analysis was conducted using data and model settings as described below.

Modelled Emissions Sources

The modelling analysis included emissions of PM_{2.5}, SO₂, and NO_x.¹⁶ A summary of estimated emissions from each scenario modelled are described in Section 1.3. Locations, parameters, and emission rates for the LNG sources were provided by MOE based on communications with proponents regarding their preliminary design estimates in January 2015.¹⁷ A brief summary of the stationary sources modelled is presented in Section 2.1.4. We determined rail and marine transportation emissions and parameters, and these are further described in Section 2.1.5. Appendix 2.3 (Modelling Source Parameters) in Volume 2 of this report provides tabulated inputs for each source's modelling parameters and emission rates (including all LNG facilities, existing port facilities, new port facilities (Canpotex) or expansion projects (Fairview Phase II), future marine emissions, and future rail emissions).

Note that non-LNG pier activities including approach, maneuvering, and departing are included, but shipping emissions from the port to the study boundary are not included due to lack of readily available data. Also note that incremental increases in emissions due to the LNG facility (vehicle traffic, increased population) are not included in the scope of this study.

During review of the draft study report by MOE and the Prince Rupert Port Authority, SO₂ emission rates for the container ships and bulk carriers were found to be overly conservative, because they did not account for the recent decrease in bunker fuel sulphur content. Additionally, the SO₂ emission rates from some LNG facilities were found to likely be underestimated due to possible underestimation of sulphur content in the feed gas. [These items have been corrected in a new scenario that was developed subsequent to this study, the results of which are presented in the *Prince Rupert Airshed Study Supplementary Report*.]

Control Parameters

We applied the recommended CALPUFF control parameters presented in Table 9.7 of the *Guidelines for Air Quality Dispersion Modelling in British Columbia* (BC MOE 2008). Two switch settings were applied that do not directly follow the default guidelines: the sub-grid scale thermal internal boundary layers (SGTIBL) and chemical transformation scheme (MCHEM). Due to the proximity of the coast, the SGTIBL option is selected to refine the coastline. The use of the

¹⁶ For all RIVAD/ISORROPIA runs NO_x emissions were broken down into NO and NO₂. For the MESOPUFF II run total NO_x was used.

¹⁷ The BC Hydro facility included in this assessment is a possible future scenario in which four new 100 MW single cycle natural gas power turbines are installed at the existing BC Hydro facility in Prince Rupert. The 400 MW assumption was made solely for the purposes of the study itself and in no way suggests BC Hydro's plans or intentions under each of the scenarios.



SGTIBL option was approved for use by MOE.¹⁸ The chemical transformation scheme is further discussed in the Atmospheric Transformation and Transport section below.

Lastly, the CALPUFF switch setting for which a required or recommended setting was not provided was the “dispersion coefficients switch setting” (MDISP). The dispersion coefficients switch setting was set to MDISP 2, as recommended for near-field impacts by the *Guidelines for Air Quality Dispersion Modelling in British Columbia* (BC MOE 2008). Chemical transformation, wet removal, and dry deposition pollutant removal were modelled, as recommended in the BC air dispersion modelling guidelines. The mass of a pollutant in a given puff decreases as the puff travels through time and space. This decrease in mass is a result of that pollutant being chemically transformed, removed due to wet deposition, or removed due to dry deposition.

In addition to the CALPUFF control parameters presented in Table 9.7 of the BC guidelines, CALPUFF Version 6.42 includes several additional control parameters (not included in CALPUFF Version 5.8) that must be specified. These additional control parameters and the corresponding values used in this analysis are included in Appendix 2.1 (Modelling Protocol) in Volume 2 of this report.

Atmospheric Transformation and Transport

The chemical transformation scheme chosen for this analysis is RIVAD with ISORROPIA equilibrium, except for Scenario F_M. Scenario F_M used the default MESOPUFF II scheme, which was also the chemical transformation scheme used in the 2014 KAA modelling. NO₂ has been identified as a pollutant of interest for this study, so MOE has decided that the PRAS modelling should apply the RIVAD chemistry scheme to more accurately simulate the conversion of nitrogen oxide (NO) to nitrogen dioxide (NO₂). Since the majority of combustion NO_x is emitted as NO, while the pollutant impacting human health and vegetation is NO₂, it is important to simulate the conversion of NO to NO₂ as accurately as possible. When this study was designed, RIVAD was expected to be the most accurate option for modelling NO to NO₂ conversion.¹⁹

The RIVAD chemistry scheme requires in-stack NO₂/NO_x data. Additionally, since primary PM_{2.5} (directly emitted as PM_{2.5}) and secondary PM_{2.5} (that forms from NO_x and SO₂ emissions) are also of importance, transformation of NO_x to nitrates (secondary PM_{2.5}) and SO₂ to sulphates (secondary PM_{2.5}) was simulated. This can be accomplished either using the default chemical transformation scheme (MESOPUFF II), RIVAD, or the more recently incorporated scheme, ISORROPIA. Employing ISORROPIA was expected to lead to more accurate predictions of secondary PM_{2.5} and wet deposition results. These options are different from the

¹⁸ BC MOE, Dennis Fudge, approved the use of SGTIBL via email on February 19, 2015.

¹⁹ Other options for estimating NO₂ concentrations include modelling NO_x in CALPUFF (without the RIVAD chemistry), and computing NO₂ concentrations as a post-processing step outside of the CALPUFF system, based on either the ozone limiting method or the ambient ratio method. While it was believed RIVAD would provide the most accurate NO₂ concentrations, results from other studies indicate RIVAD may be overestimating NO₂. Further analysis is being conducted by MOE to determine which approach is the best to use to convert NO to NO₂. However, it is believed that the RIVAD option is the best available option in CALPUFF for secondary particulate matter as well as deposition. Regardless of which option is used, as long as it is consistently used for all cases one can still assess the change in the impacts of NO₂.



recommended chemistry options in the 2008 BC Modelling Guidelines, but were selected in consultation with and approved by MOE.²⁰

For the RIVAD with ISORROPIA equilibrium algorithm, the concentrations of NO, NO₂, SO₂, ammonium sulphate, ammonium nitrate, nitric acid, and PM_{2.5} were tracked. For the MESOPUFF II scheme, the concentrations of NO_x, SO₂, ammonium sulphate, ammonium nitrate, nitric acid, and PM_{2.5} were tracked.

The RIVAD chemical mechanism used in Scenarios A through F_R incorporates an update to the previous RIVAD for transformation of SO₂ and NO/NO₂ to sulphates and nitrates/nitrites, respectively. This option also replaces the MESOPUFF II CHEMEQ model with the ISORROPIA model for inorganic gas-particle equilibrium. There are several user-selected input parameters that affect the RIVAD with ISORROPIA equilibrium mechanism: ammonia, ozone, and hydrogen peroxide background concentrations and NO₂/NO_x in-stack ratios. A constant background ammonia concentration of 0.5 ppb was applied, based on the recommended background for a forested area per US EPA's Interagency Workgroup on Air Quality Modelling (IWAQM) Phase 2 Report (US EPA 1998). A monthly background ozone concentration was also applied based on monthly averages for the Prince Rupert area provided by MOE.²¹ Using site-specific ozone values allowed the CALPUFF model to simulate the chemical transformation rates based on the amount of available ozone. Higher ozone yields faster transformation rates. The summer monthly average background values selected by MOE were slightly higher than actual expected concentrations because MOE wanted to stay on the conservative side while still employing more accurate values than using the 80 ppb default value. A constant background hydrogen peroxide concentration was also applied, using the CALPUFF default of 1 ppb. All sources except turbines will assume 10% NO₂ in the stack (i.e., 0.1 in-stack ratio). Turbines use a 30% NO₂ assumption (i.e., 0.3 in-stack ratio), based on turbine manufacturer specifications for Dry Low NO_x (DLE) combustion technology.²²

Scenario F_M includes the same emission sources as Scenario F_R, but uses the MESOPUFF II chemistry option for a direct comparison to the KAA. The modelling of two identical emission scenarios under the two chemistry schemes also provides a direct comparison of the effects of the two chemistry options. There are two user-selected input parameters that affect the MESOPUFF II chemical transformation: ammonia and ozone background concentrations. As for the RIVAD with ISORROPIA models, a constant background ammonia concentration of 0.5 ppb was applied, based on the recommended background for a forested area per US EPA's Interagency Workgroup on Air Quality Modelling (IWAQM) Phase 2

²⁰ BC MOE, Dennis Fudge, approved via email on February 19, 2015 the use of RIVAD with ISORROPIA equilibrium for the chemical transformation scheme for all scenarios except Scenario 4, which will use MESOPUFF II.

²¹ BC MOE, Dennis Fudge, provided the monthly average ozone concentrations for the Prince Rupert area via e-mail on February 10, 2015 to Trinity. MOE provided monthly averages rather than hourly values because we observed that, in the upper atmosphere, there is little diurnal change in the ozone pattern, especially when there is good mixing.

²² Turbines are assigned an NO₂/NO_x in-stack-ratio of 30% based on data from Solar Turbine vendor for DLE technology (SoLoNO_x).



Report (US EPA 1998). A constant background ozone concentration was also applied, using the CALPUFF default of 80 ppb, which is consistent with the approach used in the KAA.

The high ozone concentration used for Scenario F_M of 80 ppb is the recommended CALPUFF default, as a conservative assumption to avoid the situation where limited ozone results in a slower reaction rate of SO₂ to SO₄ or NO_x to NO₃. This assumption results in potentially higher reaction rates and total sulphur deposition rates than would occur when using site-specific ozone data; thus, the assumption is conservative when considering total sulphur deposition rates, but it could be less conservative when considering SO₂ air concentrations. Based on a sensitivity study performed as part of the KMP SO₂ Technical Assessment (ESSA et al. 2013a,b), CALPUFF SO₂ air concentrations were not noticeably affected when a site-specific regional ozone background concentration was used. Specifically, 0% change in SO₂ concentrations and 2% to 5% change in SO₄ concentrations were detected between the study results (site-specific ozone) and the original CALPUFF results (default 80 ppb ozone). Similar differences would be expected for the Prince Rupert airshed if the same study were conducted for the current Prince Rupert modelling, because the local ozone levels are similar. However, the differences could be more or less significant due to differences in the emissions levels and if the study were conducted on the scenarios using the different chemistry scheme, RIVAD with ISORROPIA.

Deposition Analysis

Gas-phase dry deposition fluxes were modelled for SO₂, NO_x, and HNO₃. Particulate-phase dry deposition was modelled for SO₄, NO₃, and PM_{2.5}. Wet deposition was modelled for all pollutants, using the liquid and frozen precipitation scavenging coefficients in the CALPUFF modelling system chemical species library. For dry deposition of gases, the dry deposition resistance model handles land use in multiple equations. The atmospheric resistance equation includes surface roughness based on predominant land use in grid cell (1 km spaced grid cells for regional domain). The canopy resistance equation also considers land use by including the leaf area index in each grid cell. In this way, and by using spatially varying precipitation in CALMET, the CALPUFF model accounts for variations from location to location within the domain when predicting deposition flux, aside from the deposition variation due to distribution of modelled concentrations. The sum of wet and dry deposition fluxes for SO₂ and SO₄ represent the total sulphur deposition as follows:

$$\text{Sulfur Deposition (kg/ha/yr)} = (\text{flux}_{\text{SO}_2} + \text{flux}_{\text{SO}_4})_{\text{wet}} + (\text{flux}_{\text{SO}_2} + \text{flux}_{\text{SO}_4})_{\text{dry}}$$

Similarly, total nitrogen deposition is the sum of wet and dry deposition fluxes for NO_x (or NO and NO₂), NO₃, and HNO₃. Additionally, deposition of nitrate and sulphate was assumed to be in the form of ammonium nitrate (NH₃NO₃) and ammonium sulphate ((NH₃)₂SO₄), resulting in a small fraction of additional nitrogen being deposited from these secondary pollutants.

QA Procedures

The QA/QC procedures for the CALPUFF processing were performed as specified in Section 10.2.1 of the *Guidelines for Air Quality Dispersion Modelling in British Columbia* (BC MOE



2008). A QA/QC log documenting checks for each scenario's modelling input and results files can be found in Appendix 2.4 (Modelling QA/QC Log) in Volume 2 of this report.

2.1.4 Stationary Source Data

Stationary source stack parameters and emissions of SO₂, NO_x, and PM_{2.5} were provided by the proponents, or a proxy source was determined from a similar facility. The details regarding which proponents provided data and which emission sources used a proxy are provided in Appendix 2.3 (Modelling Source Parameters) of Volume 2 of this report. In summary, Pacific NorthWest LNG was used as a proxy for all or some sources at several facilities, because Pacific NorthWest LNG was the proponent farthest along in the environmental permitting process. Aurora LNG used Pacific NorthWest LNG as a proxy for its entire facility. Watson Island LNG used Triton (an LNG facility modelled in the KAA) as a proxy (assuming the same capacity as Triton, i.e., 2 mtpa). The following proponents provided emissions data that were used directly:

- Pacific NorthWest LNG
- Prince Rupert LNG
- Grassy Point LNG
 - Used Pacific NorthWest as proxy only for thermal oxidizers, because thermal oxidizer emissions were out of the expected range
- WCC LNG
 - Used Pacific NorthWest as proxy only for thermal oxidizers, because thermal oxidizers emissions were absent from the inventory provided by WCC

While this study did not develop the stationary source emission rates or parameters, the emission levels and parameters were reviewed to verify each parameter fell within the expected range based on similar sources. The following stationary sources were modelled:²³

- Grassy Point LNG
- Pacific NorthWest LNG
- WCC LNG
- Prince Rupert LNG
- Aurora LNG
- Watson Island LNG
- BC Hydro
- Canpotex
- Ridley Island Coal
- Prince Rupert Grain
- Fairview

²³ The list of sources was developed in consultation with the Ministry. J.S. McMillan Fisheries and ICEC Sulphur Terminals are not included due to the low emissions compared to other facilities.



This list of stationary sources, along with the transportation sources discussed in the following section, is intended to capture all existing and potential future industrial sources within the Prince Rupert airshed. Emissions from other small regional sources (e.g., residential woodstoves, road emissions, etc.) are addressed through the inclusion of background concentrations based on representative monitoring data, as discussed in Section 2.2.1.

The BC Hydro facility included in this assessment is a possible future scenario in which four new 100 MW single cycle natural gas power turbines are installed at the existing BC Hydro facility in Prince Rupert. The 400 MW assumption was made solely for the purposes of the study itself and it in no way suggests BC Hydro's plans or intentions under each of the scenarios.

2.1.5 Emission Calculation Methodology for Transportation Sources

SO₂, NO_x, and PM_{2.5} emissions from each transportation source (marine vessels and rail locomotives) were calculated as part of this assessment study. NO and NO₂ emission rates were converted from NO_x emission rates, assuming 10% of NO_x by volume is NO₂. For the six LNG facilities, emissions from marine vessels (i.e., LNG carriers and tugboats) were calculated for shipping travel within the study area and for activity at the piers. The calculation methodology for marine vessels was consistent with the methods used in the KAA. The same marine vessel emission factors used in the KAA were applied in this study for the closest related vessel type.

Emissions from the locomotives travelling within the study area were calculated for Fairview and Canpotex, which are the only two facilities identified by MOE as having significant rail traffic. The sections below detail the emissions calculations for the marine vessels and locomotives. Appendix 2.5.1 (Marine and Rail Emissions Calculations) in Volume 2 of this report presents the detailed calculations.

Emissions from marine vessel pier activity at Fairview (Phase I and Phase II), Canpotex, Ridley Island Coal, Northland, BC Ferries and Alaska Ferries were included in the modelling analysis. Emissions and parameters were based on data used in recent modelling analyses performed for these facilities (Stantec 2009a,b; Stantec 2011).²⁴ Shipping emissions from the piers to the boundary of the study area were not included for these facilities due to a lack of readily available shipping data. The inclusion of these non-LNG shipping emissions would increase results slightly, most noticeably in the lower concentration areas near the shipping routes to the west of the ports. However, the inclusion of these emissions would likely not affect conclusions for end receptor impacts. Emissions from locomotives at the rail yard for Fairview and Canpotex were included in the modelling analysis.

²⁴ The annual average emission rates for the marine emissions from terminals were obtained from *Canpotex Potash Export Terminal and Ridley Island Road, Rail and Utility Corridor - Air Quality Technical Data Report* (Stantec 2011) (Canpotex AQTDR) and *Fairview Terminal Phase II Expansion Project - Terminal Air Quality Technical Data Report* (Stantec 2009a,b) (Fairview AQTDR).



LNG Facility Marine Shipping Emission Calculation Description

For each LNG facility the marine transportation emissions were calculated for LNG carriers and tugboats, based on the LNG carriers and tugboat main engine output rating, facility capacity, travel speed, travel distance and number of LNG carriers demanded per year. The vessel main engine output ratings for all LNG carriers and tugboats were based on the ratings specified in the *Pacific NorthWest LNG Air Quality Technical Data Report* (Stantec 2014), with the exception of the Aurora LNG facility (Aurora LNG 2015).²⁵ Information about the facility capacity, LNG carrier capacity, and number of LNG carriers per year for each facility was obtained from respective project descriptions (AECOM 2013; Woodside 2014; Aurora LNG 2015; WCC LNG 2015).²⁶ For Watson Island LNG, the LNG main engine output rating, facility capacity, and LNG carrier capacity were assumed to be the same as those for the Triton LNG facility included in the KAA. It is assumed that two tugboats will accompany each LNG carrier following the shipping route from Chatham Sound. For the shipping route to Grassy Point, zero tugboats were assumed to accompany Grassy Point LNG carriers due to the open waters of the shipping route.

The shipping routes are shown in Figure 1-3. The distance of each route segment was determined using ArcGIS and the travel time for each LNG carrier was determined based on the distance and travel speed. The travel speed was assumed to be 16 knots and reduced to six knots in Chatham Sound.

LNG Facilities Pier Activity Emission Calculation Description

For each LNG facility, the emissions were calculated for LNG carriers and tugboats, except for Pacific NorthWest LNG for which the emission rates were provided by the proponent. Emissions from each LNG carrier were calculated based on the main engine during maneuvering at the pier. Additionally, emissions from a boiler hoteling at the pier plus emissions from auxiliary engines used for unloading LNG were included. Emissions from the tugboats were calculated during maneuvering, assuming two tugboats would accompany each LNG carrier.

Emissions were calculated for the five LNG facilities (i.e., all but Pacific NorthWest LNG) based on engine operating parameters which represent an average LNG carrier of the capacity stated in the *Pacific NorthWest LNG Air Quality Technical Data Report* (Stantec 2014). These parameters included LNG carrier main engine output rating, auxiliary engine output rating, number of hours during maneuvering of each LNG carrier, and tugboat main engine output rating. The number of LNG carriers for each facility annually was calculated based on the production capacity and the average carrier capacity of the facility. The LNG loading rate stated in *Prince Rupert LNG Project Description* (AECOM 2013) was assumed to be representative of

²⁵ The capacity of the LNG carrier stated in *Aurora LNG Project Description* (Aurora LNG 2015) is greater than the capacity stated in *Pacific NorthWest LNG Air Quality Technical Data Report*. Therefore, the output rating capacity of the LNG carrier for Aurora LNG was scaled up based on the carrier capacity.

²⁶ Including *WCC LNG Project Description: Executive Summary* (WCC LNG 2015), *Grassy Point LNG Project Description* (Woodside 2014), *Prince Rupert LNG Project Description* (AECOM 2013), *Aurora LNG Project Description* (Aurora LNG 2015).



all LNG carriers. Duration of time spent hoteling was assumed to be two hours for pre-loading plus the duration of unloading.

Locomotive Emission Calculation Description

Two terminals within the study area have available information to estimate locomotive emissions: Fairview and Canpotex. The number of trains needed per year for the two terminals was obtained from air quality technical data reports associated with two recent permitting efforts (Stantec 2009b, 2011). The total number of trains expected to travel within the study area under the future scenarios was estimated as the sum of the numbers of trains for the two terminals plus 20% to account for possible rail traffic from other facilities within the study area. It was assumed that two locomotives will be required for each train. The locomotive estimates and assumptions were developed in consultation with MOE.

The emissions from locomotives were calculated based on the estimated speed and notch setting (engine load) for each rail segment within the study area. The speed and notch setting are different for incoming versus outgoing rail traffic. The travel speed was then used to determine the time of the locomotive on the rail segment, and the notch setting was used to determine the emission factors of each segment. The notch setting, travel speed, and emission factors were determined in consultation with MOE. The rail segments within the study area were determined following the Canadian National Railway Network from ArcGIS Online and the lengths were determined using ArcGIS to calculate the distance along the railway path of each segment.

2.1.6 Modelling Parameters for Transportation Sources

The emissions of marine vessels for pier activities and shipping were modelled as point sources. The emissions from locomotives travelling along the railway were modelled as line sources. The emissions from the rail yards were modelled as area sources. The following sections present how the modelling parameters of the sources were determined for each source type.

LNG Facility Marine Shipping Model Parameters

The annual average emissions from LNG vessels from each facility (calculated as described in Section 2.1.5) were combined along each shipping route segment for each modelling scenario. The annual emissions from each LNG facility were adjusted based on the travel time on the segment compared to the total travel time along that facility's route within the study area. The annual emissions of each segment were then evenly distributed among the number of point sources representing that shipping route segment.

A total of 33 marine shipping point sources were modelled for the "full build" LNG facilities. The number of point sources representing each shipping route segment was determined by the length of the segment. These sources were spaced two nautical miles apart (4 km), which was the spacing used in the KAA, and less than 4 km when the route was closer to the facilities to take consideration of slower travel speed. The elevations of all sources were assumed to be at



sea level (i.e., zero elevation). The stack parameters were consistent with those used to model the LNG carriers at the piers (see next subsection).

LNG Facility Pier Activity Model Parameters

Pacific NorthWest LNG provided the location of vessels, stack height, stack diameter, exhaust temperature and velocity for LNG carriers and tugboats, and was assumed to have two LNG carriers and two tugboats for each LNG carrier at the pier. This information about stack height, stack diameter, exhaust temperature and velocity for LNG carriers and tugboats was used for the other five LNG facilities as well. The calculated emission rates for each type of vessel were evenly distributed based on the number of sources for each facility. Two LNG carriers and four tugboats were assumed to be at the pier for each LNG facility. However, for Watson Island LNG, only one LNG carrier and two tugboats were assumed to be at the pier due to the small facility capacity compared to other LNG facilities. The locations of the marine vessels were estimated based on the project descriptions²⁶ and aerial imagery of proposed locations. All marine vessels were assumed to be at sea level.

Terminals Pier Activity Model Parameters

The Canpotex AQTDR and Fairview AQTDR discussed in Section 2.1.5 also provided the modelling parameters for Fairview Phase II marine-based emissions and Canpotex marine-based emissions. However, the modelling parameters for the other modelled terminals were not provided in the reports. Therefore, one vessel for each vessel type presented in these two reports was assumed to be representative for the marine pier activities at the remaining terminals (Fairview Phase I, Ridley Island Coal, Prince Rupert Grain, Northland, BC Ferries and Alaska Ferries).

- The stack parameters (i.e., stack height, stack diameter, temperature and exit velocity) for Fairview Phase I were assumed to be the same as Fairview Phase II.
- The stack parameters of bulk carriers for Ridley Island Coal, Prince Rupert Grain, and Northland sources were assumed to be the same as Canpotex bulk carriers.
- The stack parameters of tugboats for these three facilities were assumed to be the same as Fairview tugboats to be conservative.
- The stack parameters of ferries for BC and Alaska Ferries were assumed to be the same as LNG carriers.

The locations of the sources at these terminals were estimated based on the approximate locations provided by MOE.

Rail Yard Model Parameters

Canpotex rail yard emissions and modelling parameters were directly available from Canpotex AQTDR (Stantec 2011). The elevation was adjusted to 15 m based on a recommendation from MOE.²⁷ The area of the source was determined based on the vertices rather than the directly provided value. Fairview Phase II rail yard emissions were directly available from Fairview AQTDR. Fairview Phase I emissions were scaled based on the rail traffic (trains/year), which is

²⁷ Communication with Dennis Fudge on 2/19/2015.



expected to be 1,095 trains/year for Phase I and 3,285 trains/year for Phase II. The vertices for Fairview Phase II rail yard were converted using the southwest corner location, area, and width, provided in the Fairview AQTDR (Stantec 2009a). It was assumed that the Phase I rail yard was immediately north of the Phase II rail yard according to the facility design. The sources were divided to near-square shape as modelled objects. The initial sigma Z for the rail area source was assumed to be the same as the Canpotex rail yard source.

Locomotive along Railway Model Parameters

Locomotive emissions along the railway were modelled as line sources. The CALPUFF input parameters for line sources were based on those used in a previous study conducted by MOE for the Prince George area.²⁸ The average building length (XL) was set to be 2,300 m based on the line segment lengths for the rail line sources. Other parameters were set to CALPUFF defaults. The elevations of rail line segments were determined using the US EPA terrain processor, AERMAP, at the start point of each segment. If the difference of the elevations of adjacent rail segments determined by AERMAP were more than 5 metres, the average elevation from the adjacent segments was used. The release height was set to be consistent with rail yard modelled release height from the Canpotex AQTDR (Stantec 2011).

2.2 Results

This section presents modelling results for SO₂, NO₂, PM_{2.5} concentrations, and for sulphur (as sulphate) and nitrogen deposition for the two bookend scenarios: Scenario A (lowest emissions) and Scenario F_R (highest emissions using the RIVAD chemistry option). Each scenario is described in Section 1.3. Modelling results for the intermediate scenarios are provided in Appendix 2.6 (Concentration and Deposition Maps for Scenarios B to F_M) in Volume 2 of this report.

2.2.1 Modelling Background Concentrations based on Monitoring Data

For comparison of maximum air concentrations to established thresholds, standard procedure (and that applied for the KAA (ESSA et al. 2014) and KMP SO₂ Technical Assessment (ESSA et al. 2013a,b)) is to add a modelling background concentration to modelled air concentrations to predict the total maximum air concentrations after the new/modified sources begin operation (i.e., total air concentrations = modelled concentrations due to new and existing emissions sources plus background concentration from non-modelled emissions). The concentration results presented in this report apply a modelling background concentration for each pollutant and averaging period as detailed in the following list:

- NO₂ 1-hour averaging period: 13.0 ppb (24.44 µg/m³)
- NO₂ Annual averaging period: 3.0 ppb (5.64 µg/m³)
- SO₂ 1-hour and 3-hour averaging periods: 4.0 ppb (10.7 µg/m³)
- SO₂ Annual averaging period: 1.5 ppb (4.0 µg/m³)
- PM_{2.5} 24-hour averaging period: 7.0 µg/m³

²⁸ Communication with Dennis Fudge on 2/12/2015. Parameters provided included HBL, WBL, WML, DXL and FPRIMEL.



- PM_{2.5} Annual averaging period: 3.5 µg/m³

MOE provided the background concentrations used in this study, and they are based on available monitor data collected from several monitoring stations in the area, generally applying the upper bound of concentrations from a nearby representative community. Each data source is summarized below:

- NO₂ 1-hour background value based on 98th percentile of hourly data from Kitimat, with consideration also given to data collected from the Mobile Air Monitoring Laboratory (MAML)²⁹ while employed in Prince Rupert, and from stations in Smithers and Georgia Strait;
- NO₂ annual background value based on annual average data from Kitimat Rail station;
- SO₂ 1-hour background value based on 98th percentile of hourly data from the Georgia Strait monitor and the Kitamaat Village monitor;
- SO₂ annual background value based on annual average data from the Kitamaat Village monitor;
- PM_{2.5} 24-hour background value based on 98th percentile of daily monitor data from the Kitimat and Terrace residential area monitors, with consideration also given to data collected from the MAML while employed in Prince Rupert; and
- PM_{2.5} annual background value based on Kitimat and Terrace residential area monitors.

Use of monitoring data from nearby communities to establish the background concentration for the Prince Rupert airshed is not ideal. However, nearby monitoring data provide a better value than the alternative of modelling all existing sources in the community. Both Terrace and Kitimat are in the same climatic zone as Prince Rupert and in a confined valley that will help trap pollutants, which indicates that concentrations at those locations would be slightly higher than those in Prince Rupert. The concentrations collected at the Georgia Strait monitor were also considered, because the location represents emissions from shipping sources in a coastal community. This monitor is not in a confined airshed, but measured somewhat higher values of SO₂ and PM_{2.5} (likely due to shipping emissions). Both the higher shipping emissions and non-confined airshed more closely align with conditions in Prince Rupert.

A constant modelling background value was applied to all locations. While applying the same background concentration for all locations is the most common approach used in modelling analyses, the approach could result in overly-conservative predictions of NO₂ in more remote, low traffic areas. This conservatism applies primarily for NO₂ rather than SO₂, because the NO₂ modelling background is intended to also capture background concentrations from non-modelled regional sources (e.g., road transportation emissions). One option to provide more accurate (less conservative) total predicted NO₂ concentrations would be to apply spatially varying modelling background NO₂ concentrations based on a land use regression model.

²⁹ The MAML monitoring station was a temporary monitoring station and only operated in summer and fall (April 14, 2013 to August 15, 2013). Therefore, the data collected at the MAML station were only used to inform the decision for the short-term background concentrations (i.e., 1-hr and 24-hr background) by verifying that the more complete datasets from nearby communities were in agreement with the data collected at the MAML while in Prince Rupert.



Additionally, the modelling analysis included the emissions from existing non-LNG port facilities (including rail and pier activities) which contribute to the monitored concentrations measured in Prince Rupert. This approach may have resulted in a slight high bias on the background concentrations for NO₂ 1-hour and PM_{2.5} 24-hour, which used the Prince Rupert MAML as part of the basis.

NO₂ / NO_x Ambient Ratio

For all scenarios except Scenario F_M, the conversion of NO to NO₂ was evaluated in CALPUFF using the RIVAD chemistry option. Applying the RIVAD chemistry option resulted in varying NO₂ / NO_x ambient ratios depending on the particular conditions such as the total NO_x concentration, the background ozone concentration, and the proximity to the emission source. For Scenario F_M, the MESOPUFF II chemistry scheme did not include any method to predict NO₂ directly. NO_x emission rates were modelled as NO_x and an ambient NO₂ / NO_x ratio of 80% for the 1-hour averaging period was applied to all of the NO_x model output, regardless of the NO_x concentration, ozone concentration, or distance/time from the source.³⁰ In other words, the Scenario F_M assessment assumed that 80% of predicted 1-hour concentrations of NO_x would be in the form of NO₂ by the time the plume reached ground level. This assumption is sometimes considered overly conservative for concentrations near the emissions source but, for most locations, the ratio appropriately represents the highest expected NO₂ percentage, accounting for the daily and annual variation in NO₂ / NO_x ambient equilibrium. For the annual averaging period, the maximum NO_x concentration was scaled to assume that 75% of NO_x would be in the form of NO₂ based on US EPA's national default value.³¹

2.2.2 Modelled NO₂ Concentrations

Figure 2-3 and Figure 2-4 show the 98th percentile of the daily peak 1-hour NO₂ concentrations (8th highest daily peak at each location) for Scenario A and Scenario F_R, respectively. Between Scenario A and Scenario F_R, there is a slight increase in the maximum NO₂ value and a noticeable increase in the area encompassed within the lowest concentration contour (100 µg/m³).

Figure 2-5 and Figure 2-6 show the annual NO₂ concentrations for Scenario A and Scenario F_R, respectively. A similar relationship can be seen showing a small increase in the maximum concentration and a more noticeable increase in the extent of concentrations reaching the lowest concentration contour.

All four NO₂ concentration plots show highest concentrations near the Fairview Container Terminal. These high concentrations are likely over-predicted by CALPUFF due to the use of area sources to represent mobile diesel activities (rail yard, bomb cart trucks, reach stackers, and top lifts). Each activity was represented by a single area source, conservatively not

³⁰ Per US EPA guidance (March 1, 2011 memorandum from Tyler Fox), an ambient NO₂ / NO_x ratio of 80% can be assumed as the default value for the 1-hour averaging period.

³¹ US EPA's prescribed method for modelling NO_x emissions can be found in Section 6.2.3 of the *Guideline on Air Quality Models* (GAQM). The GAQM is codified as Appendix W to 40 CFR Part 51.



representing the buoyancy from the engines, following the methods in the Fairview Container Terminal's submitted modelling analysis used as the input for this study. NO_x emissions from the Fairview Terminal's marine vessels may also be overestimated due to conservative assumptions applied in the Fairview air dispersion modelling analysis for engine loads during various activities. Additionally, results were not excluded for locations within each facility's property, which resulted in particularly high concentrations at locations very near the emission sources themselves. These results would normally be excluded as is done for air dispersion modelling analyses conducted by proponents as part of the Environmental Assessment process.



Prince Rupert Airshed Study
98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario A

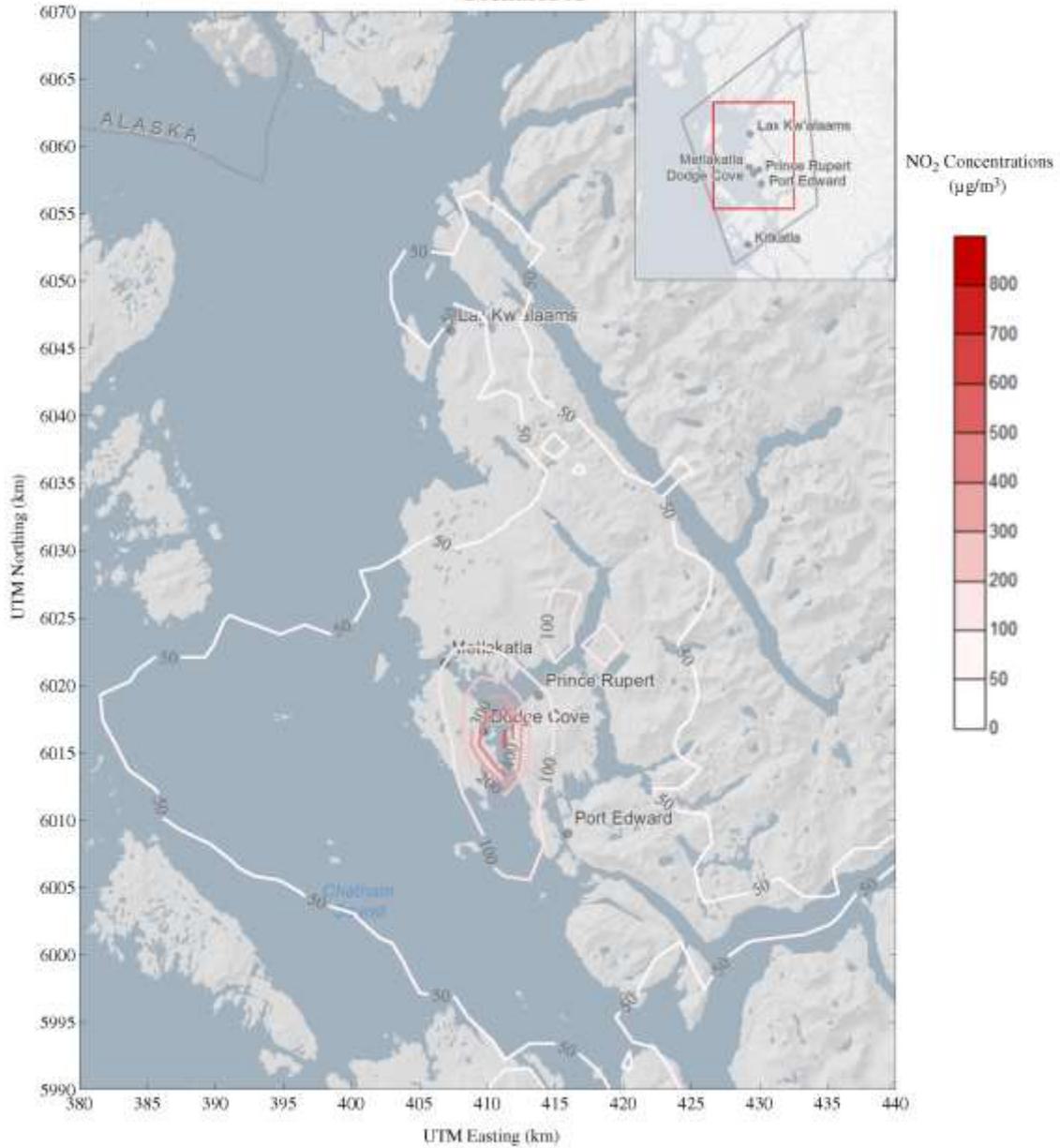


Figure 2-3: Scenario A, 98th percentile NO₂ concentrations, 1-hour average. The modelled NO₂ concentrations include a background concentration of 24 µg/m³, as discussed in Section 2.1.1.



Prince Rupert Airshed Study
98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario F_R

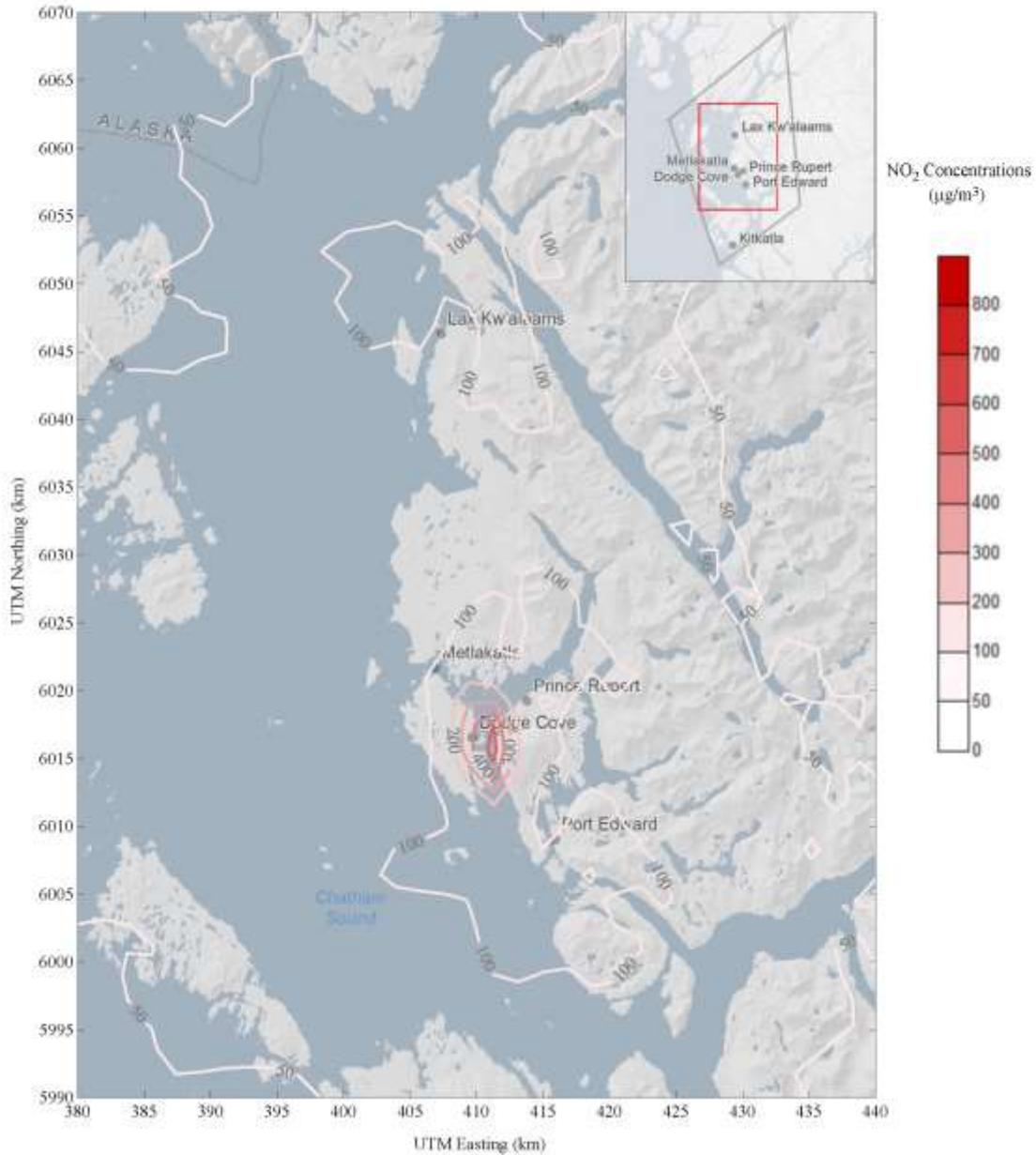


Figure 2-4: Scenario F_R, 98th percentile NO₂ concentration, 1-hour average. The modelled NO₂ concentrations include a background concentration of 24 µg/m³, as discussed in Section 2.1.1.



**Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario A**

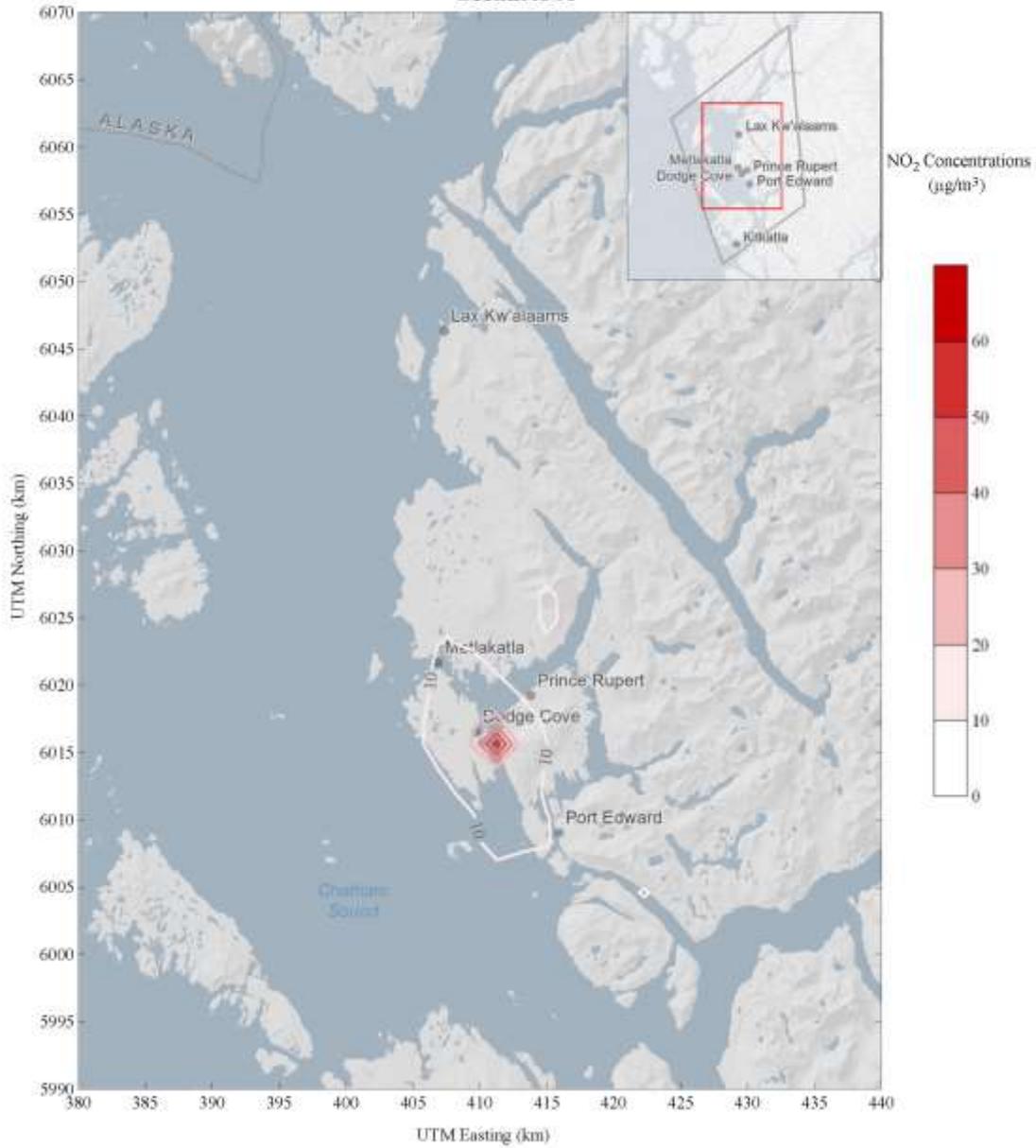


Figure 2-5: Scenario A, NO₂ concentrations, annual average. The modelled NO₂ concentrations include a background concentration of 5.6 µg/m³, as discussed in Section 2.1.1.

**Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario F_R**

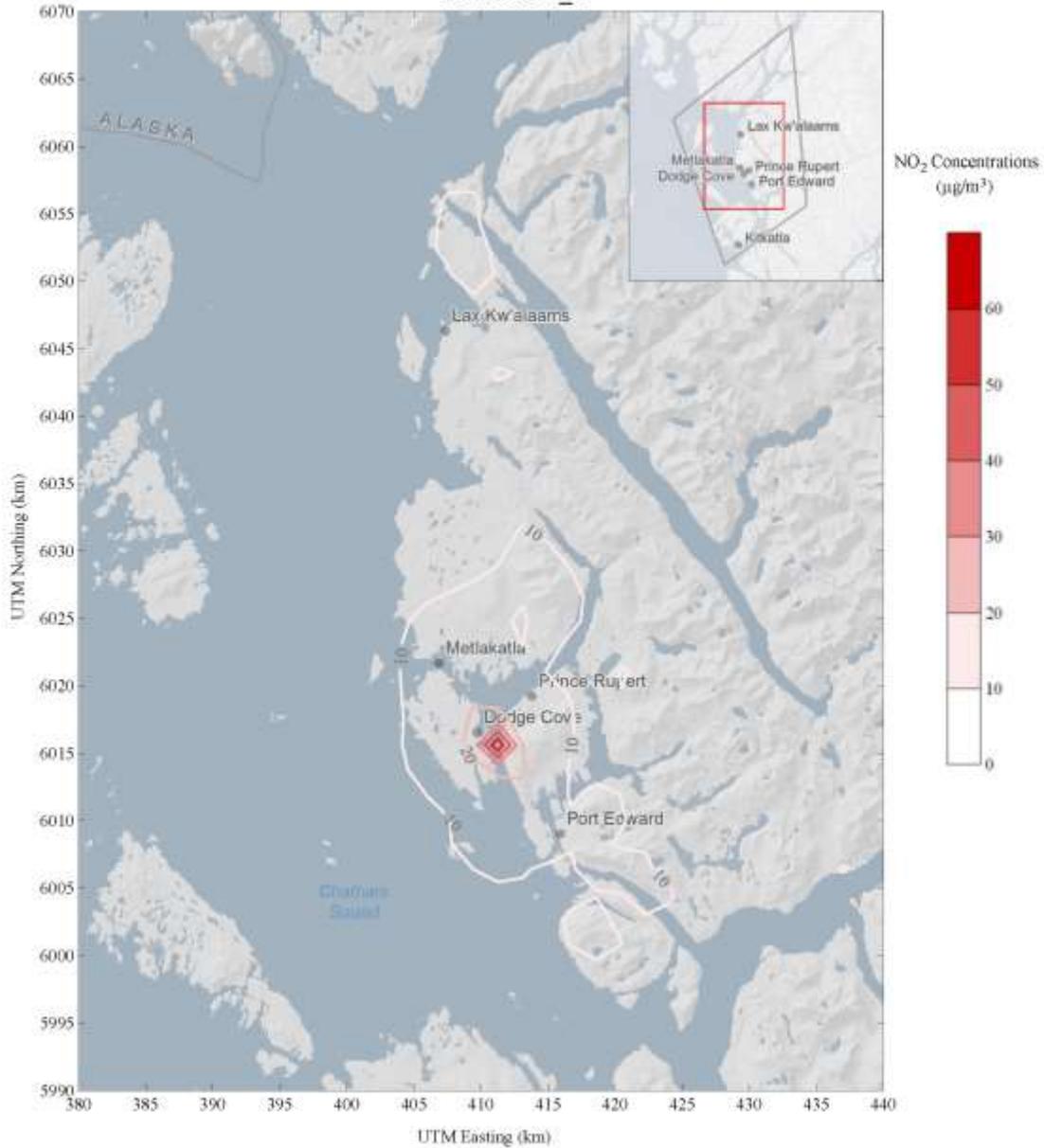


Figure 2-6: Scenario F_R, NO₂ concentration, annual average. The modelled NO₂ concentrations include a background concentration of 5.6 µg/m³, as discussed in Section 2.1.1.

2.2.3 Modelled SO₂ Concentrations

Figure 2-7 and Figure 2-8 show the 99th percentile daily peak 1-hour SO₂ concentration (4th highest daily peak at each location) for Scenario A and Scenario F_R, respectively. The SO₂ concentrations and distribution are different than for NO₂, both because the exhaust emission composition was different (level of NO_x compared to level of SO₂ in a given stack and level of NO_x versus level of SO₂ at each facility), and also because the majority of SO₂ emissions came from fewer sources. Between Scenario A and Scenario F_R, the increase in the maximum SO₂ value as well as the increase in the extent of modelled concentrations are extremely small, and result in no noticeable differences between the two figures. This similarity was expected due to the similar levels of SO₂ emissions between the two scenarios (7.5 t/d versus 7.8 t/d).

Figure 2-9 and Figure 2-10 show the annual SO₂ concentrations for Scenario A and Scenario F_R, respectively. A similar relationship can be seen showing extremely small changes in the maximum concentration and in the extent of concentrations reaching the lowest concentration contour.



Prince Rupert Airshed Study
99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario A

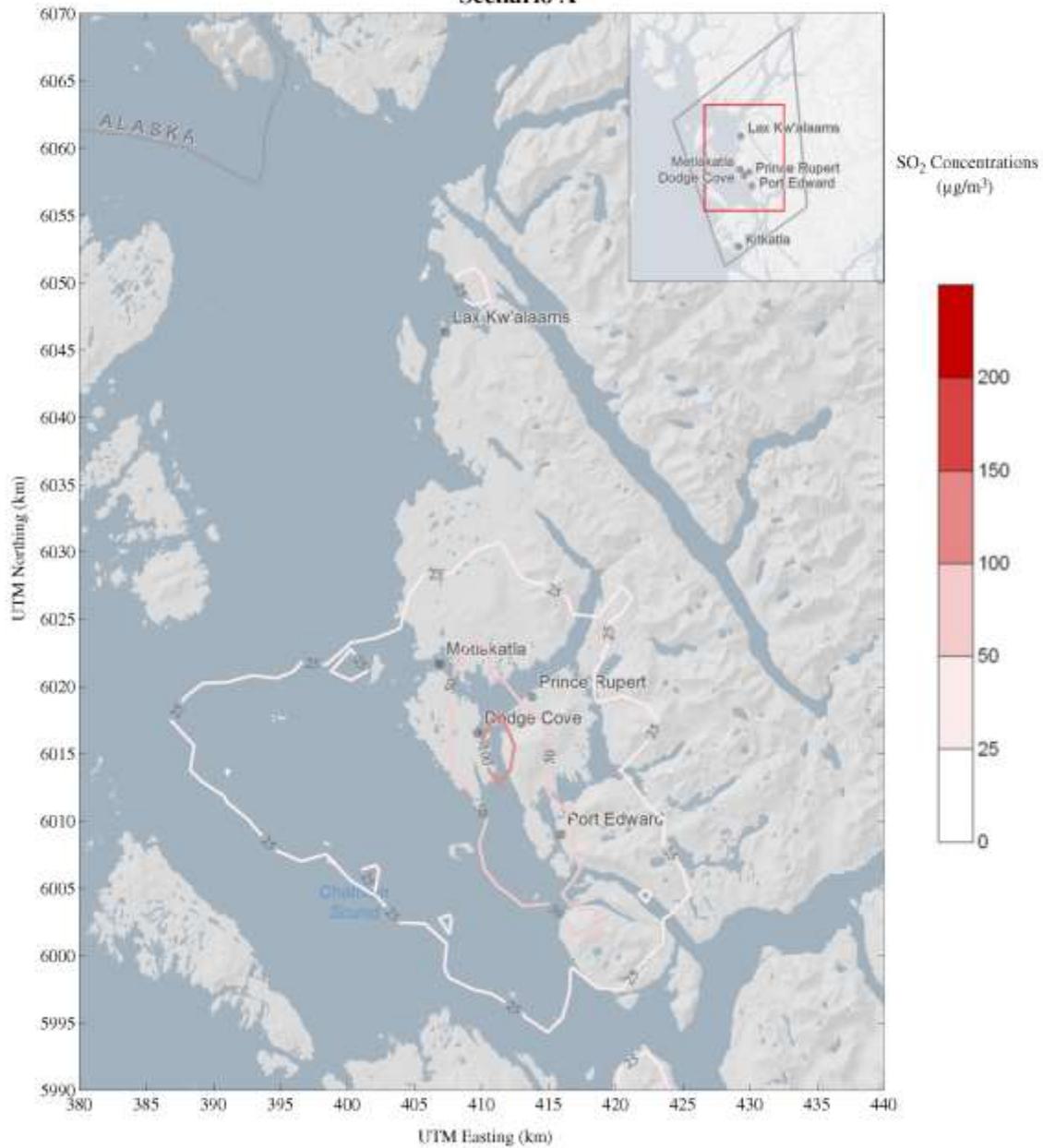


Figure 2-7: Scenario A, 99th percentile SO₂ concentration, 1-hour average. The modelled SO₂ concentrations include a background concentration of 11 µg/m³, as discussed in Section 2.1.1.

**Prince Rupert Airshed Study
99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario F_R**

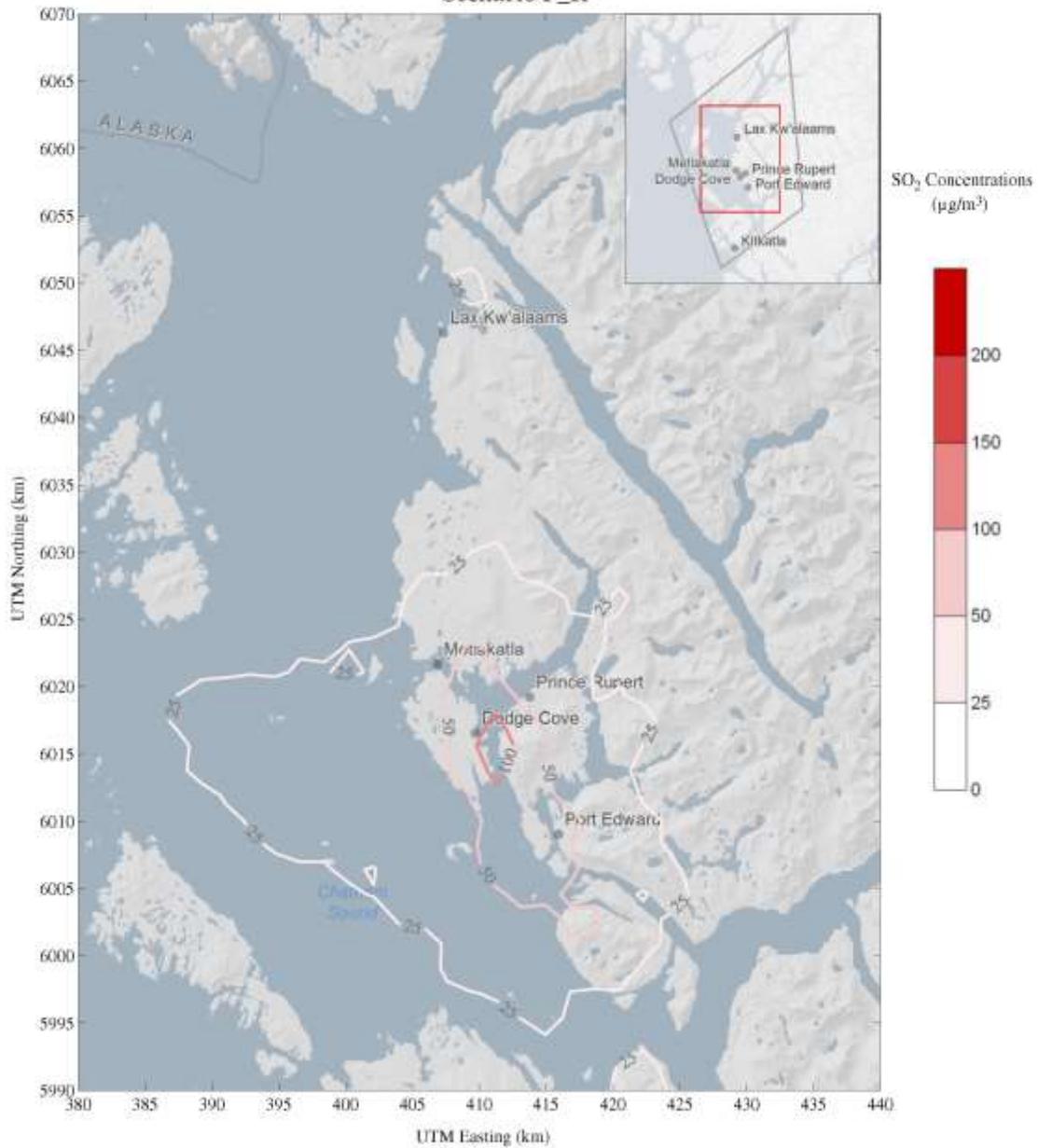


Figure 2-8: Scenario F_R, 99th percentile SO₂ concentrations, 1-hour average. The modelled SO₂ concentrations include a background concentration of 11 µg/m³, as discussed in Section 2.1.1.

**Prince Rupert Airshed Study
SO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario A**

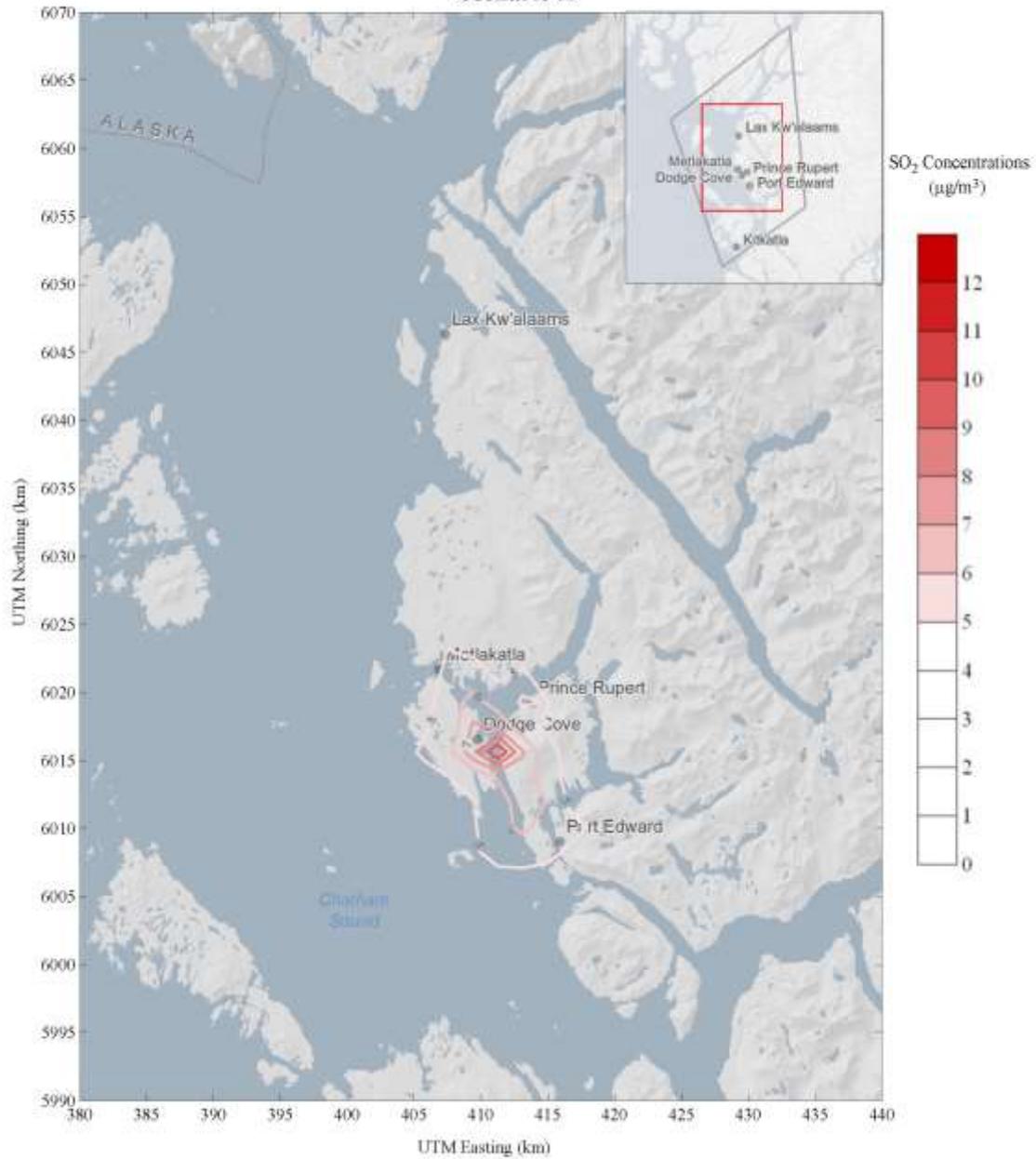


Figure 2-9: Scenario A, SO₂ concentration, annual average. The modelled SO₂ concentrations include a background concentration of 4 µg/m³, as discussed in Section 2.1.1.

**Prince Rupert Airshed Study
SO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario F_R**

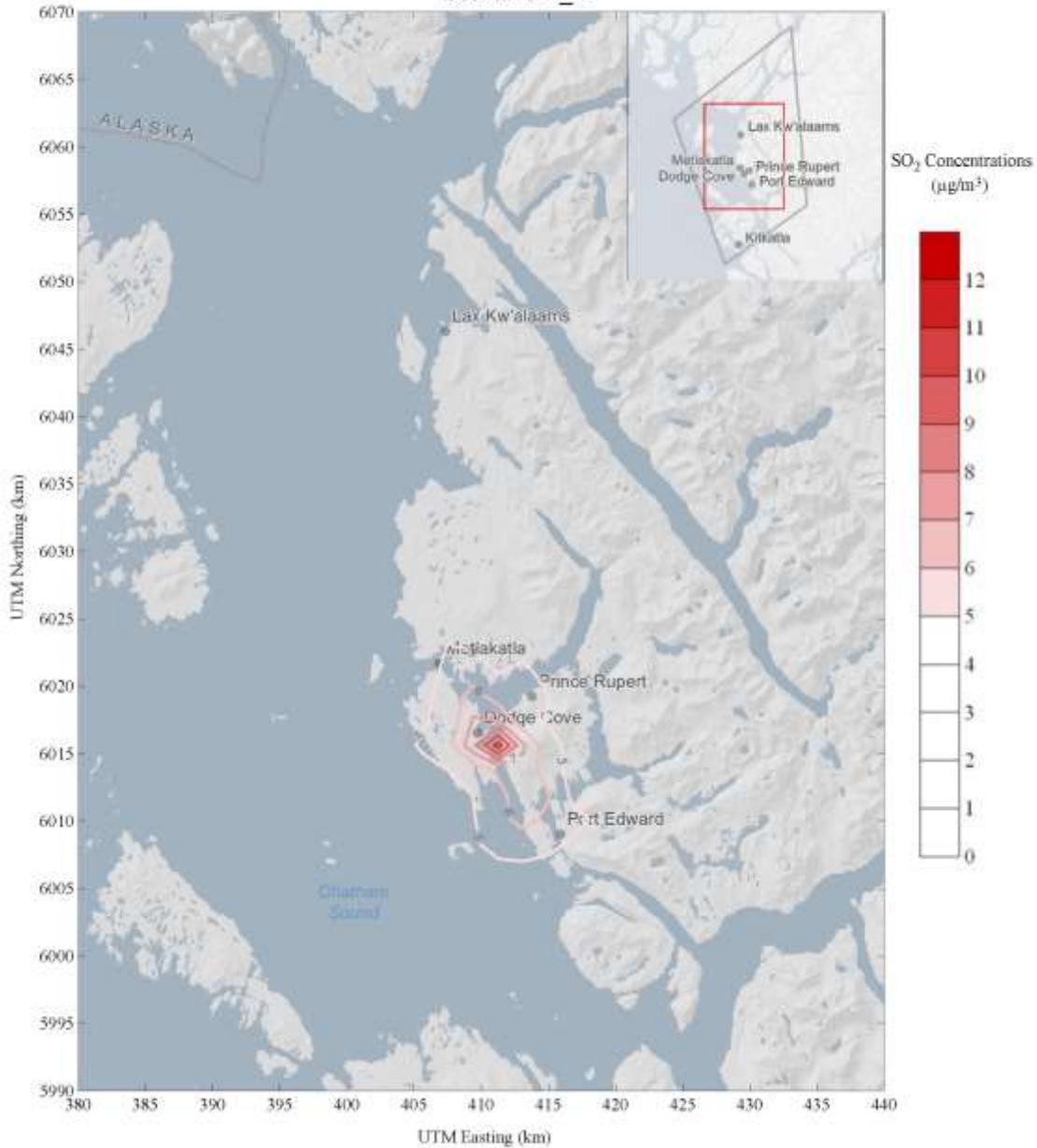


Figure 2-10: Scenario F_R, SO₂ concentration, annual average. The modelled SO₂ concentrations include a background concentration of 4 µg/m³, as discussed in Section 2.1.1.

2.2.4 Modelled PM_{2.5} Concentrations

Figure 2-11 and Figure 2-12 show the 98th percentile 24-hour PM_{2.5} concentration (8th highest daily peak at each location) for Scenario A and Scenario F_R, respectively. Between Scenario



A and Scenario F_R, there is a slight increase in the maximum $PM_{2.5}$ value as well as a more noticeable increase in the area encompassed within the lowest concentration contour ($12.5 \mu\text{g}/\text{m}^3$).

Figure 2-13 and Figure 2-14 show the annual $PM_{2.5}$ concentrations for Scenario A and Scenario F_R, respectively. A similar relationship can be seen showing a small increase in the maximum concentration and a slightly more noticeable increase in the extent of concentrations reaching the lowest concentration contour.



Prince Rupert Airshed Study
98th Percentile PM_{2.5} Concentrations, 24 hour Average
2012 Meteorological Year
Scenario A

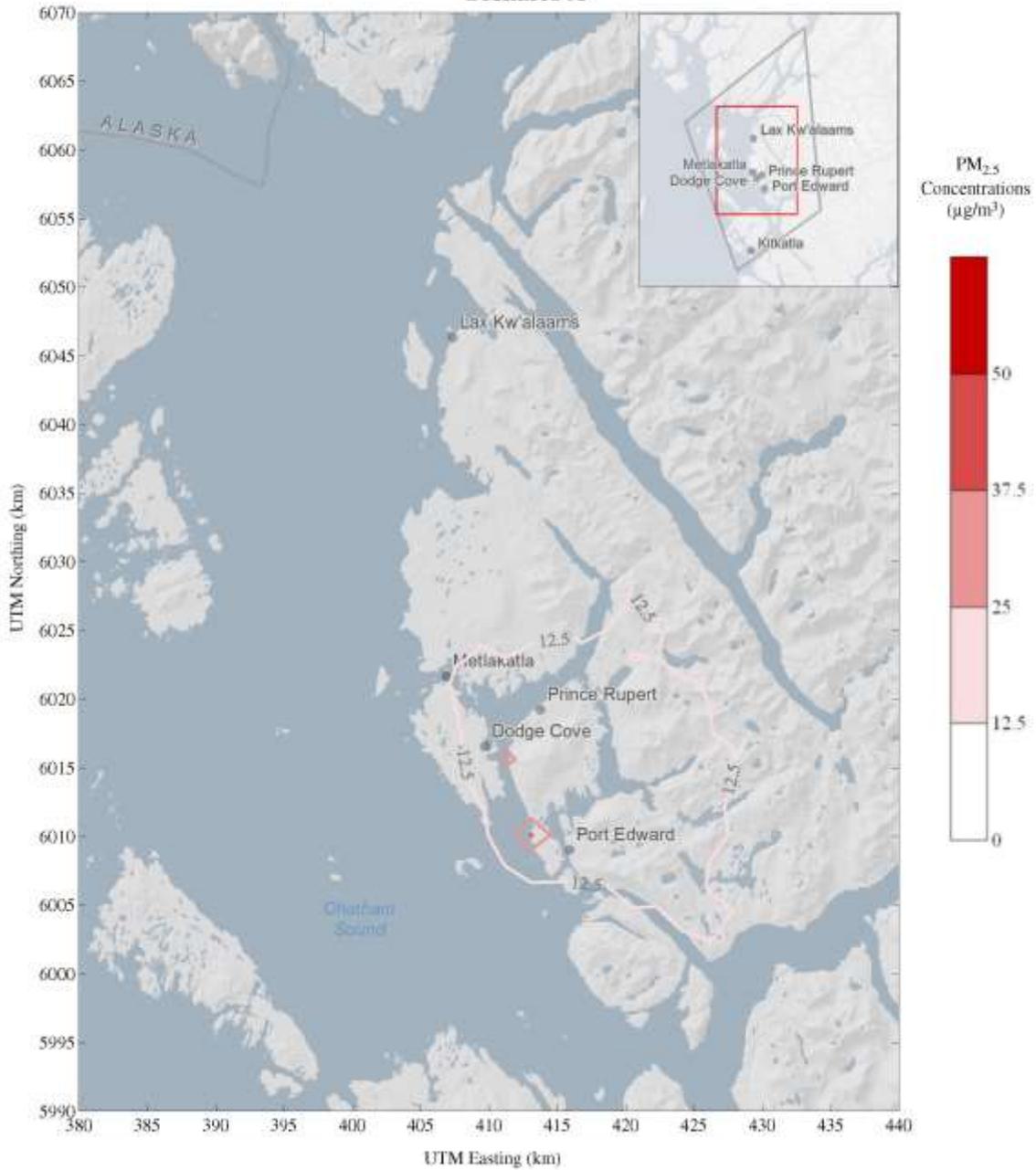


Figure 2-11: Scenario A, 98th percentile PM_{2.5} concentration, 24-hour average. The modelled PM_{2.5} concentrations include a background concentration of 7 µg/m³, as discussed in Section 2.1.1.



Prince Rupert Airshed Study
98th Percentile PM_{2.5} Concentrations, 24 hour Average
2012 Meteorological Year
Scenario F_R

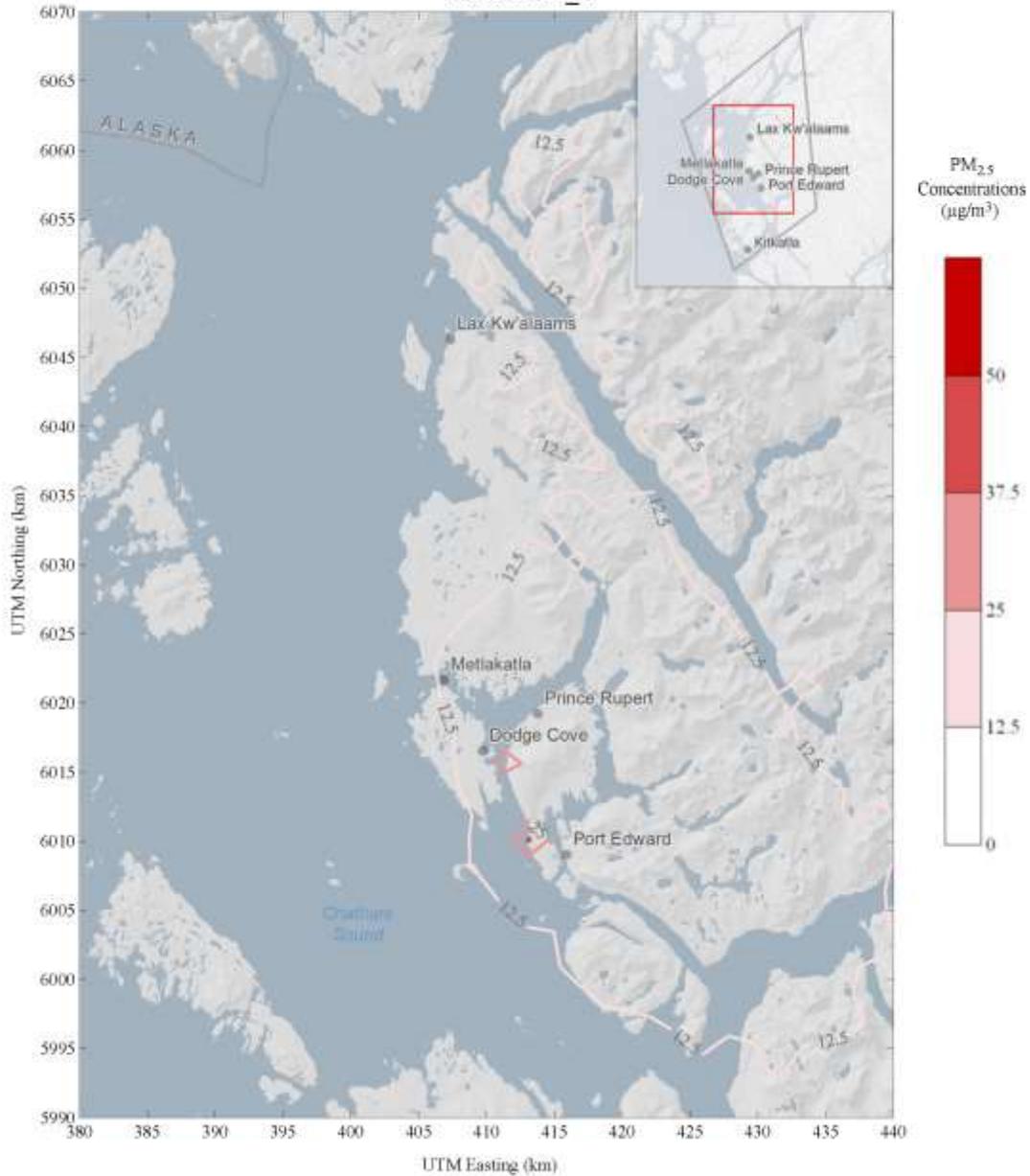


Figure 2-12: Scenario F_R, 98th percentile PM_{2.5} concentrations, 24-hour average. The modelled PM_{2.5} concentrations include a background concentration of 7 µg/m³, as discussed in Section 2.1.1.



**Prince Rupert Airshed Study
PM_{2.5} Concentrations, Annual Average
2012 Meteorological Year
Scenario A**

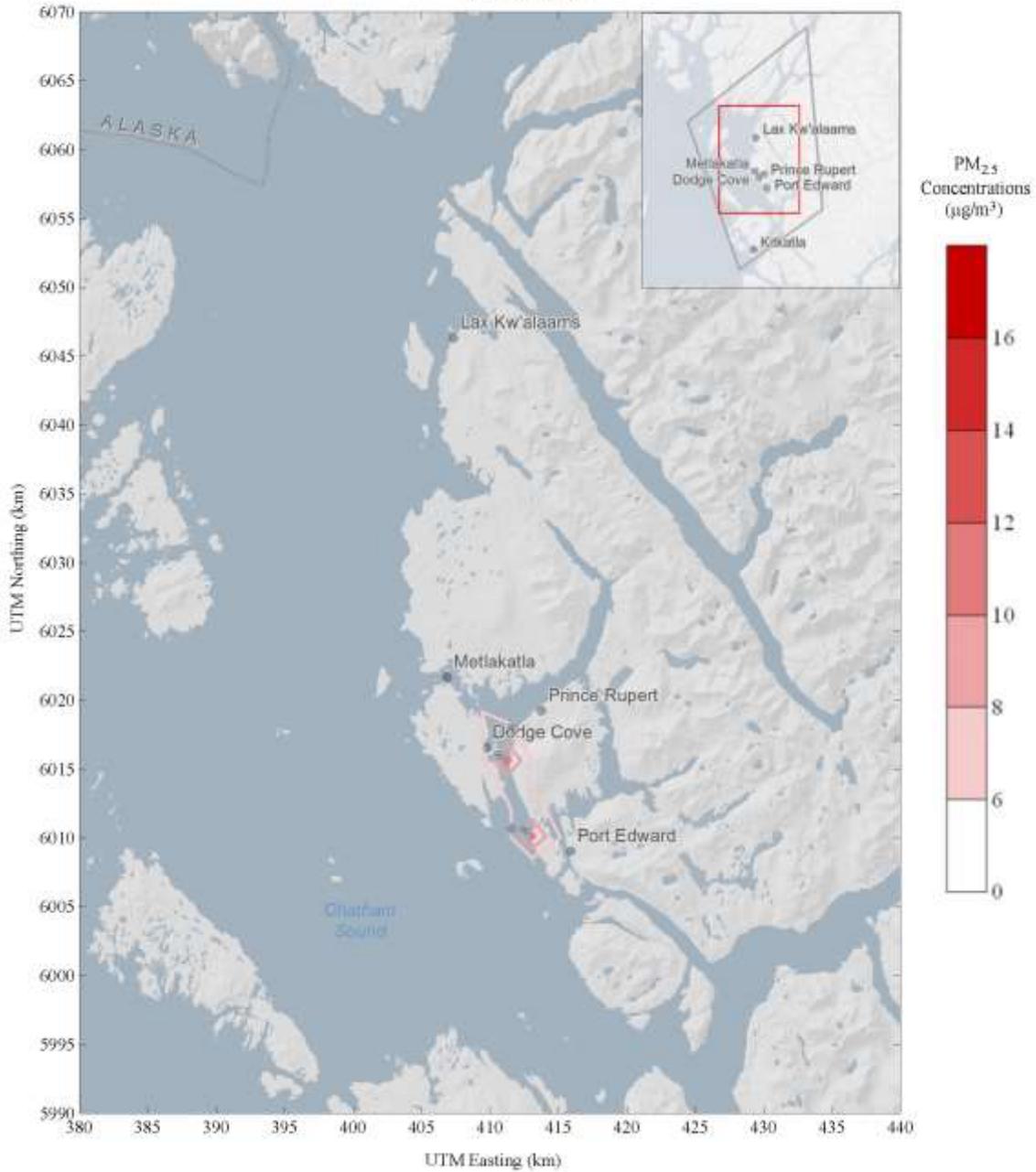


Figure 2-13: Scenario A, PM_{2.5} concentration, annual average. The modelled PM_{2.5} concentrations include a background concentration of 3.5 µg/m³, as discussed in Section 2.1.1.

Prince Rupert Airshed Study
PM_{2.5} Concentrations, Annual Average
2012 Meteorological Year
Scenario F_R

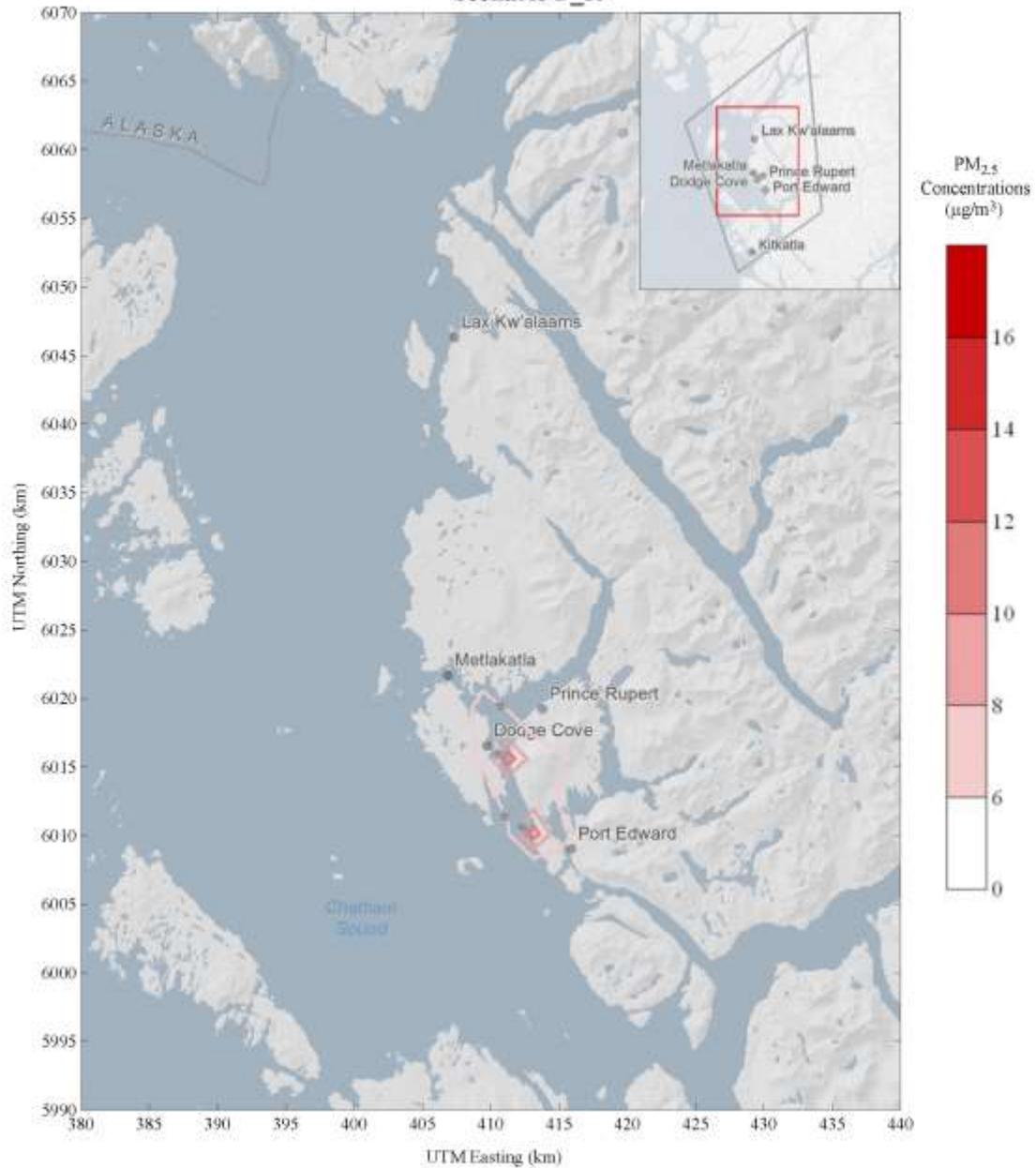


Figure 2-14: Scenario F_R, PM_{2.5} concentration, annual average. The modelled PM_{2.5} concentrations include a background concentration of 3.5 µg/m³, as discussed in Section 2.1.1.

2.2.5 Modelled Nitrogen Deposition

Figure 2-15 shows the annual average nitrogen deposition for Scenario A.³² No background deposition data are applied in the figures, but background data are applied for soil and lakes analysis in Sections 5 and 6, respectively. Figure 2-16 shows annual average nitrogen deposition for Scenario F_R. Between Scenario A and Scenario F_R there is a slight increase in the maximum value as well as a more noticeable increase in the extent of deposition. Overall, the nitrogen deposition levels are very similar across all scenarios, particularly at the higher levels in areas closest to the emissions sources. This lack of variability indicates that the emissions sources that exhibit little variation between all scenarios (non-LNG terminal (i.e., port facilities), non-LNG marine vessels, and LNG marine vessels) contribute substantially to the nitrogen deposition results. The non-LNG land-based and marine vessel emissions do not vary at all among scenarios, while the LNG marine vessel emissions do vary somewhat, because of the fewer LNG facilities built under Scenarios B, D, and E.

As expected, the nitrogen deposition distribution is similar to the annual NO₂ concentration distribution. In fact, while orographic effects due to higher precipitation and land use factors often result in higher deposition in steep terrain, by far, the dominating factor in this study is the distribution of air concentrations.

³² Note that while it is common practice to apply background concentrations to air concentration results, it is not common to apply background concentrations to deposition results. Therefore, no background nitrogen deposition is applied.



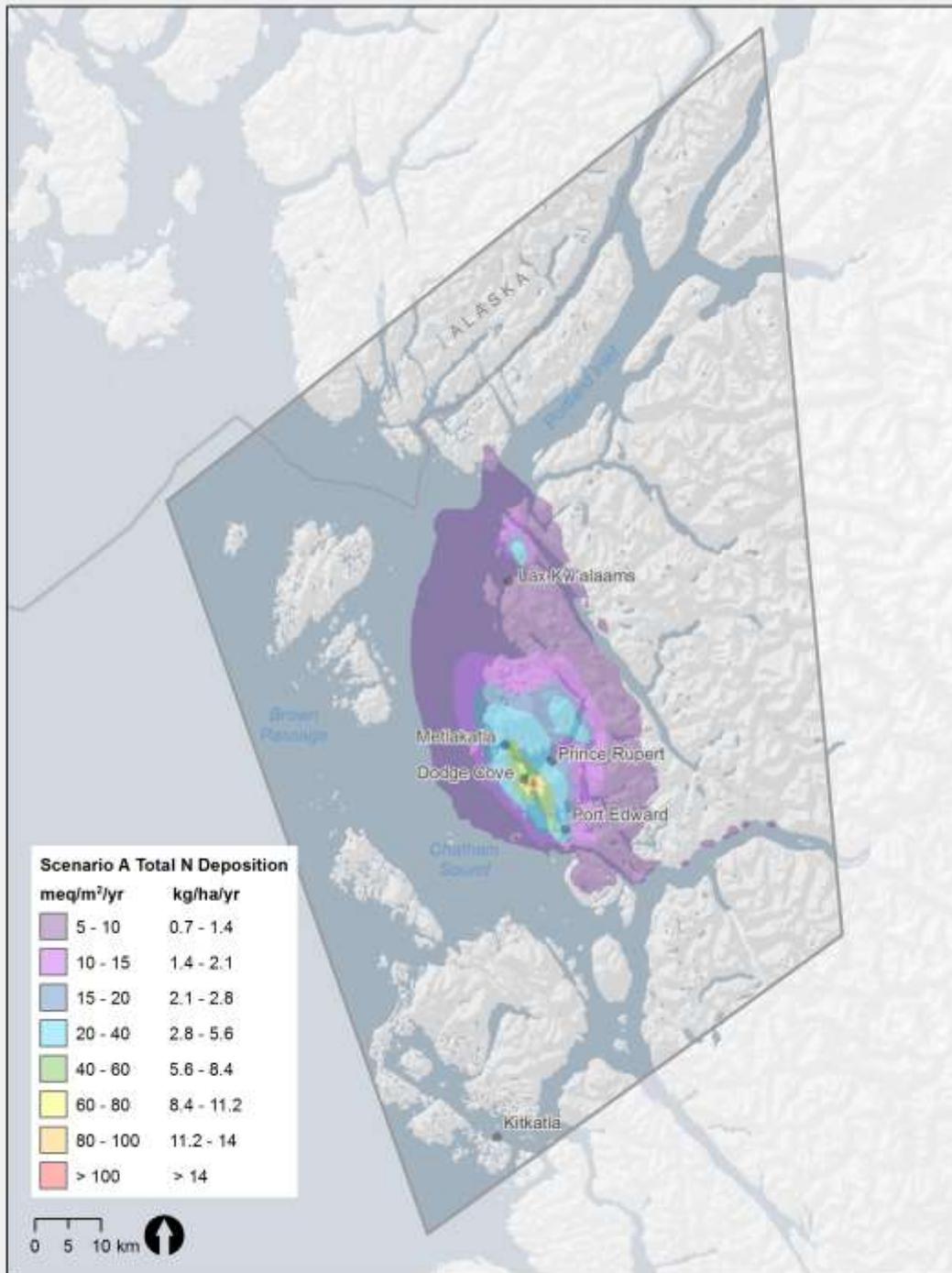


Figure 2-15: Scenario A total nitrogen deposition, annual averaging period. This map shows incremental deposition associated with this emission scenario *without* background deposition; however background levels of S and N deposition *are* considered in the analyses of exceedance for soils and lakes.

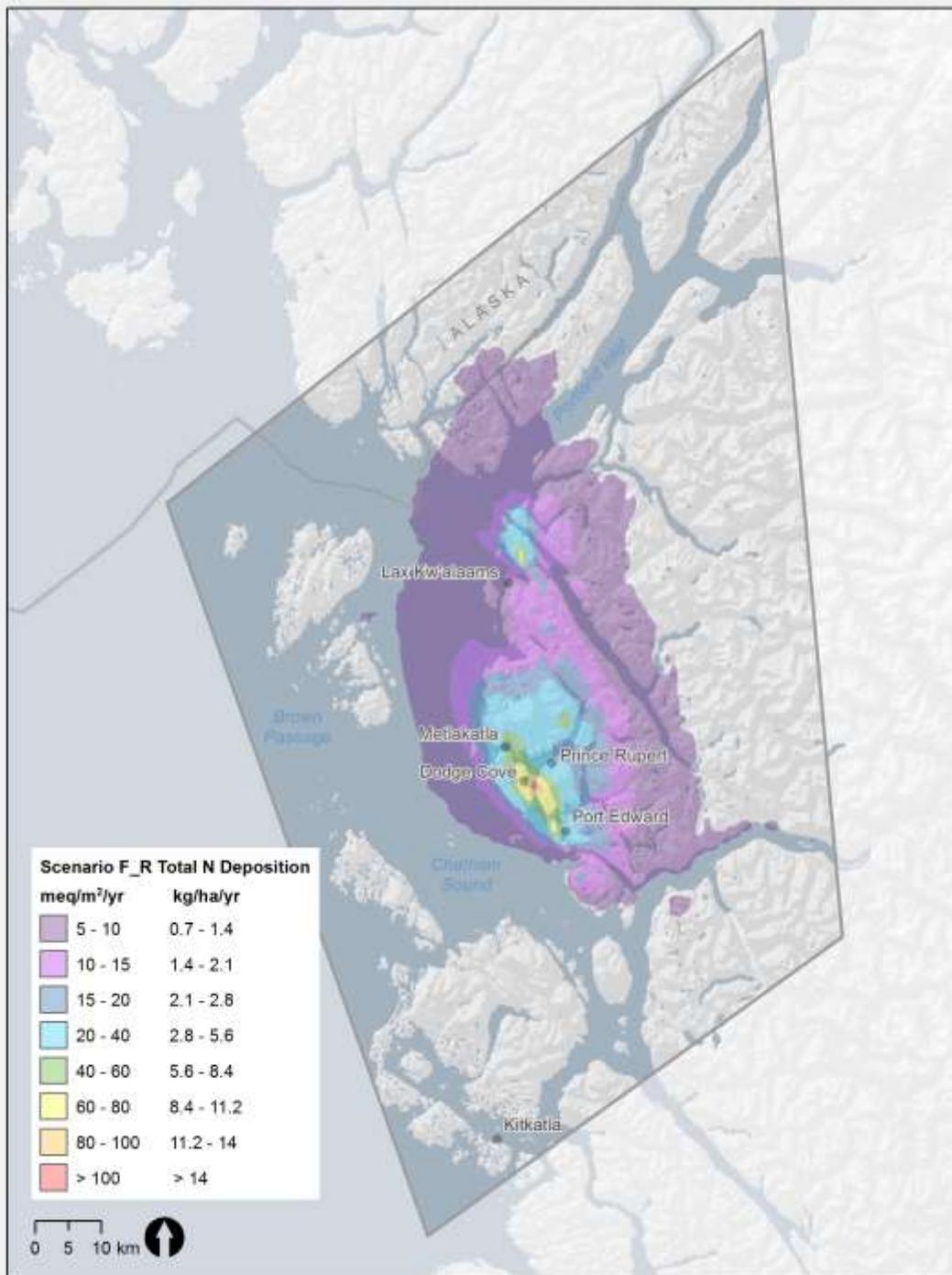


Figure 2-16: Scenario F_R, total nitrogen deposition, annual averaging period. This map shows incremental deposition associated with this emission scenario *without* background deposition; however background levels of S and N deposition *are* considered in the analyses of exceedance for soils and lakes.

2.2.6 Modelled Sulphur Deposition

Figure 2-17 shows the annual average sulphur deposition for Scenario A.¹³ No background deposition data are applied in the figures but background data are applied for soil and lakes analysis in Section 5 and 6, respectively. Figure 2-18 shows annual average sulphur deposition for Scenario F_R. Between Scenario A and Scenario F_R there is an extremely small increase in the maximum value as well as a small increase in the extent of deposition. The lack of difference in sulphur deposition between Scenario A and Scenario F_R is expected because of the similar levels of SO₂ emissions between the two scenarios (7.5 t/d versus 7.8 t/d).



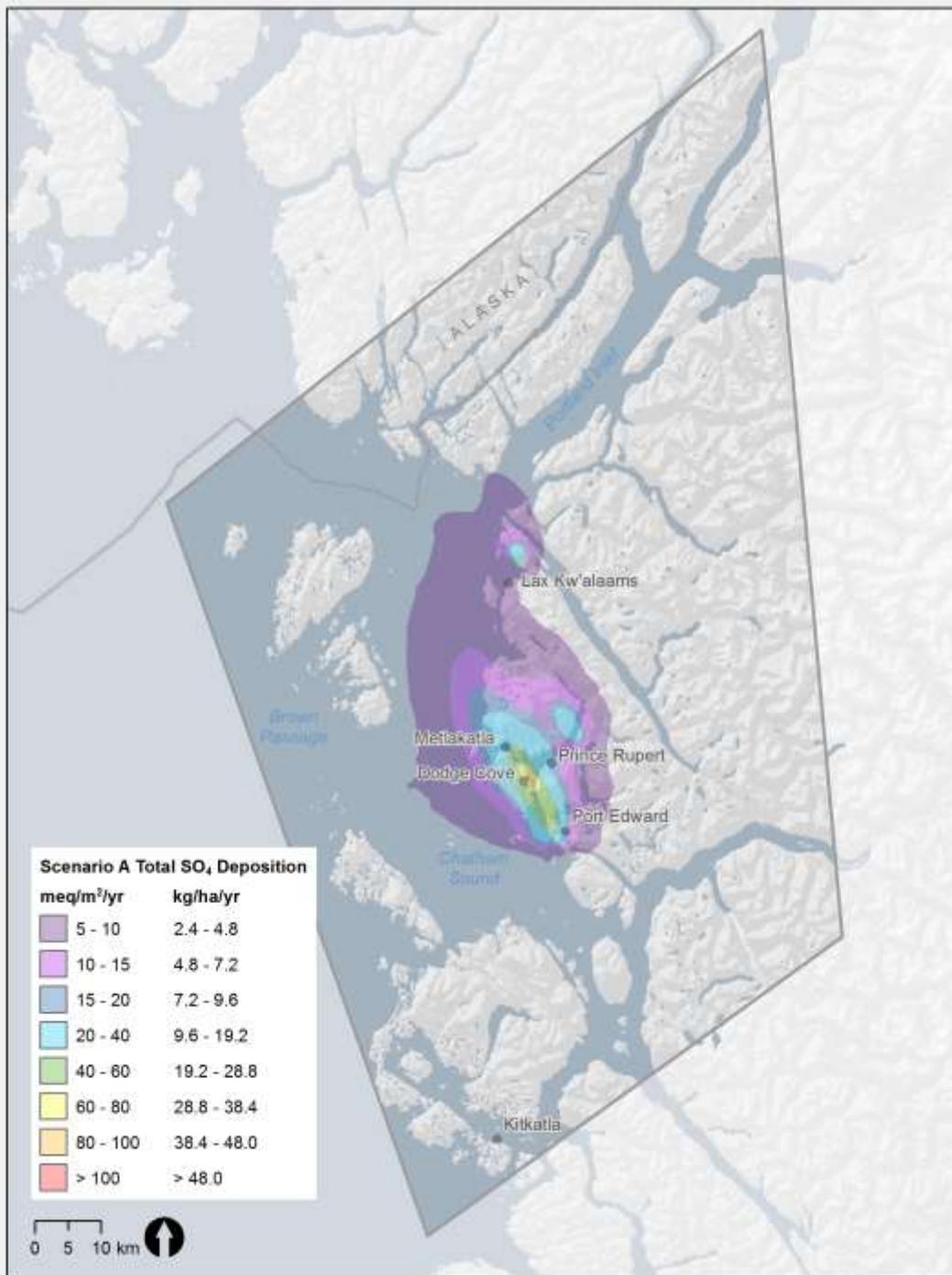


Figure 2-17: Scenario A, total sulphur deposition, annual averaging period. This map shows incremental deposition associated with this emission scenario *without* background deposition; however background levels of S and N deposition *are* considered in the analyses of exceedance for soils and lakes.

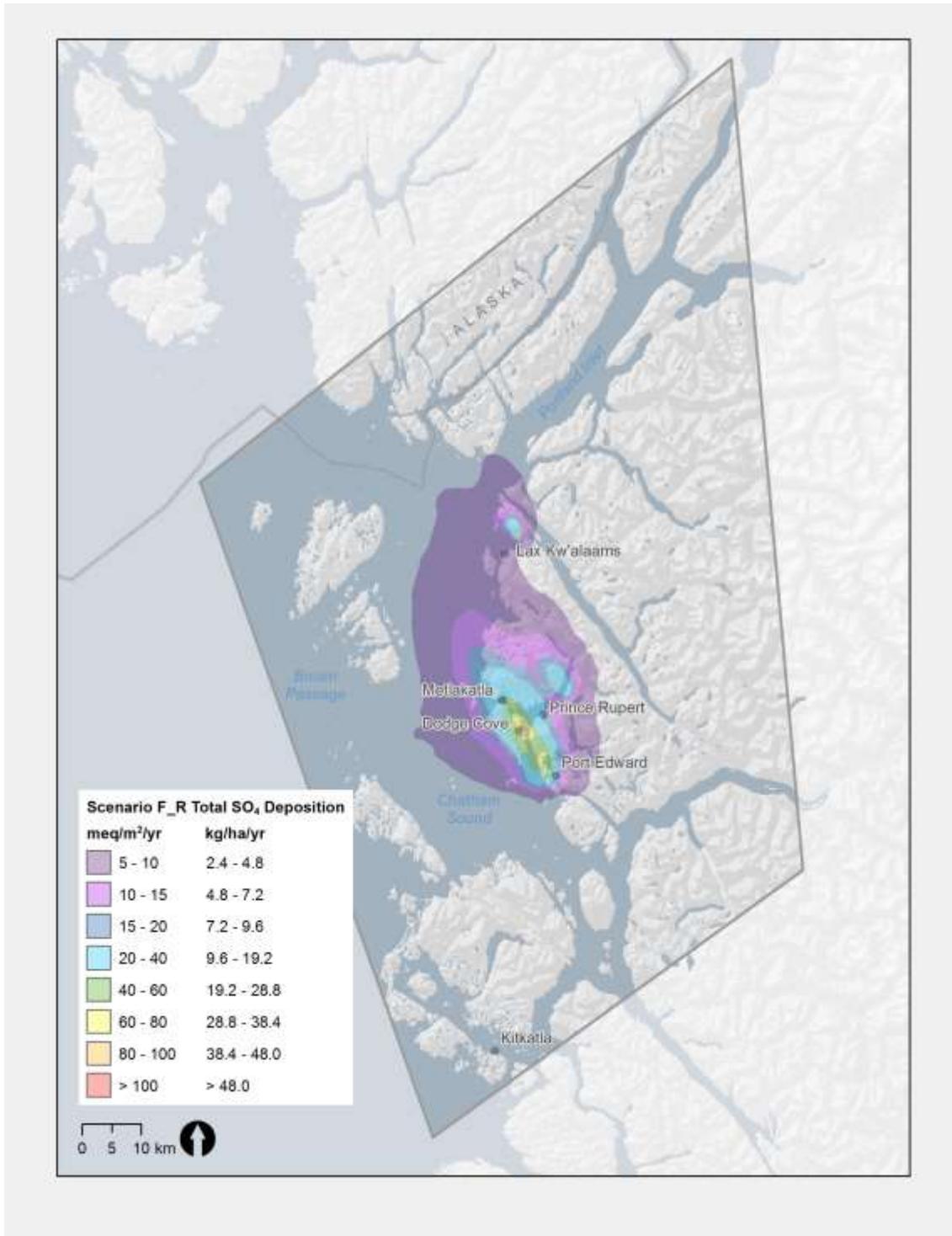


Figure 2-18: Scenario F_R, total sulphur deposition, annual averaging period. This map shows incremental deposition associated with this emission scenario *without* background deposition; however background levels of S and N deposition *are* considered in the analyses of exceedance for soils and lakes.

2.2.7 Interpretation of Results for Comparable Scenarios

The sections below discuss the results of comparable scenarios. The scenario results comparisons are grouped into three different categories: full-build scenarios, partial build scenarios, and chemical transformation options scenarios.

Comparison of Full-build Scenarios (A, C, and F_R)

Scenarios A, C, and F_R each represent all modelled LNG terminal, port facilities and power generating facilities being built at full capacity (i.e., “full build”), but with different levels of NO_x control. Scenario F_R represents the use of dry low emission technology for NO_x emissions from turbines at the LNG facilities. Scenario C represents SCR control on turbines for an 85% reduction of NO_x emissions on the turbines from Scenario F_R. Scenario A (e-drive) represents 100% electric power for all power and compressor drive combustion sources (engines and turbines) at the LNG facilities.

NO₂ Concentration Comparison

Scenario A, Scenario C, and Scenario F_R show increasing maximum NO₂ concentration levels and extent of the lowest concentration contour, as expected, because each scenario has higher modelled NO_x emission rates than the previous one. Scenario A is electric drive for all stationary LNG combustion sources; Scenario C has SCR control on all stationary LNG combustion sources; and Scenario F_R is “full build” with dry low NO_x control. However, the changes are less significant from scenario to scenario than might be expected. Seeing less difference between scenarios than expected is likely due to several emission sources remaining unchanged from scenario to scenario – most notably, all marine and rail transportation sources remain mostly constant, and have a total NO_x emission rate of 30 t/d compared to the total for Scenario F_R of 90 t/d.³³

The NO₂ 1-hour Scenario A and C plots have similar concentration contours with similar extent but Scenario A has a slightly smaller maximum concentration (500 µg/m³) isopleth and covers a smaller overall extent than Scenario C. Scenario F_R has a 500 µg/m³ contour similar to Scenario C, but the overall extent of concentration isopleths extends further north and south, with an additional isopleth of 100 µg/m³ (localized higher) near the Lax Kw’alaams area.

The NO₂ annual Scenario A and C plots are very similar in maximum concentration and contour patterns, but Scenario C has slightly larger extent of the lowest contour level (10 µg/m³). Scenario F_R has a concentration distribution similar to Scenario A and Scenario C, but the plot shows a small increase in the maximum concentration and a more noticeable increase in the extent of concentrations for the lowest concentration contour (10 µg/m³).

³³ The stationary and mobile source summary tables located on the first pages of Appendix 2.3 (in Volume 2 of this report) summarize emissions from each category. The subsequent tables in Appendix 2.3 show the emission rates from each source. Note that t/d indicates metric tons per day.



SO₂ Concentration Comparison

Scenario C and Scenario F_R SO₂ results are essentially identical, due to identical modelled SO₂ emission rates for the two scenarios. SO₂ 1-hour plots show that the increase in the maximum SO₂ concentration as well as the increase in extent of modelled concentrations are extremely small between Scenario A and Scenario C and F_R, and there is no noticeable difference between the scenarios for the lowest concentration contour.

The SO₂ annual Scenario C and F_R plots have a slightly higher maximum concentration than Scenario A. However, the extent of the lowest concentration contour is nearly the same for all three.

PM_{2.5} Concentration Comparison

The PM_{2.5} 24-hour plots show only a very slight increase in highest concentrations between Scenario A and Scenario C, and from Scenario C to Scenario F_R. A more noticeable increase is seen in the area encompassed within the lowest concentration contour (12.5 µg/m³) from Scenario A to Scenario C to Scenario F_R. The modelled PM_{2.5} concentration differences between Scenario A and Scenario C might be expected to be even more evident based on the large difference in PM_{2.5} emission rates between the two scenarios (1.4 t/d versus 5.4 t/d).³⁴ However, the sources with the highest PM_{2.5} emission rates from a single location (Prince Rupert Grain terminal and LNG terminal operations) were unchanged among the scenarios. The difference in modelled emission rates between Scenario C and Scenario F_R is related only to NO_x emissions; therefore, the small difference in PM_{2.5} modelled results is entirely due to the decrease in nitrate formation from Scenario F_R to Scenario C.

The PM_{2.5} annual maximum concentrations show an extremely slight increase in the extent of maximum and overall extent of contour levels from Scenario A to Scenario C to Scenario F_R.

Nitrogen Deposition Comparison

Scenario A, Scenario C, and Scenario F_R show increasing maximum deposition levels and extent of the deposition contour levels, as expected, because each scenario has higher modelled NO_x emission rates than the previous one. Scenario A is electric drive for all stationary LNG combustion sources; Scenario C has SCR control on all stationary LNG combustion sources; and Scenario F_R is “full build” with dry low NO_x control.

Sulphur Deposition Comparison

Scenario A has similar maximum deposition levels and extents as Scenario C and Scenario F_R. Scenario C and F_R are identical to each other and show slightly higher deposition levels and extent than Scenario A.

³⁴ The stationary and mobile source summary tables located on the first pages of Appendix 2.3 summarize emissions from each category. The subsequent tables in Appendix 2.3 show the emission rates from each source. Note that t/d indicates metric tons per day.



Partial Build Scenarios (B, D, E)

Scenarios B, D, and E each represent a partial build of the proposed LNG and energy generating facilities.

- Scenario B represents building Pacific NorthWest LNG, Aurora LNG, and the BC Hydroelectric generating facility.
- Scenario D represents building Grassy Point LNG (an outlier in location from the other LNG facilities which are being proposed in the Prince Rupert and Port Edward areas, this LNG facility is proposed near Lax Kw'alaams), Aurora LNG, and Watson Island LNG facility.
- Scenario E represents building Pacific NorthWest LNG, WCC LNG, Prince Rupert LNG, and BC Hydroelectric generating facility.

All scenarios also include the existing port facilities, new port facilities (Canpotex), and port expansion projects (Fairview Phase II). Scenario B has the lowest modelled emission rates for each pollutant, followed by Scenario D, and Scenario E has the highest modelled emission rates for each pollutant. Although the emission rates from Scenario D are not the lowest, the sources are the most spread out across the region.

NO₂ Concentration Comparison

The NO₂ 1-hour Scenario B and Scenario D concentration contour plots have nearly identical contour levels near the Prince Rupert and Port Edward areas. However, Scenario D has an additional lowest contour level (100 µg/m³) near Lax Kw'alaams due to Grassy Point LNG being included in Scenario D and not Scenario B or E. Scenario E has a similar highest concentration location between Prince Rupert and Port Edward, but the extent of the lowest contour level near these areas covers a larger area. Scenario E does not result in concentrations greater than the lowest contour level near the Lax Kw'alaams area.

The NO₂ annual concentration plots for Scenarios B, D, and E have nearly identical contour levels, except for the lowest contour level (10 µg/m³). Scenario B is slightly more expansive for the lowest contour level near the Prince Rupert and Port Edward areas than Scenario D, and Scenario E is even more expansive than Scenario B. Scenario D has an additional 10 µg/m³ ring near Lax Kw'alaams that neither Scenario B or E show due to Grassy Point LNG being included in Scenario D and not Scenario B or E.

SO₂ Concentration Comparison

The SO₂ 1-hour concentration plots for Scenarios B, D, and E all have similar concentration contour levels with the same maximum contour level. Scenario D has a slightly more expansive lowest contour level (50 µg/m³) than Scenario B towards the south, and Scenario E has a slightly more expansive lowest contour level than Scenario D also towards the south.

The SO₂ annual Scenario B, D, and E plots all have similar concentration contour levels. The overall maximum concentrations are nearly identical. Scenario D has a slightly more expansive lowest contour level (5 µg/m³) than Scenario B, and Scenario E has slightly more expansive contours than both D and B.



This lack of variation of modelled SO₂ concentrations across scenarios indicates the dominance of SO₂ emissions from the non-LNG terminal marine vessels on SO₂ results.

PM_{2.5} Concentration Comparison

The PM_{2.5} 24-hour Scenario B and Scenario D concentration plots have nearly identical contours. Scenario E has the same maximum contour levels as Scenario B and D, but the lowest contour level (12.5 µg/m³) is more expansive over land than Scenario B and D.

The PM_{2.5} annual concentration plots for Scenario B, D, and E all have nearly identical contours. The overall maximum concentrations are also nearly identical. Scenario D has slightly more expansive contours than B, and Scenario E has slightly more expansive contours than D and B.

Nitrogen Deposition Comparison

Scenarios B, D, and E vary because of localized deposition levels of different sources being modelled in each scenario. Overall, the maximum extent of deposition levels in the Prince Rupert and Port Edward areas occurs for Scenario E and the higher deposition levels in the Lax Kw'alaams area occur for Scenario D.

Sulphur Deposition Comparison

Scenarios B, D, and E vary because of localized deposition from different sources being modelled in each scenario. Overall the maximum extent of impacts in the Prince Rupert and Port Edward areas is from Scenario E and the maximum in the Lax Kw'alaams area is from Scenario D. Scenario B has the lowest overall deposition levels and extents.

RIVAD with ISORROPIA versus MESOPUFF II Scenarios (F_R, F_M)

Scenario F_R and Scenario F_M have the same source inputs (emission rates and stack parameters), but apply different chemical transformation mechanisms. Scenario F_R uses the RIVAD with ISORROPIA mechanism, while Scenario F_M uses the MESOPUFF II mechanism. These chemical transformation options are discussed in further detail in Section 2.1.3, and the comparison between the two scenarios is detailed in Section 2.3.3.



2.3 Main Sources and Implications of Quantitative Scientific Uncertainty

The primary source of uncertainty in the air dispersion and deposition modelling is the preliminary nature of the emission rates and stack parameters for the LNG facilities, port facilities, and marine and rail transportation emissions. While we made several conservative assumptions with respect to transportation emissions, little information is available regarding the level of uncertainty or extent of assumptions from proponent data. With respect to local scale results in the town of Prince Rupert and near the facilities, the absence of building data needed to predict building downwash effects from all stationary facilities except Prince Rupert LNG is also expected to result in uncertainty to varying extents. In general, it is expected that the absence of building downwash results in under-prediction in locations near the facility. This under-prediction from building downwash is not expected to be significant at distances approaching the nearest residential areas in Prince Rupert and Port Edward.

Meteorological data uncertainty is typically and consistently the key source of uncertainty in any predictive air dispersion modelling analysis, because it is not possible to know with any certainty what the weather will be in future years and how well the modelled meteorological year represents future years. One difference between the KAA and this study is the use of the Weather Research and Forecasting (WRF) model data in lieu of the Mesoscale Model 5 (MM5) data for the CALMET meteorological processing. Meteorological data uncertainty is discussed further in Section 2.3.1 below.

For the KAA and Kitimat airshed, several studies were conducted to evaluate model performance and model sensitivity. While some of these studies relate generally to the CALPUFF modelling system performance, they are not directly applicable to the Prince Rupert Airshed Study, because the CALMET dataset is different (different years, different underlying data sources, different area, different processing methods in some cases), the terrain and coastal influences are different, the chemistry modules are different (with the exception of Scenario F_M), and the emission sources are different.

Other potential sources of uncertainty are the layering approach and chemistry options used. These topics are discussed further in the sections below.

2.3.1 Meteorological Data Uncertainty

Performing the CALMET validation discussed in Section 2.1.3 and in Appendix 2.2 (CALMET Methodology) in Volume 2 of this report, provided insight into the level of confidence in the quality of the meteorological dataset. We used the surface station meteorological data provided by MOE to evaluate the CALMET model output generated using several different switch setting options in order to determine the most appropriate CALMET control file configuration. The CALMET validation concluded that the hybrid meteorological fields produced from observations and prognostic model data are representative for the region and the coastal flow is depicted realistically. The correlation between the observed and modelled fields is considered sufficiently high to justify the use of the selected model parameters as a final set.



2.3.2 Layering Approach Study

The layering approach described in Section 2.1.1 is a source of uncertainty, though less significant and more readily quantifiable than the sources described above. There may be differences in the results between the two approaches (modelling each facility separately and adding results in a post-processing step versus including all sources in a single CALPUFF input file), because the CALPUFF dispersion model includes chemical interactions between plumes (as SO₂ converts to SO₄ and NO_x converts to NO₃). In the Kitimat Airshed Emissions Effects Assessment (KAA), a study on the layering approach was conducted. In order to assess the effect of the layering approach for KAA, one scenario was modelled as a “scenario-specific” run with all emissions sources in a single input file, and the results compared with the results from a run of the same scenario using the layered approach.

The modelling results changed less than 0.3% on average for SO₂ concentration and sulphur deposition. In this case, “on average” means the average, across all receptors, of the absolute difference (between layered versus scenario-specific for each receptor) of annual average concentrations or deposition. The differences in NO_x modelling results were similarly minimal, with the NO_x concentrations changing less than 0.1% on average. While the average nitrogen deposition changed approximately 6.5%, the average change was less than 0.02 kg/ha/yr, indicating the higher percent changes in nitrogen deposition were an artifact of the large number of receptors with extremely low model results. Additionally, for SO₂ concentrations and sulphur deposition, less than 4% of receptors saw a difference greater than 1%. Overall, the layered approach showed a slight negative bias (e.g., average of 0.02% under-prediction for sulphur deposition), but the differences for sulphur deposition ranged from 6% under-prediction to 5% over-prediction.

The biases associated with applying the layering method for the KAA were inconsequential. The biases are expected to be inconsequential for the Prince Rupert Airshed Study as well, because the distances between sources and level of emission rates and background concentrations are similar.

2.3.3 Chemical Transformation Options

An additional source of uncertainty is the use of a new chemical transformation option within CALPUFF known as RIVAD with ISORROPIA. This module was most recently updated in 2010 in CALPUFF version 6.4 and is discussed in Section 2.1.3. Scenario F_R and Scenario F_M use the same “full build” source input, but Scenario F_R used the RIVAD with ISORROPIA chemistry option and Prince Rupert-specific monthly background ozone data, while Scenario F_M used the MESOPUFF II chemistry option and the default background ozone value.

The comparison of results at maximum locations shows that nitrogen and sulphur depositions vary significantly between the two different chemistry options, with over a 200% increase in RIVAD sulphur deposition results over MESOPUFF II sulphur deposition results at maximum deposition locations. For concentration results at maximum locations, RIVAD results are lower than MESOPUFF. Sulphur dioxide (SO₂) concentrations range from -0.1% difference for the

SO₂ 1-hour averaging period to -10.7% difference for the SO₂ 3-hour averaging period. Nitrogen dioxide (NO₂) concentrations range from -32.2% (annual daylight growing season) to -55.2% (1-hour 98th percentile) change from MESOPUFF to RIVAD. The following sections detail the overall results comparison between the two scenarios for each modelled pollutant.

NO₂ Concentration Comparison

The NO₂ 1-hour RIVAD (Scenario F_R) and MESOPUFF II (Scenario F_M) scenario plots generally have the same plot contour distribution with highest concentration locations coinciding and general location of contours aligning. However, the MESOPUFF II scenario has a significantly higher gradient and maximum concentration than the RIVAD scenario (RIVAD scenario maximum contour level is 500 µg/m³ compared to MESOPUFF II scenario with maximum contour level of 700 µg/m³), but the extent of the lowest contour level (100 µg/m³) is more expansive for the RIVAD scenario. The differences in the highest concentrations are expected, because the MESOPUFF II scheme does not predict the transformation of NO to NO₂; rather, an assumption that 80% of the modelled NO_x is in the form of NO₂ is applied across the domain. In reality, and as modelled using RIVAD, the NO emitted from the stack converts to NO₂ over time and space. Therefore, the MESOPUFF II scheme over-predicts NO₂ concentrations near the emission sources by applying this 80% NO₂ / NO_x ambient ratio assumption. In areas farther from emission sources, the predicted NO₂ concentrations using the MESOPUFF II option are typically lower than those using the RIVAD option.

The NO₂ annual concentration plots show a similar relationship as the NO₂ 1-hour plots. The overall maximum concentration plot for RIVAD is 50 µg/m³ and for MESOPUFF II it is 60 µg/m³. Again the lowest contour level is more expansive for the RIVAD scenario than the MESOPUFF II scenario.

SO₂ Concentration Comparison

The SO₂ 1-hour contour plots between the RIVAD and MESOPUFF II scenarios are nearly identical, because the chemical transformation mechanisms have minimal impact on SO₂ concentrations.

The SO₂ annual concentration plots for RIVAD and MESOPUFF II scenarios are also similar, but the MESOPUFF II resulted in a slightly higher maximum concentration and overall extent of concentrations over the RIVAD scenario. This relationship indicates that the RIVAD with ISORROPIA chemistry scheme resulted in a faster rate of transformation from SO₂ to SO₄.

PM_{2.5} Concentration Comparison

The PM_{2.5} 24-hour Scenario F_R and Scenario F_M plots have identical maximum concentration level contours, but the RIVAD with ISORROPIA scenario has a significantly more expansive extent of the lowest concentration contour (12.5 µg/m³). The greater extent of concentration contours for the RIVAD with ISORROPIA scheme is likely due to the ISORROPIA mechanism more accurately calculating formation of secondary PM_{2.5} (sulphates and nitrates) throughout the domain.



The PM_{2.5} annual Scenario F_R and Scenario F_M plots have similar contour shapes and extents. Similar to the 24-hour averaging period, Scenario F_R has an overall larger extent of each contour level.

Nitrogen Deposition Comparison

The general distribution of deposition levels is similar between both scenarios with higher levels at higher terrain locations, but Scenario F_R has significantly larger extent of all contour levels than Scenario F_M. This increase in nitrogen deposition in the far-field could be due to faster transformation rates to NO₃, which could then be deposited at a faster rate, since the wet and dry deposition parameters are more favourable to deposition for NO₃ than for NO or NO₂.

Sulphur Deposition Comparison

Scenario F_R has significantly larger maximum level and extent of deposition levels than Scenario F_M. This increase in sulphur deposition could be due to faster transformation rates to SO₄, which could then be deposited at a faster rate, since the wet and dry deposition parameters for SO₄ are more favourable to sulphur deposition than the deposition parameters for SO₂. The larger difference for sulphur deposition than for nitrogen deposition indicates that the differences in either the transformation rate or deposition parameters diverge more for SO₄. Since the deposition parameters are very similar for NO₃ and SO₄, we can infer the SO₂ to SO₄ transformation rate difference using RIVAD with ISORROPIA is the primary driver for the higher sulphur deposition under Scenario F_R.

2.4 Recommendations on Impact Assessment Guidance

Environmental assessment requirements should include:

- Dispersion modelling analysis following the *Guidelines for Air Quality Dispersion Modelling in British Columbia* (BC MOE 2008).
- If possible, the modelling analyses by each proponent should use the same CALMET datasets and same regional source emissions inventory. Both of these datasets can be based on the datasets developed for and used in this study after additional review, studies, and possibly refinements are performed by MOE.
- A baseline air concentration monitoring study for NO₂, SO₂, PM_{2.5}, and possibly other pollutants, with network design based on proponent dispersion modelling results. One or two monitor locations for each pollutant should be sufficient, with one sited to capture maximum fence-line concentrations and one sited to capture maximum concentrations in community locations (as defined in Section 3).
- The NO₂ monitors should also be equipped to measure NO levels, and should be used to inform the final approach used to assess NO₂ concentrations (i.e., whether to use RIVAD, the ozone limiting method, or the ambient ratio method).
- For analysis of air quality and deposition levels for the project case and cumulative case, data from the site-specific baseline air monitoring studies is preferred over using monitoring data from nearby communities (as was used for this study). Site-specific baseline monitoring data are also preferred over using modelling analysis of existing (baseline) emission sources. While modelled background concentrations from existing



industrial sources may provide a reasonable background for pollutants only from industrial sources (e.g., SO₂), pollutants such as particulate matter and NO₂ are generated from many non-industrial sources (e.g., vehicle traffic and residential woodstoves), which are not captured in a typical modelling analysis.

- The air monitoring network would also benefit from a co-located surface meteorological station, particularly at fenceline monitors that are not in close proximity to the Prince Rupert Airport.
- Data from new meteorological stations or other stations not used in development of the WRF dataset could also be used to more thoroughly assess the representativeness of the WRF and CALMET datasets.
- A baseline deposition monitoring study for nitrogen and possibly sulphur.
- All monitors should continue operation in the same locations to measure post-project air concentrations to compare to model predictions and to compare to the most current human health and vegetation impact levels after operations have reached full capacity.



3 Human Health

In the first section, the overall approach to the health assessment is described. An approach to provide a screening-level human health assessment is proposed, with a conceptual basis similar to that of the Canadian Council of Ministers of the Environment (CCME) in the establishment of air quality management criteria (and associated “bands” of air quality) for particulate matter and ozone. The results of the air dispersion modelling are reviewed in light of this health assessment scheme.

3.1 Methods

The human health assessment was conducted through the following sequence of tasks:

1. Residential, recreational, cultural, and commercial areas for which human health effects should be assessed were identified.
2. The CCME air quality management categorization scheme was adapted to characterize risk management levels for $PM_{2.5}$, NO_2 and SO_2 , based on numerical thresholds applied to ambient concentration statistics.
3. Dispersion model results (consisting of one year of hourly average ambient air concentrations for the identified residential and commercial human health receptor locations) were processed to compute summary statistics for the purposes of comparison with the ambient concentration thresholds, for different residential, recreational, cultural, and commercial locations identified in Task 1.

3.2 Review of Evidence for Health Effects for SO_2 , NO_2 and $PM_{2.5}$

Oxides of sulphur (SO_x) include sulphur dioxide (SO_2), sulphur trioxide (SO_3), and gas-phase sulphuric acid (H_2SO_4). Only SO_2 is present in the atmosphere in concentrations significant for human exposure, and it serves as the indicator for SO_x (US EPA 2008a). Oxides of nitrogen (NO_x) are complex mixtures of many oxides including NO_2 , nitric oxide (NO), and all other oxidized nitrogen-containing compounds formed from NO_2 and NO. NO_2 is the most important of the gaseous NO_x and serves as the indicator (US EPA 2008b). Most studies on health effects of gaseous SO_x and NO_x focus on SO_2 and NO_2 , respectively.

The term particulate matter (PM) is used to describe chemically and physically diverse substances that exist in the form of discrete particles (liquid droplets or solids) over a wide range of sizes. Particles can originate from natural and anthropogenic sources, may be emitted directly or formed in the atmosphere by transformations of gaseous emissions, such as sulphur oxides, nitrogen oxides, and volatile organic compounds. Assessment of the health effects of PM is complicated due to variations in chemical and physical properties with time, region, meteorology, and source. $PM_{2.5}$ is the indicator for fine particles, with $PM_{2.5}$ referring to particles with a nominal mean aerodynamic diameter less than or equal to $2.5 \mu m$ (US EPA 2009).

Five sources of information were used to identify health outcomes causally linked with environmental exposure to SO_x , NO_x , and $PM_{2.5}$:



1. US EPA *Integrated Science Assessment for Sulfur Oxides – Health Criteria* (US EPA 2008a). (Note: *sulfur* is the American spelling of *sulphur*).
2. US EPA *Integrated Science Assessment for Oxides of Nitrogen – Health Criteria* (US EPA 2008b).

These two documents represent the most recent authoritative reviews of scientific literature on health effects of exposures to ambient oxides of sulphur and nitrogen.

3. To update the literature on health effects of sulphur oxides (particularly SO₂), a search was conducted using the US National Library of Medicine (PubMed) database. The search took place on October 25, 2012 and identified literature published between 2008 and that date. This work is described in detail as part of the KMP SO₂ Technical Assessment Report (ESSA et al. 2013). A summary of this review is provided below.
4. In November 2013, the Clean Air Scientific Advisory Committee of the US EPA issued an updated *First External Review Draft of the Integrated Science Assessment for Oxides of Nitrogen – Health Criteria* (US EPA 2013). This document updates the literature on health effects of nitrogen oxides.
5. US EPA *Integrated Science Assessment for Particulate Matter* (US EPA 2009).

The Scientific Advisory Committee of the US EPA considered scientific evidence for health effects of short-term and long-term exposures to SO₂, NO₂ and PM_{2.5}. Exposure durations from several minutes to a month were considered to be short-term, and exposures averaged over months or years were considered long-term (US EPA 2008a,b, 2009). Evidence was integrated across scientific disciplines: epidemiology; controlled human exposure experiments; and toxicology. Causal determinations were based on consistency of findings (as opposed to reliance on a single study) from a large number of independent studies, coherence of evidence from various fields, and the biological plausibility of observed effects.

3.2.1 Health Effects with a Causal Association to Sulphur Dioxide (SO₂)

This section provides a summary of the conclusions of a comprehensive scientific review by the US EPA (as of 2008) on the relationship between various health effects and exposures to SO₂ as well as conclusions of a previous review of literature between 2008 and 2012 which is described in detail in a previous report (ESSA et al. 2013). It is summarized here for the convenience of the reader. For more detail and for original references, the reader is directed to the previous report. More recent literature on SO₂ was not reviewed as part of this project.

In 2008, the US EPA Committee concluded that the scientific evidence was sufficient to infer a causal relationship between short-term exposure to SO₂ and respiratory morbidity. Inhaled SO₂ and its reaction products can stimulate chemosensitive receptors in the tracheobronchial tree and initiate a reflexive contraction of smooth muscles in the bronchi (bronchoconstriction). The key evidence for the US EPA (2008a) conclusion came from human clinical studies. Volunteers were exposed to SO₂ under controlled conditions in the absence of other pollutants. These studies consistently demonstrated decreased lung function accompanied by respiratory symptoms (e.g., wheeze and chest tightness) in exercising mild to moderate asthmatics following peak exposures (5-10 min duration) to SO₂ at concentrations of about 1,050 to 1,570 µg/m³. Physical exercise was used in these experiments to increase lung ventilation rate and, as a result, SO₂ uptake. Some asthmatic subjects experienced decreases in lung function at SO₂ concentrations of about 520 to 790 µg/m³. In clinical studies of exercising individuals without asthma, decreases in lung function were observed only at SO₂ concentrations greater



than about 2,620 $\mu\text{g}/\text{m}^3$. Supporting evidence for a causal relationship between short-term exposure to SO_2 and respiratory morbidity came from epidemiological studies reporting increases in respiratory symptoms, emergency department visits and hospitalizations for respiratory diseases, and decreases in lung function associated with increased SO_2 levels (US EPA 2008a).

Studies published from 2008 to 2012 generally supported the US EPA conclusion regarding a causal relationship between short-term SO_2 and respiratory morbidity. Most of the identified epidemiological studies demonstrated a link between increased SO_2 concentrations in the air and respiratory effects. In clinical studies among non-smoking healthy volunteers, exposure to SO_2 for four hours at concentrations up to about 5,240 $\mu\text{g}/\text{m}^3$ had no effect on lung function and did not cause an increase in biochemical markers of airway irritation or inflammation. Data from recent studies and those reviewed by the US EPA in 2008 suggest that ambient SO_2 does not induce respiratory diseases in healthy people but rather exacerbates existing diseases. It was clearly demonstrated that individuals with asthma represented a population susceptible to the effects of short-term exposures to SO_2 .

Thus, decreased lung function and respiratory symptoms were health outcomes for which a causal relationship with SO_2 was unequivocally established. The Scientific Advisory Committee of the US EPA (US EPA 2008a) defined populations susceptible to the adverse effects of a pollutant as populations that “might exhibit an adverse health effect to a pollutant at concentrations lower than those needed to elicit the same response in the general population, or exhibit a more severe adverse effect than the general population when exposed to the same pollutant concentrations”. The Advisory Committee concluded that subjects with asthma were a population particularly susceptible to the respiratory effects of SO_2 . Physical exercise increased the sensitivity of individuals with asthma to the effects of SO_2 .

The Advisory Committee characterized the evidence as suggestive but not sufficient to infer a causal relationship between short-term exposure to SO_2 and mortality (US EPA 2008a). This “suggestive” evidence came from epidemiological studies that reported associations between increased ambient SO_2 concentrations and mortality from all causes and from specific causes. The US EPA pointed out that interpretation of findings from epidemiological studies was complicated, in particular due to difficulties in differentiating the effects of SO_2 from the effects of other air pollutants.

Studies published from 2008 to 2012 that examined associations between ambient SO_2 concentrations and mortality from all causes, from all non-accidental causes, and from cause-specific mortality, support the US EPA conclusion. When pollutants other than SO_2 were not accounted for in the statistical analyses, positive and statistically significant associations between SO_2 concentrations in the air and mortality were reported in 20 studies. No significant association was seen in five studies and a significant negative association was reported in one study. Since SO_2 was only one of many air pollutants, such analyses could not rule out the possibility that SO_2 was only a marker of other pollutants but not a “causal” factor. An attempt to differentiate between the effects of different air pollutants by including them in a statistical model simultaneously was made in seven studies (two- or multi-pollutant analyses). In six of these studies, the positive association seen in the single-pollutant analysis was reduced and lost statistical significance. Overall, despite many positive associations reported between ambient SO_2 concentrations and mortality, the data suggest that these may not be “true” associations but



a reflection of the effects of other air pollutants (more commonly, the causal association is attributed to particulate matter and ozone).

The Advisory Committee (US EPA 2008a) concluded that the evidence was inadequate to infer the presence or absence of a causal relationship for:

- short-term SO₂ exposure and cardiovascular morbidity;
- long-term SO₂ exposure and respiratory morbidity;
- long-term SO₂ exposure and non-respiratory morbidity; and
- long-term SO₂ exposure and mortality.

Studies published from 2008 to 2012 investigated the possible relationship between short-term SO₂ exposure and indices of cardiovascular health, such as electrocardiographic parameters, pulse rate, blood pressure, biochemical markers of cardiovascular risk, hospitalizations and emergency department visits for cardiovascular diseases. The results do not show a consistent pattern that would suggest a causal link between SO₂ and cardiovascular morbidity.

Studies published from 2008 to 2012 examined possible associations between long-term exposure to SO₂ and respiratory diseases and non-respiratory outcomes including indices of cardiovascular health, cancer, prenatal/neonatal outcomes (e.g., low birth weight, preterm births, birth defects, and stillbirths) as well as total, cardiovascular and respiratory mortality. Due to lack of consistency across studies and inability in many studies to discriminate between the effects of SO₂ and the effects of other air pollutants, the recent literature does not substantially deviate from the US EPA (US EPA 2008a) finding regarding inadequacy of the existing data for a conclusion about causality.

3.2.2 Health Effects with a Causal Association to Nitrous Dioxide (NO₂)

This section provides a summary of the conclusions of a comprehensive scientific review by the US EPA (as of 2013) on the relationship between various health effects and exposures to NO₂. This summary replicates and summarizes the corresponding text in the Kitimat Airshed Assessment report, for the convenience of the reader. More recent literature on NO₂ was not reviewed as part of this project.

In 2008, the Scientific Advisory Committee of the US EPA issued a report (US EPA 2008b) which concluded that there was sufficient scientific evidence to infer a likely causal relationship between short-term exposure to NO₂ and respiratory effects. Epidemiological, controlled human exposure studies, and animal toxicological studies demonstrated that exposure to NO₂ could affect lung host-defense and immune systems and increase the risk of susceptibility to viral and bacterial infections, increase airway inflammation, airway responsiveness to specific allergen challenges and to nonspecific challenges, such as cold air, histamine, methacholine, or SO₂. These are potential mechanisms by which exposure to NO₂ may exacerbate upper and lower airway symptoms (US EPA 2008b).

In its more recent November 2013 draft report (US EPA 2013), the US EPA strengthened the causal determination from a likely causal relationship to a more certain causal relationship mainly because recent epidemiological studies reduced uncertainty regarding confounding by co-pollutants; associations between short-term NO₂ exposure and respiratory effects remained



positive after adjustments for other air pollutants such as particulate matter, ozone, and sulphur dioxide.

Scientific evidence for other combinations of exposure duration and health effects was classified by the US EPA (2008b) as either suggestive of a causal relationship (short-term exposure and total mortality, long-term exposure and respiratory effects) or inadequate for making any conclusion regarding causality (long-term exposure and cardiovascular, reproductive, developmental effects, total mortality and cancer). Based on recent literature, the US EPA (2013) upgraded causal determinations for several outcomes for which scientific evidence was previously classified as inadequate, and changed it to suggestive of a causal relationship or likely to be a causal relationship. In some cases, recent studies demonstrated health effects where previous findings were inconsistent or negative. In other cases, recent studies reduced the uncertainty regarding potential confounding from co-pollutants. New data added to the understanding of biological mechanisms by which health effects may occur (US EPA 2013).

Pre-existing asthma, chronic obstructive pulmonary disease (COPD), genetic factors for oxidant and inflammatory damage, and low socio-economic status, may result in greater susceptibility to the effects of NO₂ exposure (US EPA 2008b, 2013). The evidence that children (0-14 years) and older individuals (≥65 years) represent populations susceptible to the effects of NO₂ was stronger and was classified by the US EPA (2013) as “adequate”.

3.2.3 Health Effects with a Causal Association to Fine Particulate Matter (PM_{2.5})

This section provides a summary of the conclusions of a comprehensive scientific review by the US EPA (as of 2009) on the relationship between various health effects and exposures to PM_{2.5}. More recent literature on PM_{2.5} was not reviewed as part of this project.

Causal determinations for short-term exposure to PM_{2.5} are summarized in Table 2-1 of the US EPA (2009) report. Causal determinations for long-term exposures are summarized in Table 2-2 of that report. In the following sections, we provide some data extracted from the US EPA (2009) report regarding the scientific basis for causal inferences for short- and long-term PM_{2.5} exposures. More details can be found in Section 2.3.1.1 (pp. 2-9 to 2-11) and in Chapter 6 of the US EPA report for short-term exposure, in Section 2.3.1.2 (pp. 2-11 to 2-13), and in Chapter 7 for long-term exposure.

Short-Term Exposure

Causal relationship

Cardiovascular Effects

In epidemiological studies, exposures to PM_{2.5} were consistently positively associated with emergency department (ED) visits, hospital admissions (predominantly for ischemic heart disease and congestive heart failure), and cardiovascular mortality.

PM_{2.5}-induced changes in measures of cardiovascular function (most consistently for altered vasomotor function) among healthy and health-compromised adults were demonstrated in controlled human exposure studies. Toxicological studies in non-human animals demonstrated altered vessel tone and microvascular reactivity, thus providing evidence for biological



plausibility of the vasomotor effects observed in the controlled human exposure and epidemiological studies.

Mortality

Consistent positive associations between short-term exposure to PM_{2.5} and all-cause, cardiovascular-, and respiratory-related mortality were reported in epidemiological studies.

Likely to be a causal relationship

Respiratory Effects

Epidemiological studies report consistent positive associations between short-term exposure to PM_{2.5} and ED visits and hospital admissions for COPD and respiratory infections. Positive associations observed for asthma ED visits and hospital admissions for adults and children combined were not consistently positive for children alone. Multi-city epidemiological studies reported consistent positive associations between short-term exposure to PM_{2.5} and mortality from respiratory diseases. Panel studies show associations with respiratory symptoms, pulmonary function, and pulmonary inflammation among asthmatic children. Controlled human exposure studies report (although not consistently) small decrements in various measures of pulmonary function following exposures to PM_{2.5}. Controlled human exposure studies in adult volunteers also demonstrate increased markers of pulmonary inflammation, oxidative responses, exacerbations of allergic responses and allergic sensitization following exposure to diesel exhaust particles. Toxicological non-human animal studies report a range of effects, including altered lung function, mild pulmonary inflammation and injury, oxidative responses, airway hyper-responsiveness in allergic and non-allergic animals, exacerbations of allergic responses, and increased susceptibility to infections. The evidence “is somewhat restricted by limited coherence between some of the findings from epidemiological and controlled human exposure studies for the specific health outcomes reported and the sub-populations in which those health outcomes occur” (US EPA 2009).

Inferences regarding central nervous system (CNS) effects and their scientific basis are summarized (Section 6.4.4 of US EPA 2009) for PM of all particle sizes (rather than PM_{2.5} specifically). The US EPA concluded that “**evidence is inadequate** to determine if a causal relationship exists between short-term exposures to PM_{2.5}, PM_{10-2.5}, or UFPs [ultrafine particles] and CNS effects.”

Long-Term Exposure

Causal relationship

Cardiovascular Effects

The strongest evidence comes from large, multi-city U.S.-based studies that consistently report associations between long-term exposure to PM_{2.5} and cardiovascular mortality. Supporting evidence comes from a large US-based epidemiological study that reports associations between PM_{2.5} and cardiovascular diseases among post-menopausal women. Epidemiological studies of subclinical markers of cardiovascular diseases provide inconsistent findings. Toxicological studies report accelerated development of atherosclerosis in susceptible mice



exposed to concentrated ambient particles, effects on coagulation, experimentally-induced hypertension, and vascular reactivity, thus providing evidence for biological plausibility of the findings from human studies.

Mortality

The epidemiological literature reports associations between long-term PM_{2.5} exposure and mortality. The evidence is strongest for cardiovascular mortality. Positive associations were also reported for lung cancer mortality. The evidence for an association between long-term exposure to PM_{2.5} and respiratory mortality is limited. The evidence for cardiovascular and respiratory morbidity due to short- and long-term exposures provides biological plausibility for mortality from cardiovascular and respiratory diseases.

Likely to be a causal relationship

Respiratory Effects

Epidemiological studies provide evidence for associations between long-term PM_{2.5} exposure and decrements in lung function growth in children, increased respiratory symptoms, and development of asthma. The evidence for an association between long-term exposure to PM_{2.5} and respiratory mortality is limited. Toxicological studies with concentrated ambient particles, diesel exhaust, roadway air, and wood smoke provide some evidence for altered pulmonary function, mild inflammation, oxidative responses, immune suppression, histopathological changes in the respiratory tract, and exacerbated allergic responses. Pre- and postnatal exposure to ambient levels of urban particles affected lung development in experimental non-human animals. Impaired lung development is a mechanism by which PM may decrease lung function growth in children.

Suggestive of a causal relationship

Reproductive and Developmental

Evidence is accumulating for the effects of PM_{2.5} exposure on low birth weight and infant mortality, particularly due to respiratory diseases during the post-neonatal period. Associations between long-term exposure to PM and preterm birth, growth restriction, birth defects or decreased sperm quality are not consistently reported. Toxicological studies support an association between PM and adverse reproductive and developmental outcomes, but provide little information on possible mechanisms or biological plausibility for an association between long-term PM exposure and adverse birth outcomes (e.g., low birth weight or infant mortality).

Cancer, Mutagenicity, and Genotoxicity

Multiple epidemiological studies demonstrate a consistent positive association between PM_{2.5} and lung cancer mortality, but (generally) not with lung cancer incidence. Animal toxicological studies have not focused on specific size fractions of PM. A number of animal studies provide biological plausibility for the epidemiological results by demonstrating that ambient PM and PM from specific combustion sources are mutagenic and genotoxic. A limited number of epidemiological and toxicological studies examined epigenetic effects and demonstrated some changes in methylation. It has to be determined how these alterations could influence cancer



initiation and promotion. Inflammation and immune suppression induced by PM may increase susceptibility to cancer.

Potentially Susceptible Populations

Factors increasing susceptibility to adverse health effects of PM (all size fractions combined) are listed in Table 8-2 of the US EPA (2009) report. These include:

- older adults (≥65 years old);
- children (<18 years old);
- genetic polymorphisms;
- cardiovascular diseases;
- respiratory illnesses;
- socio-economic status (SES) and surrogates for SES such as educational attainment and residential location.

Limited evidence indicates that diabetes, obesity, and pregnancy increase susceptibility to the effects of PM.

3.2.4 Summary of Causality Determinations for SO₂, NO₂ and PM_{2.5}

A summary of the status of current causality determinations for the linkage between various categories of health effects and exposure to both short-term and long-term exposure to SO₂, NO₂ and PM_{2.5} is provided in Table 3-1. The determinations for SO₂ are based on the 2008 US EPA Integrated Assessment (US EPA 2008a), and a previously conducted literature review covering 2008 to late October 2012, previously described (ESSA et al. 2013). The determinations for NO₂ are taken directly from the recent US EPA *Integrated Science Assessment for Oxides of Nitrogen (External Review Draft)* report (US EPA 2013). The determinations for PM_{2.5} are from the US EPA *Integrated Science Assessment for Particulate Matter* (US EPA 2009).

Table 3-1: Weight of evidence in support of causation for different health effects and durations of exposure to oxides of sulphur and nitrogen and fine particulate matter (PM_{2.5}).

Health effect	Evidence for causality		
	SO _x /SO ₂	NO _x /NO ₂	PM _{2.5}
Short-term exposure			
Respiratory effects	Sufficient to infer a causal relationship	Causal relationship	Causal relationship
Mortality	Suggestive but not sufficient to infer a causal relationship	Likely to be a causal relationship	Causal relationship
Cardiovascular effects	Inadequate to infer the presence or absence of a causal relationship	Likely to be a causal relationship	Likely to be a causal relationship
Long-term exposure			
Respiratory effects	Inadequate to infer the presence or absence of a causal relationship	Likely to be a causal relationship	Likely to be a causal relationship



Health effect	Evidence for causality		
	SO _x /SO ₂	NO _x /NO ₂	PM _{2.5}
Cardiovascular effects	Inadequate to infer the presence or absence of a causal relationship	Suggestive of a causal relationship	Causal relationship
Reproductive and developmental effects	Inadequate to infer the presence or absence of a causal relationship	Suggestive of a causal relationship	Suggestive of a causal relationship
Mortality	Inadequate to infer the presence or absence of a causal relationship	Suggestive of a causal relationship	Causal relationship
Cancer	Inadequate to infer the presence or absence of a causal relationship	Suggestive of a causal relationship	Suggestive of a causal relationship

The status of the causal relationships is subject to change, and tends to include more health endpoints over time in the higher categories (causal, likely to be causal). This is due to the accumulation of evidence over time that is needed to meet the requirement for consistency in findings, and the gradual removal of sources of uncertainty such as exposure estimates and confounding. This suggests that the potential for additional short-term and long-term health outcomes may need to be considered in a subsequent assessment.

3.3 Adaptation of an Air Quality Management Scheme for PM_{2.5}, SO₂, and NO₂

In order to provide a crude characterization of the continuum of potential health risk and the level of management attention to be applied for different scenarios leading to different exposures to PM_{2.5}, SO₂ and NO₂, a health effects assessment scheme was developed. The scheme allows for the assignment of different levels of exposure (i.e., in the form of summary statistics of ambient concentrations) to a series of categories corresponding to increasing need for management attention based on indications of increased potential public health risk. This was based on the existing air quality management framework developed by the CCME which provides a relevant categorization scheme, but is currently limited to providing categories based on numerical management thresholds for particulate matter and ozone derived from current and future CAAQS for these two pollutants.

3.3.1 Adaptation of CCME-Compatible Thresholds for BC Air Quality Objectives for PM_{2.5}, SO₂ and NO₂

The CCME has recently published an air quality management scheme which contains proposed air management threshold values for ozone and particulate matter (PM_{2.5}) (CCME 2012). These are illustrated in Figure 3-1. The key properties of this categorization scheme are the provision of three thresholds for ambient concentrations (specifically, thresholds for various statistics of the ambient concentrations, such as the annual mean or an upper percentile (e.g., 98th or 99th) value of hourly concentrations). These three thresholds divide potential ambient exposure statistics into four categories that are associated with colours.



These four categories are:

- Green: the lowest category associated with very low exposures. A management threshold value separates the Green and Yellow category, and is associated with the range of ambient concentrations associated with “clean” environments.
- Red: the highest category is associated with concentrations above the management threshold level set equal to the Canadian Ambient Air Quality Standards (CAAQS).
- Yellow: a third management threshold lies midway between the levels that separate Green and Yellow, and the CAAQS levels. Concentration values below this level, but higher than Green, are assigned Yellow.
- Orange: above the midway threshold, but below the Red category, the concentration values are assigned to the category labelled Orange.

Management Level	Management Actions	Proposed Air Management Threshold Values					
		Ozone (ppb)		PM _{2.5} Annual (µg/m ³)		PM _{2.5} 24h (µg/m ³)	
		2015	2020	2015	2020	2015	2020
RED	Actions for Achieving Air Zone CAAQS						
Threshold	63 ppb	62 ppb	10.0 µg/m ³	8.8 µg/m ³	28 µg/m ³	27 µg/m ³	
ORANGE	Actions for Preventing CAAQS Exceedance						
Threshold	56 ppb		6.4 µg/m ³		19 µg/m ³		
YELLOW	Actions for Preventing AQ Deterioration						
Threshold	50 ppb		4.0 µg/m ³		10 µg/m ³		
GREEN	Actions for Keeping Clean Areas Clean						

Figure 3-1: Illustration of the CCME Air Management Categorization Scheme (extracted from CCME 2012).

The air management categorization scheme used for this health assessment was derived from the CCME approach, but adapted to employ the BC Air Quality Objectives for PM_{2.5}, and Interim Air Quality Objectives for SO₂ and NO₂. Table 3-2 illustrates this scheme, with threshold values provided for PM_{2.5}, NO₂ and SO₂, followed by an explanation of how these values were derived.



Table 3-2: Adaptation of the CCME Air Management Categorization Scheme to apply BC Air Quality Objectives for PM_{2.5} and Interim Air Quality Objectives for SO₂ and NO₂.

PM _{2.5} Annual Average	PM _{2.5} 24h Average (98 th %ile)	SO ₂ Annual Average	SO ₂ Hourly (99 th %ile)	NO ₂ Annual Average	NO ₂ Hourly (98 th %ile)
8 µg/m ³	25 µg/m ³	30 µg/m ³	200 µg/m ³	60 µg/m ³	188 µg/m ³
6 µg/m ³	17 µg/m ³	15 µg/m ³	100 µg/m ³	32 µg/m ³	105 µg/m ³
4 µg/m ³	10 µg/m ³	1 µg/m ³	5 µg/m ³	5 µg/m ³	22 µg/m ³

British Columbia has Air Quality Objectives for PM_{2.5} that are lower than the CAAQS. The lower values (8 µg/m³ for an annual average and 25 µg/m³ for a 24 hour average) were employed in the adapted scheme in place of the CAAQS, as the upper threshold (i.e., Red from Orange).

To date, CAAQS have not been established for SO₂ and NO₂. British Columbia does not employ a criterion for the annual average concentration of SO₂, however there is a Canadian National Ambient Air Quality Objective of 30 µg/m³ (CCME 1999). In November 2014, British Columbia adopted Interim Air Quality Objectives for SO₂ and NO₂ (BC MOE 2014). The Interim Objective that applies to the hourly 99th percentile for SO₂ is 200 µg/m³. The Interim Objective that applies to the annual mean for NO₂ is 60 µg/m³. The Interim Objective that applies to the hourly 98th percentile for NO₂ is 188 µg/m³. Each of these values has been employed in the adapted scheme in Table 3-2, as the threshold that separates Red from Orange. A new proposed CAAQS value for SO₂ is under development and discussion (which may also result in proposed CCME management levels) and is expected to be publicly released in the near future (2015). A new proposed CAAQS for NO₂ is also expected to be developed, but the timing of its public release is less clear.

Table 3-2 also includes other threshold values consistent with the CCME approach. Values to define the lower or Green thresholds for SO₂ and NO₂ were provided by MOE. These values were based on observed levels in more than 35 communities in BC in the years 2010-2012 that are not affected by significant local sources of these pollutants, and using the 10th percentile values (to be consistent with the CCME characterization of this category as being akin to levels expected in “a clean location on a good day”). The lower thresholds adopted by CCME for the two PM_{2.5} CAAQS (4 µg/m³ and 10 µg/m³) have been employed here. It is important to note that these Green/Yellow threshold levels are not equivalent to the concept of background concentrations discussed below. By extension, the mid-way (Yellow/Orange) points were calculated as approximately halfway between the upper (Orange/Red) thresholds based on the Air Quality Objectives and the lower (Green/Yellow) threshold values. To simplify the scheme, some rounding (downward) of the mid-way thresholds was applied (e.g., 15.5 rounded down to 15, 102.5 rounded to 100).



Given that only one year of meteorological data was used in the air dispersion modelling, for present purposes the 99th and 98th percentile values have been derived from a single year of air dispersion modelling data.

3.3.2 Interpretation of CCME Air Quality Management Levels

The air quality management levels (as designated by the CCME Air Quality Management Scheme) do not have a direct relationship to health risk. The results, and the colour-coded categorization scheme, are intended to provide an indication of the level of management attention that should be paid to the air quality in an air zone. The transitions from Green to Yellow, from Yellow to Orange, and from Orange to Red, do not correspond to abrupt changes in the health status of the community. Rather, they provide an indication that further analysis and management attention is required. The intent of the management levels (as distinct from health risk thresholds) is captured in the following quote from the description of the CCME Air Zone Management Framework (AZMF):

“Under the AZMF, progressively more rigorous actions are to be implemented at an air zone level as air quality approaches or exceeds the CAAQS. Four “Management Levels”, covering all PM_{2.5} and ozone concentrations, provide general guidance on the nature of the management, monitoring and reporting actions to be implemented in air zones” (CCME 2012).

It is important to note that this PRAS report does not attempt to describe whether the level of health risk should be deemed acceptable or unacceptable. The report’s results are limited to the assignment of CCME management levels as those concepts are defined by the CCME (CCME 2012).

A key barrier to defining absolute levels to differentiate acceptable versus unacceptable levels of exposure relates to the shape of the dose-response curve at levels below the CAAQS. For PM_{2.5} and NO₂, the dose-response curve is generally considered to be quasi-linear (US EPA 2008b, 2010, 2013). This implies that it is not possible to define a threshold for which no harm is expected when exposures are below this threshold. In other words, there is an incremental increase in risk with each increment of exposure even when exposures are well below the CAAQS. The shape of the dose-response for exposures to SO₂ might be quite different. As of 2009, US EPA found that there was “no evidence to indicate that exposure to 200-300 ppb SO₂ for 5-10 minutes represents a threshold below which no respiratory effects occur” (US EPA 2009b). However, an alternate argument may be made with more up-to-date information to derive a threshold below which respiratory effects are considered to be very unlikely, even for vulnerable populations. This type of threshold determination would allow for a closer linkage between the threshold and the concept of an *acceptable* level of exposure from the human health perspective.

IMPORTANT: The colour categories used in the human health effects assessment component of this study have the meanings intended by the CCME (CCME 2012) and do not have the same interpretation as the risk categories for the environmental receptors in this report (vegetation, soils, lakes).



3.4 Results

3.4.1 Locations Considered for Human Health

The human health assessment considered 34 different locations across three receptor types: community locations, recreational and cultural locations, and industrial locations. The communities are all identified in the left-hand panel of Figure 3-2, and receptor locations across all three types are shown in the right-hand panel.

3.4.2 Threshold-based Categorization Calculated using the EPA NAAQS Protocol

In consultation with MOE, it was determined that the preferred approach to employing the CCME-compatible air zone management categorization scheme was to use the US EPA's specific methods of calculating the appropriate statistic for the modelled concentrations, including treatment of background concentrations. This was conducted with the exception of the requirement to average over three years which was not possible given only one year of modelled results. In the case of the BC Air Quality Objectives for PM_{2.5}, SO₂ and NO₂, attainment of the objectives is specifically noted as being based on a single year of data (see notes i,j,l of Table 1 of the BC Air Quality Objectives) (BC MOE 2014).

A key element in employing the US EPA method was to characterize an area by considering the point within the area that had the largest value (i.e., the maximum) of each statistic (i.e., for both averages and percentile values). Additionally, the US EPA approach calls for a specific method to calculate the 99th percentile and the 98th percentile values. The method of calculation involved the following:

- The calculation was done at every grid point, so that there was no spatial pooling of concentration values.
- A constant background value, consisting of the 99th (for SO₂) or 98th (for NO₂ and PM_{2.5}) percentile of estimated regional background concentration, was added to the corresponding concentration statistic at each grid point.
- For the 99th percentile values (for SO₂), the daily maximum of hourly averages was calculated. The fourth highest daily maximum (including the added background value) was taken as the 99th percentile value for purposes of comparison with the threshold value. (The fourth highest was chosen since 1% of 365 days is 3.65 days.)
- The calculation of the 98th percentile (for NO₂ and PM_{2.5}) was identical to the calculation of the 99th percentile (for SO₂) except for the exclusion of seven days rather than three. (The eighth highest was chosen since 2% of 365 days is 7.3 days.) For PM_{2.5}, the upper percentile statistic of interest is the 24-hour average, rather than the daily maximum of the hourly averages.
- For each location (which consists of multiple grid points), the largest such percentile value among the grid points was compared to the corresponding thresholds in order to assign a colour category.



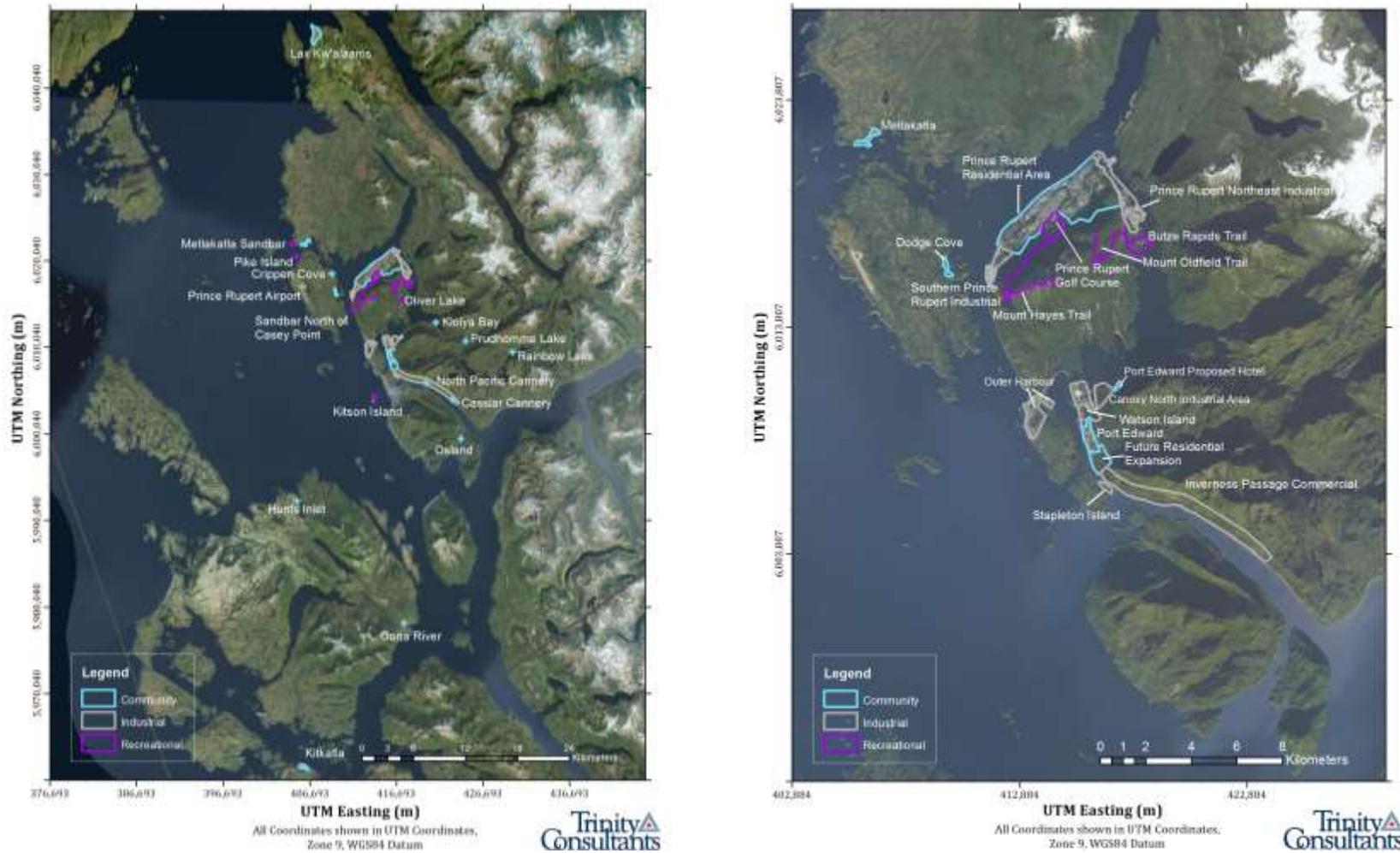


Figure 3-2: Left panel: Location of the community, industrial and recreational/cultural receptors assessed in the study. Labels are provided for point locations and farthest communities in the study area: Lax Kw'alaams and Kitkatla. The remaining area-based receptors are shown in the right panel. Right panel: Zoomed location of the community, industrial and recreational/cultural receptors assessed in the study. Point locations and two communities (Lax Kw'alaams and Kitkatla) in the left panel are not shown in this map.

When calculating annual average values for comparison to thresholds, several of the same points apply:

- The calculation was done at every grid point, so that there was no spatial pooling of concentration values.
- A constant background value, the annual average of estimated regional background concentrations, was added to the concentration at each grid point.
- For each location (which consists of multiple grid points), the largest such annual average value among the grid points was compared to the corresponding threshold in order to assign a colour category.

The background values used for each calculation are listed in the table below, and in the upper-left hand corner of each table that follows. It is important to note that the concept of background concentrations for these purposes and the management threshold for Green/Yellow in the CCME categorization scheme are not the same. In many cases, the background estimates exceeds the Green/Yellow management threshold such that all locations are in the Yellow category even without the contribution from additional modelled emissions.

PM _{2.5} Annual Average	3.50 µg/m ³
PM _{2.5} 24-Hour 98 th Percentile	7.00 µg/m ³
SO ₂ Annual Average	4.00 µg/m ³
SO ₂ Hourly 99 th Percentile	10.67 µg/m ³
NO ₂ Annual Average	5.64 µg/m ³
NO ₂ Hourly 98 th Percentile	24.44 µg/m ³

3.4.3 Categorization of Annual Average Concentrations of PM_{2.5}

Table 3-3 provides the values for the maximum annual average concentration of PM_{2.5} among the grid points assigned to each location, for each of the six scenarios. The colours are assigned based on the thresholds described in Table 3-2. Results are rounded to one decimal place for display in the tables, and therefore may have an unexpected colour. For example, the value in Scenario D at Dodge Cove was 6.0015, so that cell is Orange.

Table 3-3: Maximum annual average concentration of PM_{2.5} within each location, and associated colour categorization.

Concentrations in µg/m ³ Background = 3.50 µg/m ³	Scenario					
	A	B	C	D	E	F_R
Human Health Receptor Location						
Residential						
Dodge Cove	6.3	6.0	6.7	6.0	6.3	6.8
Future Residential Expansion	4.8	4.8	5.0	4.8	4.9	5.2
Kitkatla	3.6	3.6	3.6	3.6	3.6	3.6
Lax Kw'alaams	4.0	3.8	4.1	3.9	4.0	4.2



Concentrations in $\mu\text{g}/\text{m}^3$ Background = $3.50 \mu\text{g}/\text{m}^3$	Scenario					
	A	B	C	D	E	F_R
Human Health Receptor Location						
Metlakatla	4.9	4.7	5.2	4.7	4.9	5.3
Port Edward Proposed Hotel	4.8	4.6	5.1	4.7	4.7	5.2
Port Edward Residential	5.3	5.1	5.6	5.2	5.3	5.7
Prince Rupert Residential	6.1	5.6	6.4	5.7	6.1	6.5
Rainbow Lake	4.1	4.0	4.2	4.0	4.2	4.4
Prudhomme Lake	4.3	4.1	4.5	4.2	4.3	4.7
Kloiya Bay	4.6	4.4	4.8	4.4	4.6	5.0
North Pacific Cannery	4.4	4.2	4.6	4.3	4.5	4.8
Cassiar Cannery	4.4	4.1	4.5	4.1	4.4	4.7
Osland	4.0	3.9	4.2	3.9	4.1	4.4
Hunts Inlet	3.7	3.6	3.7	3.7	3.7	3.8
Oona River	3.7	3.6	3.7	3.6	3.7	3.8
Crippen Cove	6.1	5.7	6.3	5.7	6.0	6.5
Cultural & Recreational						
Prince Rupert Golf Course	5.0	4.7	5.2	4.8	5.0	5.4
Mount Oldfield Trail	5.1	4.8	5.5	4.8	5.2	5.8
Mount Hayes Trail	7.6	7.1	8.3	7.3	7.9	8.7
Butze Rapids Trail	4.7	4.4	4.8	4.5	4.6	5.0
Metlakatla Sandbar	4.4	4.2	4.6	4.2	4.4	4.7
Pike Island	4.4	4.2	4.6	4.3	4.4	4.7
Sandbar North of Casey Point	7.4	6.9	7.8	7.0	7.5	7.9
Oliver Lake	4.8	4.6	5.0	4.6	4.8	5.2
Kitson Island	4.1	4.1	4.3	4.1	4.2	4.4
Industrial						
Canoxy North Industrial	5.1	4.9	5.5	5.1	5.0	5.6
Outer Harbour Industrial	26.1	25.6	26.8	25.6	26.5	27.0
Inverness Passage Commercial	4.9	4.7	5.3	4.7	5.1	5.6
Prince Rupert NE Industrial	4.6	4.4	4.8	4.4	4.6	5.0
Southern Prince Rupert Industrial	21.4	20.9	21.7	21.0	21.4	21.9
Stapleton Island Industrial	4.5	4.3	4.6	4.4	4.5	4.7
Watson Island Industrial	5.6	5.4	6.4	5.9	5.6	6.5
Prince Rupert Airport	4.5	4.3	4.6	4.3	4.5	4.7



3.4.4 Categorization of 98th Percentile of 24-Hour Averaged Concentrations of PM_{2.5}

Table 3-4 provides the values for the maximum of the 98th percentile of the 24-hour averaged concentrations of PM_{2.5} among the grid points assigned to each location, for each of the six scenarios. The colours are assigned based on the thresholds described in Table 3-2.

Table 3-4: Maximum 98th percentile of the 24-hour averaged concentration of PM_{2.5}.

Concentrations in µg/m ³ Background = 7.00 µg/m ³	Scenario					
	A	B	C	D	E	F_R
Human Health Receptor Location						
Residential						
Dodge Cove	20.2	19.7	20.5	19.3	20.5	21.2
Future Residential Expansion	14.5	14.3	15.0	14.6	14.8	15.6
Kitkatla	7.8	7.7	8.1	7.8	8.0	8.7
Lax Kw'alaams	9.7	8.8	10.1	8.9	9.7	10.6
Metlakatla	12.4	11.7	13.2	11.6	12.2	13.4
Port Edward Proposed Hotel	15.7	13.7	16.4	15.0	13.7	17.0
Port Edward Residential	18.5	17.1	19.5	17.5	17.6	20.2
Prince Rupert Residential	20.1	18.6	20.4	18.8	19.5	21.4
Rainbow Lake	11.5	10.5	12.1	10.8	11.5	13.3
Prudhomme Lake	12.9	12.1	13.7	12.2	12.9	15.1
Kloiya Bay	15.8	14.0	16.4	14.7	14.4	16.8
North Pacific Cannery	11.7	10.8	13.1	11.3	12.4	14.4
Cassiar Cannery	12.1	10.7	13.1	11.0	12.9	14.4
Osland	11.2	10.2	12.0	9.9	11.4	13.3
Hunts Inlet	8.7	8.2	9.0	8.4	8.7	9.6
Oona River	8.4	8.1	9.0	8.2	8.8	9.7
Crippen Cove	17.8	16.4	18.7	16.2	18.3	19.4
Cultural & Recreational						
Prince Rupert Golf Course	16.9	14.8	17.6	15.3	16.3	18.7
Mount Oldfield Trail	17.1	15.6	19.0	15.1	17.3	20.7
Mount Hayes Trail	28.9	26.9	30.2	26.8	29.4	31.3
Butze Rapids Trail	15.2	13.7	15.7	14.1	14.6	16.9
Metlakatla Sandbar	9.9	9.2	10.4	9.3	9.9	10.6
Pike Island	9.9	9.5	10.5	9.6	10.0	10.7
Sandbar North of Casey Point	27.0	25.9	27.4	25.8	26.8	28.2
Oliver Lake	16.2	14.2	17.0	14.5	15.2	17.8
Kitson Island	11.4	11.3	12.2	11.3	12.3	13.5



Concentrations in $\mu\text{g}/\text{m}^3$ Background = 7.00 $\mu\text{g}/\text{m}^3$	Scenario					
	A	B	C	D	E	F_R
Human Health Receptor Location						
Industrial						
Canoxy North Industrial	18.0	16.9	19.9	19.0	16.4	20.6
Outer Harbour Industrial	117.3	117.3	117.4	117.3	117.2	117.5
Inverness Passage Commercial	15.6	14.0	17.4	14.2	16.9	19.5
Prince Rupert NE Industrial	14.6	13.0	15.0	13.0	13.9	16.2
Southern Prince Rupert Industrial	66.6	65.9	66.9	66.4	66.1	67.2
Stapleton Island Industrial	12.5	11.8	13.5	12.0	13.0	14.7
Watson Island Industrial	18.6	18.4	19.6	18.5	17.8	20.5
Prince Rupert Airport	10.3	9.9	11.0	10.1	10.4	11.2

3.4.5 Categorization of Annual Average Concentrations of SO₂

Table 3-5 provides the values for the maximum of the annual average concentrations of SO₂ among the grid points assigned to each location, for each of the six scenarios. The colours are assigned based on the thresholds described in Table 3-2.

Table 3-5: Maximum annual average concentration of SO₂ within each location, and associated colour categorization.

Concentrations in $\mu\text{g}/\text{m}^3$ Background = 4.00 $\mu\text{g}/\text{m}^3$	Scenario					
	A	B	C	D	E	F_R
Human Health Receptor Location						
Residential						
Dodge Cove	7.9	7.5	7.9	7.5	7.7	7.9
Future Residential Expansion	5.0	4.6	5.0	4.7	4.8	5.0
Kitkatla	4.0	4.0	4.0	4.0	4.0	4.0
Lax Kw'alaams	4.2	4.1	4.2	4.2	4.1	4.2
Metlakatla	4.9	4.7	4.9	4.8	4.8	4.9
Port Edward Proposed Hotel	4.7	4.3	4.7	4.6	4.4	4.7
Port Edward Residential	5.2	4.6	5.3	5.0	4.8	5.3
Prince Rupert Residential	6.0	5.8	6.0	5.8	5.9	6.0
Rainbow Lake	4.1	4.1	4.1	4.1	4.1	4.1
Prudhomme Lake	4.2	4.1	4.2	4.1	4.1	4.2
Kloiya Bay	4.3	4.2	4.3	4.2	4.2	4.3
North Pacific Cannery	4.6	4.3	4.6	4.3	4.5	4.6
Cassiar Cannery	4.4	4.2	4.4	4.2	4.4	4.4
Osland	4.2	4.1	4.2	4.1	4.2	4.2
Hunts Inlet	4.1	4.0	4.1	4.0	4.1	4.1



Concentrations in $\mu\text{g}/\text{m}^3$ Background = 4.00 $\mu\text{g}/\text{m}^3$	Scenario					
Human Health Receptor Location	A	B	C	D	E	F_R
Oona River	4.1	4.0	4.1	4.0	4.1	4.1
Crippen Cove	6.8	6.5	6.8	6.5	6.6	6.8
Cultural & Recreational						
Prince Rupert Golf Course	4.8	4.6	4.8	4.7	4.7	4.8
Mount Oldfield Trail	4.9	4.5	4.9	4.6	4.7	4.9
Mount Hayes Trail	12.3	11.6	12.4	11.8	12.0	12.4
Butze Rapids Trail	4.4	4.2	4.4	4.3	4.3	4.4
Metlakatla Sandbar	4.5	4.3	4.5	4.4	4.4	4.5
Pike Island	4.6	4.4	4.6	4.4	4.5	4.6
Sandbar North of Casey Point	7.2	6.7	7.2	6.8	7.0	7.2
Oliver Lake	4.5	4.3	4.5	4.4	4.4	4.5
Kitson Island	4.6	4.3	4.6	4.3	4.5	4.6
Industrial						
Canoxy North Industrial	5.5	4.3	5.6	5.4	4.5	5.6
Outer Harbour Industrial	7.3	4.8	7.5	6.2	6.3	7.5
Inverness Passage Commercial	5.4	4.8	5.4	4.9	5.3	5.4
Prince Rupert NE Industrial	4.5	4.3	4.5	4.3	4.5	4.5
Southern Prince Rupert Industrial	26.6	26.2	26.7	26.4	26.5	26.7
Stapleton Island Industrial	4.9	4.3	4.9	4.4	4.8	4.9
Watson Island Industrial	7.4	4.6	7.7	7.3	4.9	7.7
Prince Rupert Airport	5.0	4.8	5.0	4.9	4.9	5.0

3.4.6 Categorization of 99th Percentile of Hourly Average Concentrations of SO₂

Table 3-6 provides the values for the maximum of the 99th percentile of the daily maximum hourly concentrations of SO₂ among the grid points assigned to each location, for each of the six scenarios. The colours are assigned based on the thresholds described in Table 3-2.

Table 3-6: Maximum 99th Percentile of the daily maximum of hourly averaged concentrations within each location, and associated colour categorization.

Concentrations in $\mu\text{g}/\text{m}^3$ Background = 10.67 $\mu\text{g}/\text{m}^3$	Scenario					
Human Health Receptor Location	A	B	C	D	E	F_R
Residential						
Dodge Cove	103.6	103.2	103.6	103.3	103.5	103.6
Future Residential Expansion	112.3	31.6	112.7	41.1	112.4	112.7
Kitkatla	12.3	11.4	12.3	11.5	11.9	12.3



Concentrations in $\mu\text{g}/\text{m}^3$ Background = 10.67 $\mu\text{g}/\text{m}^3$	Scenario					
	A	B	C	D	E	F_R
Human Health Receptor Location						
Lax Kw'alaams	20.9	15.7	20.9	20.9	15.9	20.9
Metlakatla	44.1	39.3	44.3	39.9	42.9	44.3
Port Edward Proposed Hotel	37.3	24.2	39.5	32.8	28.5	39.5
Port Edward Residential	72.0	35.9	80.0	79.7	67.6	80.0
Prince Rupert Residential	92.8	92.0	92.8	92.1	92.6	92.8
Rainbow Lake	16.6	14.4	17.1	15.9	16.3	17.1
Prudhomme Lake	18.1	16.2	18.5	17.5	17.5	18.5
Kloiya Bay	22.8	22.3	23.4	22.6	22.3	23.4
North Pacific Cannery	27.9	17.7	27.9	20.1	27.9	27.9
Cassiar Cannery	21.9	15.5	21.9	17.4	21.2	21.9
Osland	19.1	15.3	19.3	17.2	18.1	19.3
Hunts Inlet	15.8	13.7	16.0	14.2	15.0	16.0
Oona River	14.5	12.7	14.6	12.8	14.0	14.6
Crippen Cove	69.9	69.8	69.9	69.9	69.8	69.9
Cultural & Recreational						
Prince Rupert Golf Course	45.5	45.5	45.5	45.5	45.3	45.5
Mount Oldfield Trail	49.7	49.7	49.8	49.7	49.5	49.8
Mount Hayes Trail	181.9	176.8	181.9	177.3	176.9	181.9
Butze Rapids Trail	33.1	28.8	33.6	28.8	29.6	33.6
Metlakatla Sandbar	29.2	27.6	29.4	29.0	28.1	29.4
Pike Island	29.1	27.2	29.2	27.5	27.8	29.2
Sandbar North of Casey Point	136.9	136.7	136.9	136.7	136.9	136.9
Oliver Lake	30.0	29.8	30.0	29.9	28.0	30.0
Kitson Island	59.3	33.8	60.6	33.8	58.1	60.6
Industrial						
Canoxy North Industrial	62.6	27.2	68.5	68.5	36.7	68.5
Outer Harbour Industrial	63.3	62.5	67.0	67.0	63.3	67.0
Inverness Passage Commercial	86.9	33.2	86.9	49.0	86.9	86.9
Prince Rupert NE Industrial	32.9	32.6	32.9	32.6	32.9	32.9
Southern Prince Rupert Industrial	505.3	505.3	505.3	505.3	505.3	505.3
Stapleton Island Industrial	93.6	28.8	93.6	30.8	93.6	93.6
Watson Island Industrial	107.6	36.8	124.1	118.0	49.9	124.1
Prince Rupert Airport	43.4	43.1	43.4	43.4	43.4	43.4



3.4.7 Categorization of Annual Average Concentrations of NO₂

Table 3-7 provides the values for the maximum of the annual average concentrations of NO₂ among the grid points assigned to each location, for each of the six scenarios. The colours are assigned based on the thresholds described in Table 3-2.

Table 3-7: Maximum annual average concentration of NO₂ within each location, and associated colour categorization.

Concentrations in µg/m ³ Background = 5.64 µg/m ³	Scenario					
	A	B	C	D	E	F_R
Human Health Receptor Location						
Residential						
Dodge Cove	24.2	24.1	24.7	23.6	24.5	27.5
Future Residential Expansion	11.5	11.4	11.7	11.0	11.9	12.7
Kitkatla	5.8	5.8	5.8	5.8	5.8	6.0
Lax Kw'alaams	6.9	6.3	7.1	7.3	6.9	8.3
Metlakatla	10.4	10.0	10.7	9.8	10.8	12.5
Port Edward Proposed Hotel	8.0	7.9	8.3	7.8	8.3	9.4
Port Edward Residential	11.3	11.5	11.6	10.8	11.7	12.8
Prince Rupert Residential	17.2	16.9	17.6	16.7	18.3	19.5
Rainbow Lake	6.6	6.4	6.7	6.4	6.8	7.2
Prudhomme Lake	6.8	6.7	6.9	6.6	7.0	7.6
Kloiya Bay	7.2	7.0	7.4	7.0	7.5	8.2
North Pacific Cannery	10.2	9.9	10.4	9.8	10.7	11.4
Cassiar Cannery	9.9	9.7	10.1	9.6	10.4	11.0
Osland	7.2	7.1	7.4	6.9	7.7	8.2
Hunts Inlet	6.1	6.0	6.1	6.0	6.1	6.4
Oona River	6.0	6.0	6.1	5.9	6.1	6.4
Crippen Cove	17.2	16.9	17.7	16.5	17.9	19.9
Cultural & Recreational						
Prince Rupert Golf Course	9.5	9.3	9.8	9.2	10.2	11.1
Mount Oldfield Trail	9.2	8.9	9.7	8.7	10.7	12.4
Mount Hayes Trail	30.5	30.5	31.4	30.2	33.1	36.2
Butze Rapids Trail	7.7	7.4	7.9	7.3	8.0	8.8
Metlakatla Sandbar	8.6	8.4	8.9	8.2	8.9	10.3
Pike Island	9.0	8.8	9.3	8.6	9.1	10.8
Sandbar North of Casey Point	28.4	27.9	28.9	27.5	30.6	31.6
Oliver Lake	7.9	7.7	8.1	7.5	8.2	9.1
Kitson Island	7.9	7.7	8.1	7.1	8.6	9.1
Industrial						
Canoxy North Industrial	8.7	8.7	9.1	8.6	8.8	10.4



Concentrations in $\mu\text{g}/\text{m}^3$ Background = 5.64 $\mu\text{g}/\text{m}^3$	Scenario					
Human Health Receptor Location	A	B	C	D	E	F_R
Outer Harbour Industrial	11.8	11.5	12.9	10.5	18.1	19.1
Inverness Passage Commercial	13.2	12.9	13.5	12.7	14.1	15.0
Prince Rupert NE Industrial	8.3	7.4	8.5	7.4	9.0	9.7
Southern Prince Rupert Industrial	104.1	103.8	104.6	103.5	105.7	107.0
Stapleton Island Industrial	9.2	8.8	9.4	8.6	9.7	10.4
Watson Island Industrial	11.5	11.6	12.2	11.7	12.0	14.2
Prince Rupert Airport	10.1	9.8	10.4	9.5	10.2	11.6

3.4.8 Categorization of 98th Percentile of Hourly Average Concentrations of NO₂

Table 3-8 provides the values for the maximum of the 98th percentile of the daily maximum hourly concentrations of NO₂ among the grid points assigned to each location, for each of the six scenarios. The colours are assigned based on the thresholds described in Table 3-2.

Table 3-8: Maximum 98th percentile of the daily maximum hourly averaged concentrations within each location, and associated colour categorization.

Concentrations in $\mu\text{g}/\text{m}^3$ Background = 24.44 $\mu\text{g}/\text{m}^3$	Scenario					
Human Health Receptor Location	A	B	C	D	E	F_R
Residential						
Dodge Cove	620.3	620.2	620.4	620.2	620.3	620.4
Future Residential Expansion	83.3	78.3	86.5	77.8	150.2	151.3
Kitkatla	31.7	30.5	32.7	30.6	33.5	38.0
Lax Kw'alaams	63.5	38.9	72.7	133.8	45.7	133.8
Metlakatla	106.5	106.3	107.1	106.6	108.0	109.7
Port Edward Proposed Hotel	61.4	59.3	66.3	62.8	81.9	88.5
Port Edward Residential	84.4	83.5	87.7	83.8	123.2	123.7
Prince Rupert Residential	485.1	485.0	485.2	485.0	485.3	485.5
Rainbow Lake	41.2	40.7	42.6	38.7	47.6	50.0
Prudhomme Lake	44.1	44.0	46.6	44.4	58.1	61.5
Kloiya Bay	56.3	55.2	59.8	53.7	64.5	75.5
North Pacific Cannery	68.8	63.3	70.7	60.7	86.7	90.5
Cassiar Cannery	63.0	62.7	63.0	64.1	69.9	74.3
Osland	45.1	45.1	46.8	42.3	60.5	67.5
Hunts Inlet	41.7	40.1	43.6	38.7	48.8	56.3
Oona River	36.6	34.7	38.9	33.8	44.4	50.6
Crippen Cove	374.4	374.3	374.5	374.3	374.4	374.6



Concentrations in $\mu\text{g}/\text{m}^3$ Background = 24.44 $\mu\text{g}/\text{m}^3$	Scenario					
Human Health Receptor Location	A	B	C	D	E	F_R
Cultural & Recreational						
Prince Rupert Golf Course	124.6	124.6	124.6	124.7	124.6	127.2
Mount Oldfield Trail	93.2	92.0	95.6	89.2	120.7	127.2
Mount Hayes Trail	706.3	710.4	707.2	709.6	697.5	712.6
Butze Rapids Trail	63.7	65.2	66.1	58.1	67.1	76.0
Mettlakatla Sandbar	65.7	65.4	66.3	64.9	67.4	72.7
Pike Island	69.7	70.3	71.5	70.0	72.5	82.1
Sandbar North of Casey Point	802.9	802.8	802.9	802.7	802.8	802.9
Oliver Lake	63.9	67.8	66.5	63.1	69.6	83.5
Kitson Island	78.5	79.9	84.5	73.0	147.3	150.3
Industrial						
Canoxy North Industrial	70.4	69.0	75.1	80.6	95.8	100.4
Outer Harbour Industrial	124.5	124.5	124.5	124.5	144.3	144.3
Inverness Passage Commercial	135.1	135.1	135.1	135.1	153.9	157.0
Prince Rupert NE Industrial	103.9	59.9	103.9	58.6	133.4	133.7
Southern Prince Rupert Industrial	1791.8	1790.3	1792.3	1795.0	1790.4	1795.0
Stapleton Island Industrial	71.1	70.1	73.2	62.7	124.6	129.8
Watson Island Industrial	95.8	95.8	95.8	95.9	106.0	114.3
Prince Rupert Airport	78.3	78.1	78.5	77.8	85.1	86.4

3.4.9 Summary of Categorization of Results

The human health assessment has been conducted using a modified version of the CCME Air Zone Management Framework, using thresholds based on the BC Air Quality Objectives for $\text{PM}_{2.5}$ (annual and daily) and based on the BC Interim Air Quality Objectives for both SO_2 (annual and hourly) and NO_2 (annual and hourly). This includes derived thresholds which categorize modelled concentrations into four management categories, depicted by the colours Green, Yellow, Orange and Red, with the colour transitions implying the need for increased efforts to manage air quality as described by the CCME (CCME 2012). The results of the risk categorization are summarized in Figure 3-3.





Figure 3-3: Summary of risk management levels (as defined by CCME) for human health, by scenario. A circle is shaded if the study found that result for any of the 34 locations. Numbers in the circles convey how many of the 34 locations were in each colour category for each scenario.

3.4.10 Frequency Distribution of Pollutants for Locations Categorized as Red

The CCME air management scheme focuses attention on two statistics of the pattern of air pollution concentrations for each pollutant, the annual average and a high percentile statistic (e.g., 98th, 99th) that is indicative of less common high pollutant level episodes. It is also important to consider the overall frequency of different levels of pollutants over the entire timeframe of analysis (e.g., every hour for one or more years). To provide this broader context, the histograms below display the frequency distribution of modelled concentrations (i.e., excluding background) in locations where the corresponding upper air quality management threshold has been exceeded (the location is categorized as Red). In each case, histograms are provided for both Scenarios A and F_R.

Reading the histograms

Histograms are a type of bar graph. The histograms presented in this section (Figure 3-4 to Figure 3-9) illustrate the relative frequency on the y-axis with which concentrations of PM_{2.5}, SO₂ and NO₂ fall within specified ranges. They answer questions such as “In what percentage of the hours in a year are the modelled concentrations in the range between 50 and 100 µg/m³?” The ranges (for histograms, they are normally called “bins”) are shown on the x-axis. The relative frequency (e.g., 5%) provides the proportion of the hours or days for which concentrations were within each bin, among all grid points for each location.

For this analysis, the hourly or daily values are temporally and spatially pooled within each location. For example, for a location which included 10 grid points in the dispersion model, and

given that there are 8,760 hours in a year, the histogram provides the relative frequency of concentration values among all 87,600 values for that location. This is intended to provide additional insight into the expected patterns of concentration values over the course of a year to augment the categorization associated with the narrow focus of the CCME management thresholds.

As discussed above, as part of the US EPA standard protocol when comparing dispersion model results to regulatory thresholds, a contribution of air pollutant concentration from background sources (i.e., sources not modelled) must be added to the modelled concentrations.

Some of the histogram bins have been chosen to reflect thresholds for modelled concentrations that, when added to the background value, would yield a total concentration at the management threshold. The table below summarizes the adjustment used to obtain the binning delimiters for PM_{2.5}, SO₂, and NO₂.

As an example, consider the BC Air Quality Objective for 24 hour averaged PM_{2.5} concentrations of 25 µg/m³ (first column of Table 3-9). For the purposes of applying the CCME management levels, modelled concentrations are added to the designated background level of 7 µg/m³ (from Section 2.2.1). Therefore, modelled results that exceed 18 µg/m³ after being added to the 7 µg/m³ for background would exceed the 25 µg/m³ threshold (i.e., 18.5 + 7 = 25.5). For this reason, we adjust the thresholds for comparison to modelled data downward to adjust for the background concentrations that are not added to the modelled values displayed in the histogram.

Table 3-9: Adaptation of the CCME Air Management Categorization Scheme to apply BC Air Quality Objectives for PM_{2.5} and Interim Air Quality Objectives for SO₂ and NO₂, adjusted for background level for comparison with modelled concentrations.

PM _{2.5} 24h Average (98 th %ile)	PM _{2.5} 24h Average (98 th %ile) Adjusted for Background of 7 µg/m ³	SO ₂ Hourly (99 th %ile)	SO ₂ Hourly (99 th %ile) Adjusted for Background of 10.67 µg/m ³	NO ₂ Hourly (98 th %ile)	NO ₂ Hourly (98 th %ile) Adjusted for Background of 24.44 µg/m ³
25 µg/m ³	18 µg/m ³	200 µg/m ³	190 µg/m ³	188 µg/m ³	164 µg/m ³
17 µg/m ³	10 µg/m ³	100 µg/m ³	90 µg/m ³	105 µg/m ³	81 µg/m ³
10 µg/m ³	3 µg/m ³	5 µg/m ³	0 µg/m ³	22 µg/m ³	0 µg/m ³

In the histogram shown in Figure 3-4, the modelled concentration ranges have been chosen to have bin limits of 3, 10, and 18 µg/m³ rather than the management thresholds of 10, 17, 25 µg/m³ from the first column of Table 3-9. This reflects the fact that the background estimates (in this case 7 µg/m³) are not included in the concentrations shown on the x-axis. The coloured



bars at the top indicate what management level that concentration range would be assigned to after adding in the corresponding background level.

For each main histogram (e.g., Figure 3-4), a second zoomed-in histogram (e.g., Figure 3-5) is shown to allow the reader to better see the pattern of the less frequent higher concentration levels (which therefore are very small bars on the main graph). This is done by adjusting the y-axis in the zoomed-in version to show only the range from 0% to 2% (or in one case 0.5%). From the zoomed-in histogram, for example in Figure 3-5, it is possible to see that the modelled 24-hour averaged concentration range of 40 to 50 $\mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ occurs approximately 1% of the time in the Outer Harbor Industrial location for Scenario A.

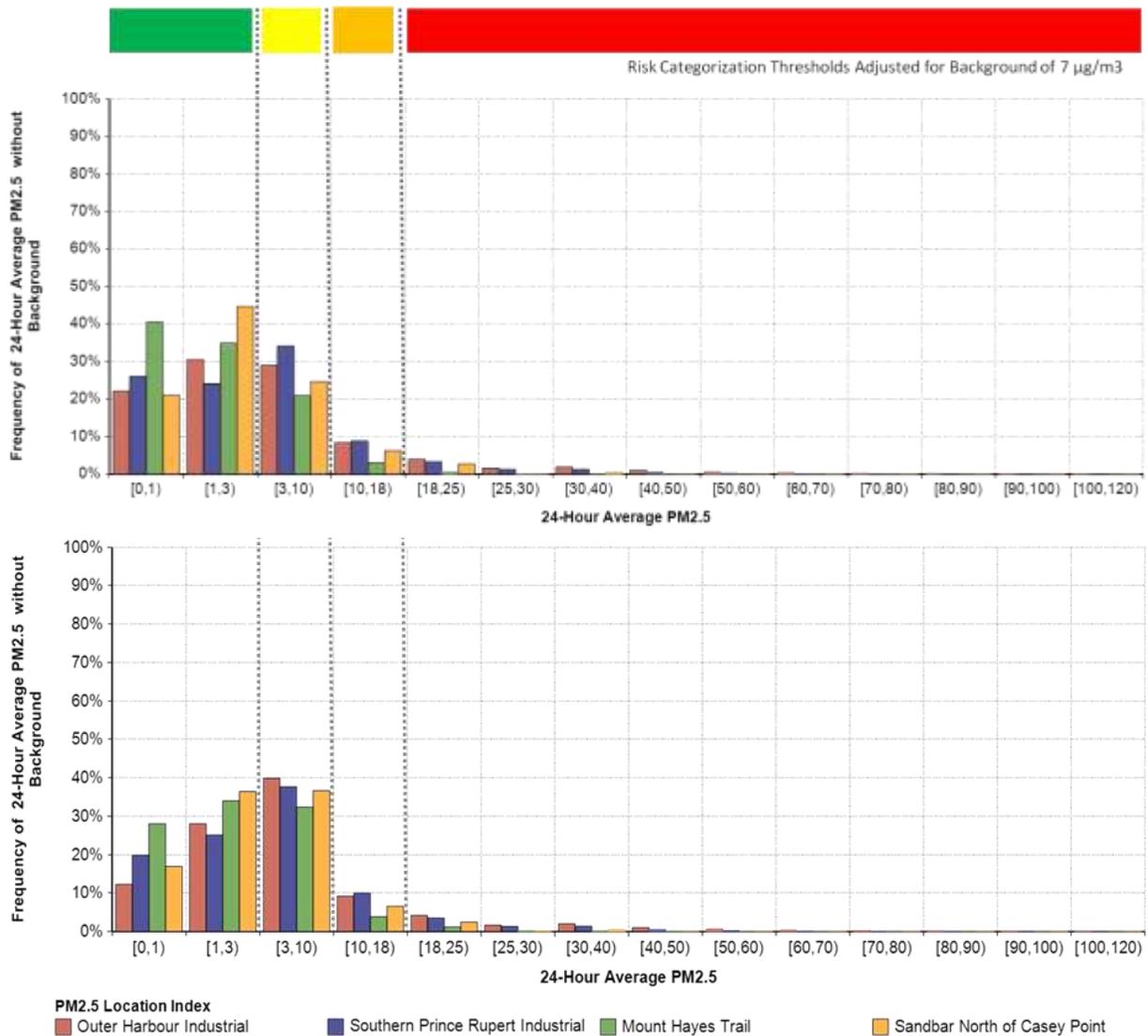


Figure 3-4: A histogram of the 24-hour averaged concentrations of $\text{PM}_{2.5}$ for Scenario A (upper panel) and Scenario F_R (lower panel) in locations where the BC Air Quality Objective has been exceeded.



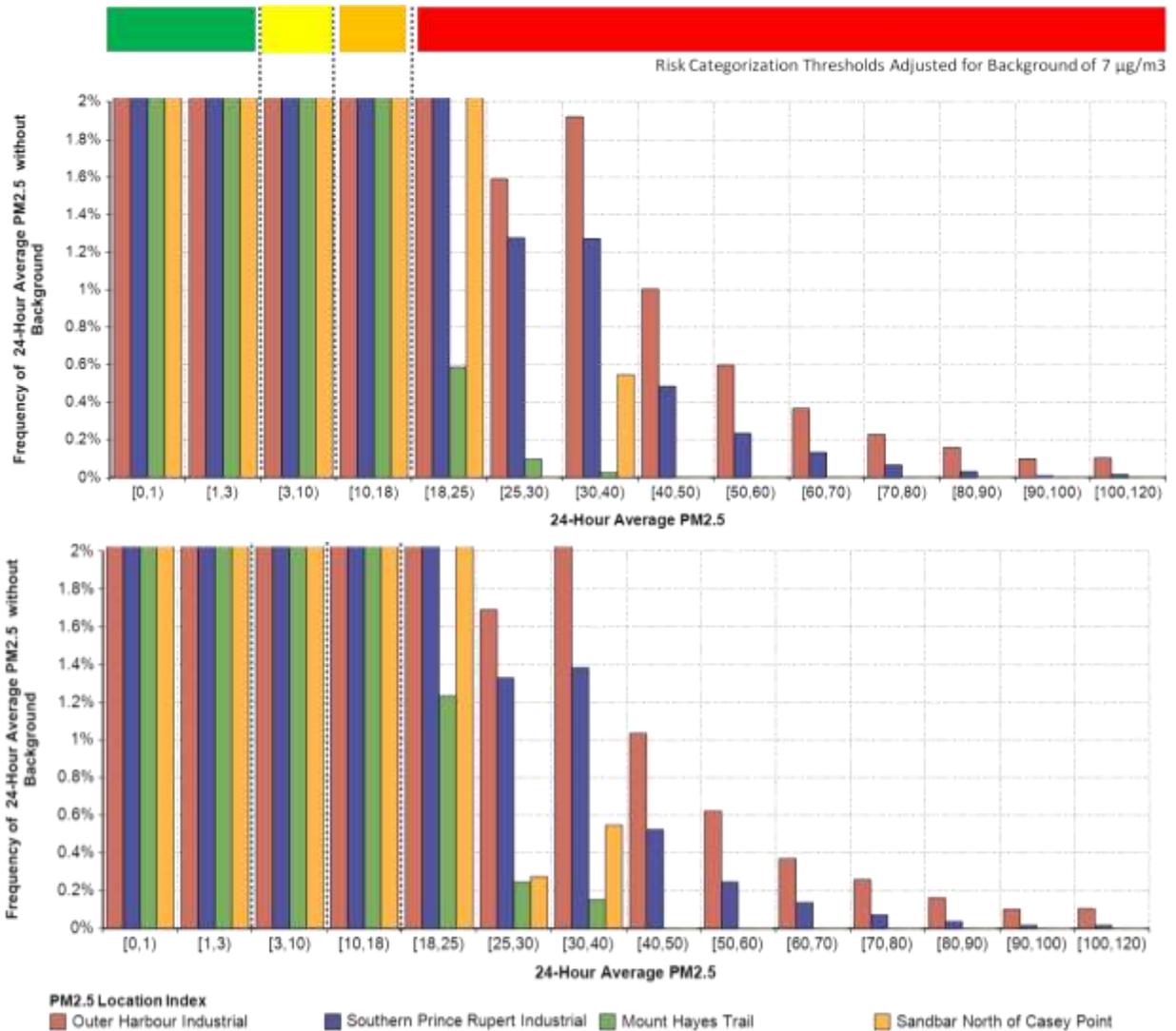


Figure 3-5: A zoomed-in histogram (y-axis is truncated at 2%) of the 24-hour averaged concentrations of PM_{2.5} for Scenario A (upper panel) and Scenario F_R (lower panel) in locations where the BC Air Quality Objective has been exceeded.

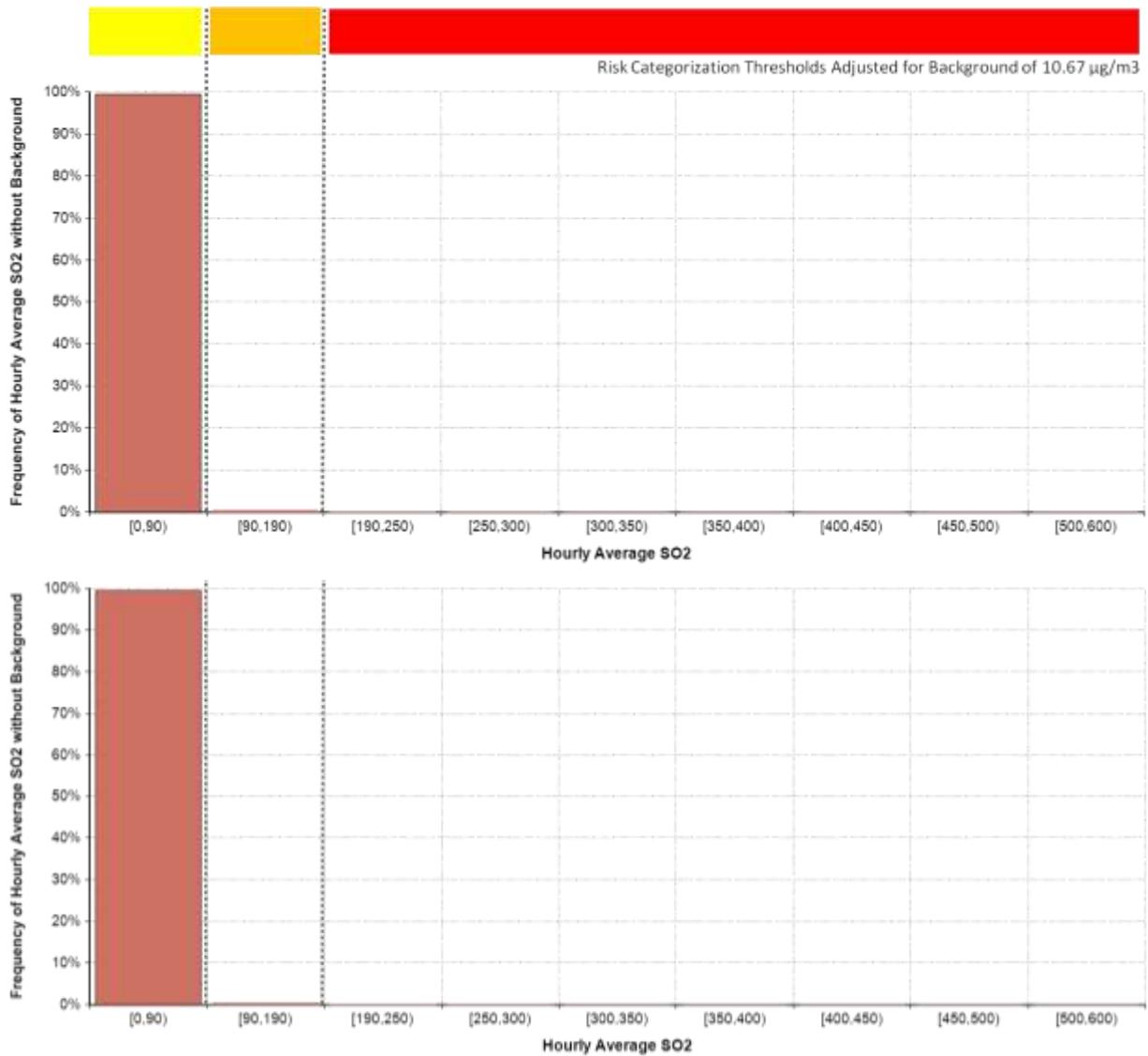


Figure 3-6: A histogram of the hourly concentrations of SO₂ for Scenario A (upper panel) and Scenario F_R (lower panel) in Southern Prince Rupert Industrial, where the BC Air Quality Objective has been exceeded.



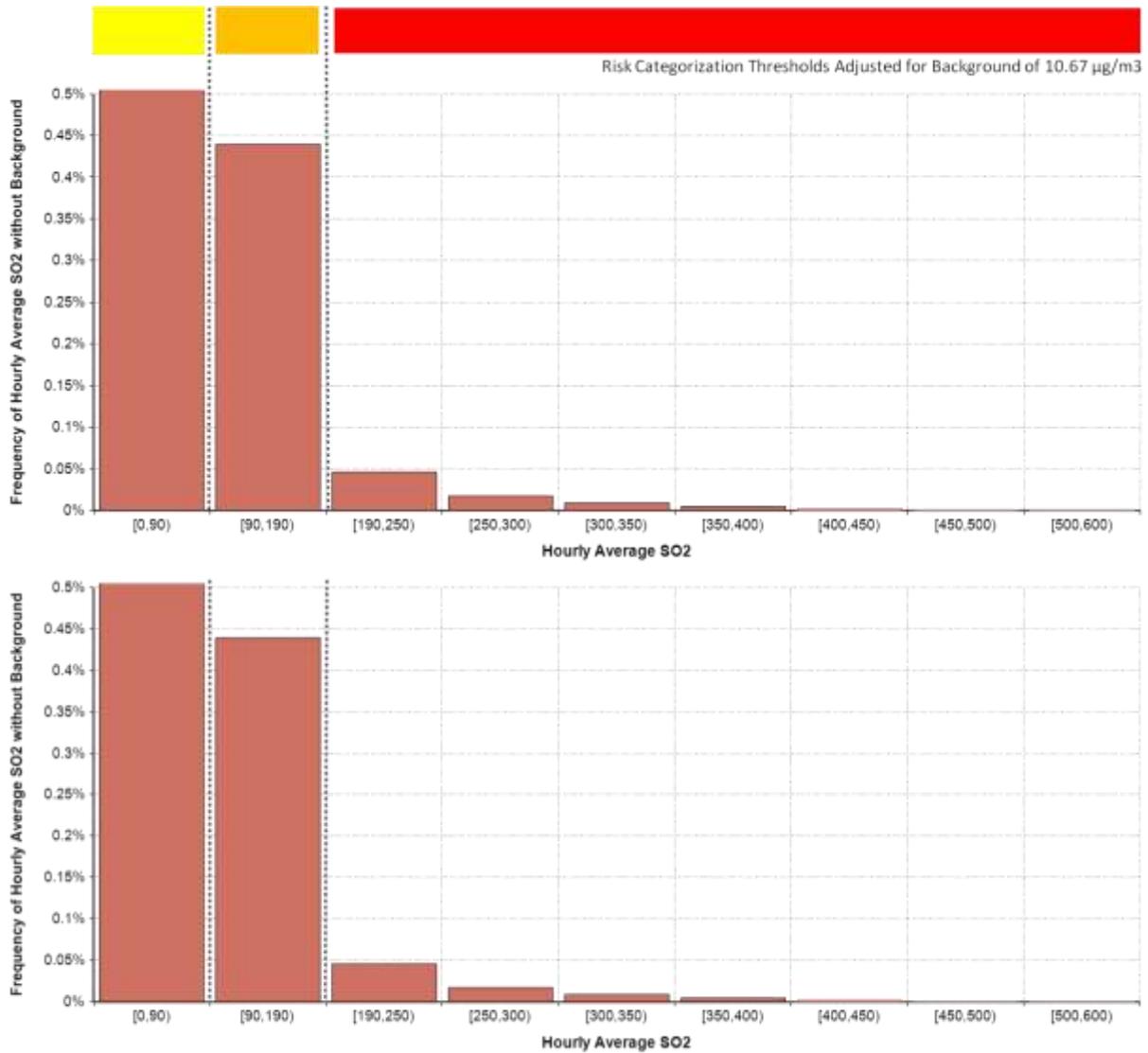


Figure 3-7: A zoomed-in histogram (y-axis is truncated at 0.5%) display for the frequency distribution of the hourly concentrations of SO₂ for Scenario A in Southern Prince Rupert Industrial, where the BC Air Quality Objective has been exceeded.



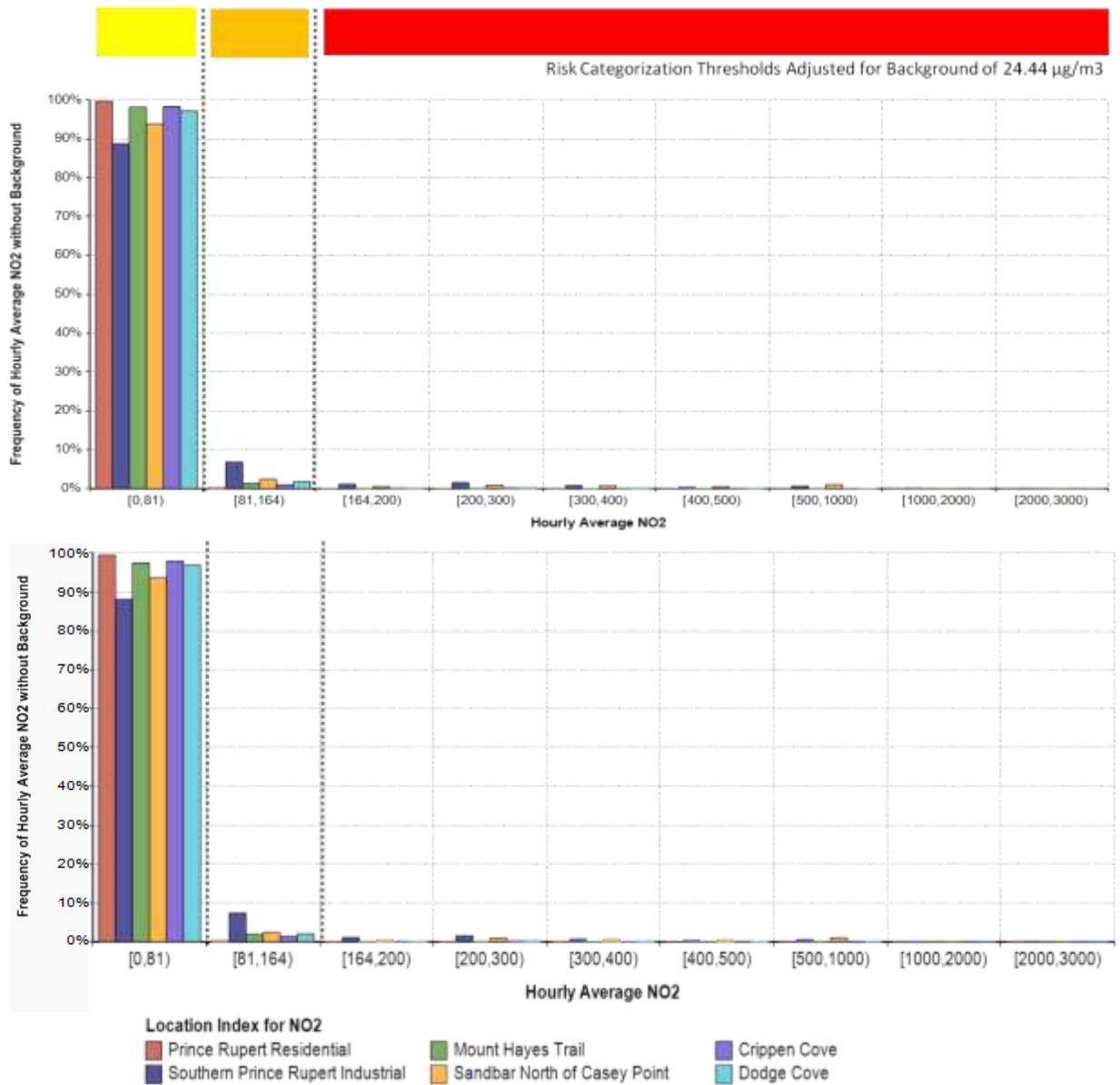


Figure 3-8: A histogram for the frequency distribution of the hourly concentrations of NO₂ for Scenario A (upper panel) and Scenario F_R (lower panel) in locations where the BC Air Quality Objective has been exceeded.



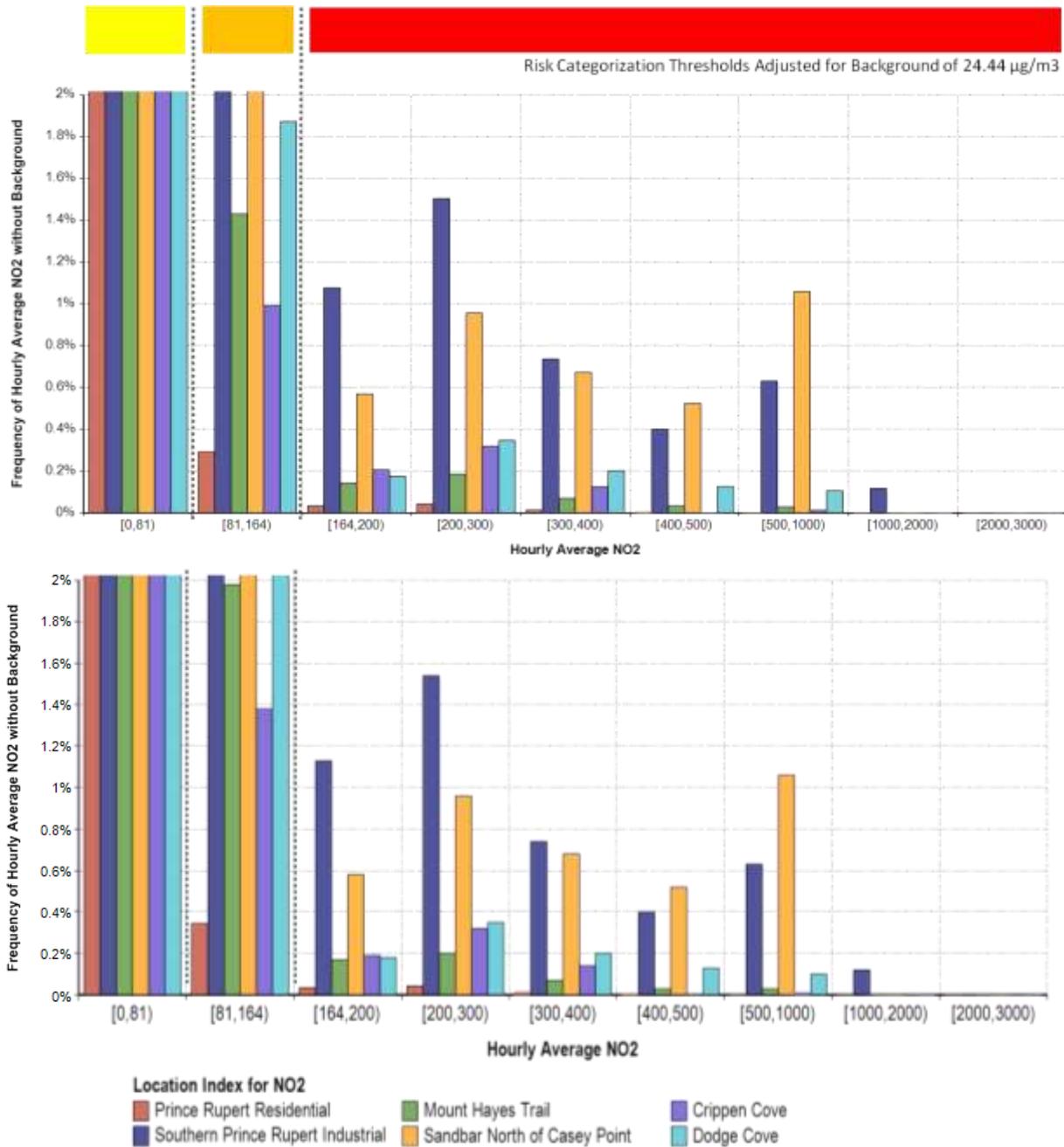


Figure 3-9: A zoomed-in histogram (y-axis is truncated at 2%) display for the frequency distribution of the hourly concentrations of NO₂ for Scenario A (upper panel) and Scenario F_R (lower panel) in locations where the BC Air Quality Objective has been exceeded.

The annual averages for each of these same sets of locations (i.e., those categorized as Red) are shown in the following sequence of figures. Figure 3-10 shows the annual average for PM_{2.5}, Figure 3-11 shows the annual average for SO₂, while Figure 3-12 shows the annual average for NO₂. Note that for these graphs, the annual average is calculated as the average across gridpoints within the location, rather than the maximum gridpoint which is used for comparison in the categorization scheme.



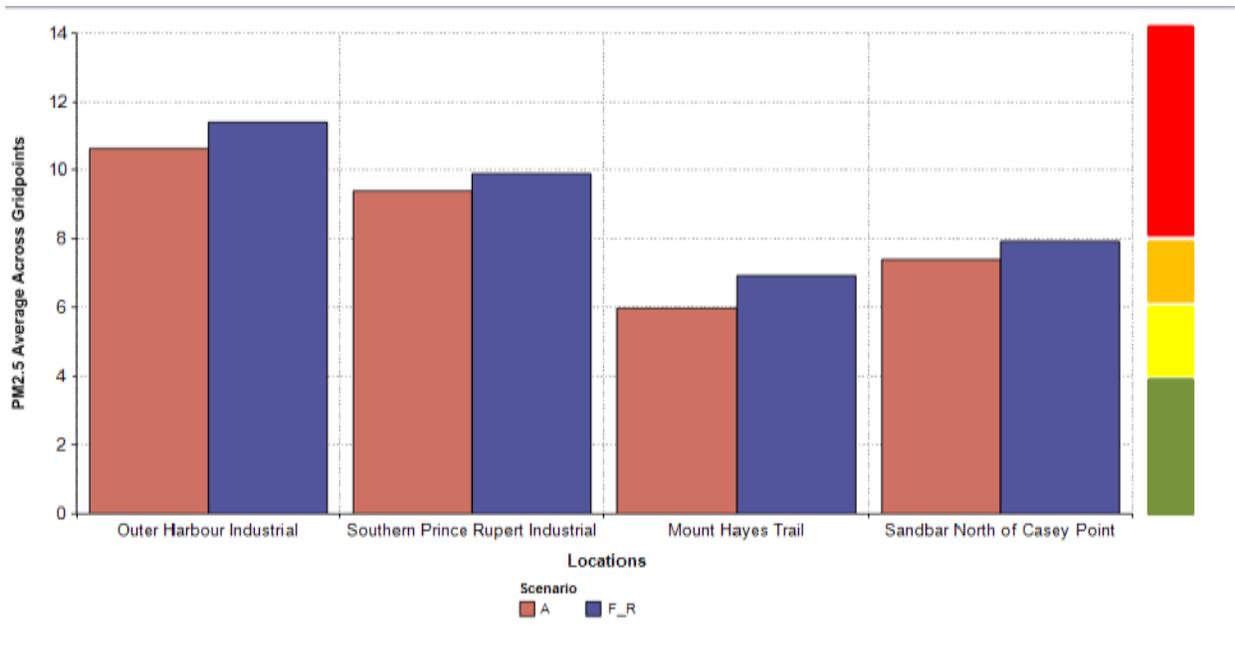


Figure 3-10: Annual average of PM_{2.5}, averaged across gridpoints for each location, in locations where the BC Air Quality Objective has been exceeded, for Scenarios A and F_R.

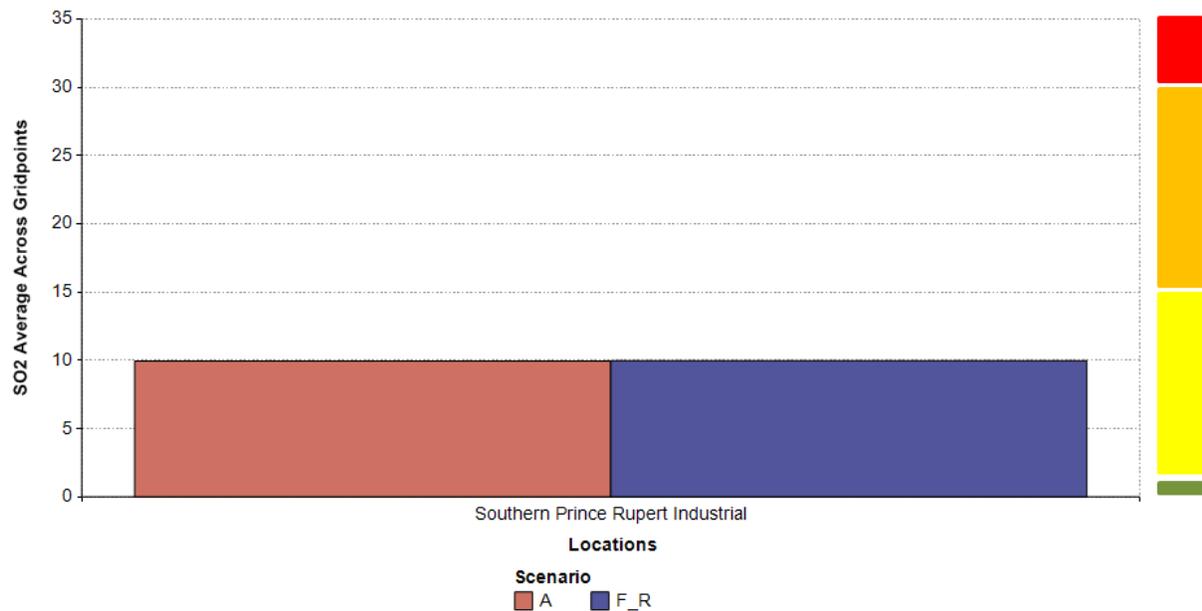


Figure 3-11: Annual average of SO₂, averaged across gridpoints for each location, in locations where the BC Air Quality Objective has been exceeded, for Scenarios A and F_R.



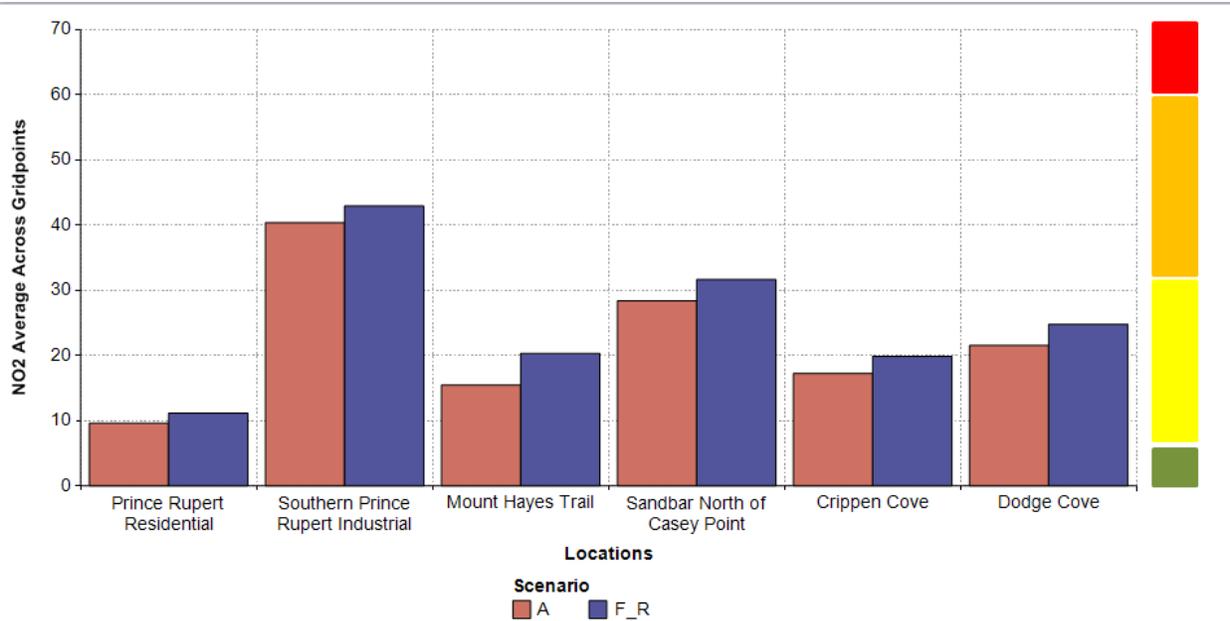


Figure 3-12: Annual average of NO₂, averaged across gridpoints for each location, in locations where the BC Air Quality Objective has been exceeded, for Scenarios A and F_R.

3.5 Main Sources and Implications of Quantitative Scientific Uncertainty

The human health assessment results carry forward all of the uncertainties associated with dispersion modelling including the uncertainty in the emissions assumptions that serve as inputs to the dispersion modelling. In this section, only the incremental uncertainty associated with the health assessment process is described.

The main source of uncertainty in the human health assessment is associated with the conversion of a spatially and temporally distributed pattern of concentration estimates into a four category scheme using selected summary statistics like the spatial maxima of annual averages and 98th or 99th percentile concentrations. The CCME categorization scheme provides a mechanism for doing this conversion, but it has certain limitations that are inherent to any such categorization scheme. These limitations include:

- The characterization of a location only by its maximum grid point.
- For the 98th and 99th percentile values, the addition of background estimates to modelled estimates for these statistics can create a significant overestimate of the actual percentile value of the two additive random processes, especially when combined with taking the maximum of those percentiles in each location.
- In some cases, the categorization is driven largely by background estimates, which limits the ability to differentiate meaningfully among scenarios.



- The addition of the annual average estimate for SO₂ is recommended but is not formally part of the human-health oriented BC Air Quality Objectives or Interim Objectives. The status of this objective in the categorization scheme is subject to further discussion.

The most important limitation of this assessment approach is that the colour-coded management levels could be misinterpreted as constituting thresholds of health risk. For many air pollutants, there is a continuum of risk associated with increasing levels, as opposed to a single value that separates concentration values into “safe” and “unsafe” levels. This misinterpretation can be further exacerbated by the assignment of the colour RED and its alarming connotations. It also has the potential to lead to undue focus on what may in some cases be infrequent exceedances of management thresholds, at the expense of understanding the overall frequency of concentration estimates experienced on a day-to-day basis which, for some pollutants, may actually dominate the public health impact. This remains as a significant communication challenge in conveying such results to decision-makers and the public, while avoiding the natural, but incorrect, interpretation of these four management levels as constituting step-wise changes in a community’s health status.

3.6 Recommendations on Impact Assessment Guidance

It may be considered useful, to complement the characterization according to the CCME management levels, if the proponents provided histograms (or similar characterizations of the relative frequency of concentration estimates without background). This will help to more fully characterize the spectrum of day-to-day concentrations that is inevitably lost when converting the modelled data into the CCME air zone management scheme. It is particularly helpful in placing the concept of *exceedances* in the appropriate perspective with respect to their overall relative frequency.



4 Vegetation

4.1 Methods

The methods used for the vegetation assessment for the PRAS are essentially the same as those used for the Kitimat Airshed Emissions Effects Assessment (KAA) (ESSA et al. 2014). Figure 4-1 shows the locations of receptors included in the vegetation assessment. Vegetation receptors were spaced at 1 km intervals. Results at human health receptors (100-metre spacing) were also included in the vegetation assessment. Receptors on water were not included in the vegetation assessment.

Oxides of sulphur and nitrogen are both known to be directly injurious (either visible injury to leaves or reductions in growth or yields) to vegetation when they occur in ambient exposures that surpass thresholds in concentration, time, or some critical combination. Minimum exposure times or concentrations bound potential effects on the low end (e.g., very low concentrations or very short exposure durations), and the end of the growing season generally bounds the potential long-term low-level chronic effects over the course of the year. Effects on perennial vegetation can accumulate over multiple growing seasons causing growth reductions or declines in plant vigour. Critical exposure durations and concentrations have been established in the scientific literature and those form the basis for risk assessments in North America and Europe. That substantial scientific literature has allowed the development of air quality objectives (Canada), standards (United States), and recommendations and standards (Europe). The literature relating to effects of SO₂ and NO₂ has been reviewed recently (WHO 2000; US EPA 2011; Laurence 2012; European Environment Agency 2014). Air quality objectives and guidelines have been left unchanged for a number of years; there is little new research on the direct effects of the pollutants (most was conducted in the 1970s-1980s) and there is little or no evidence that the existing objectives and standards are not effective (US EPA 2008, 2011). In the case of NO₂, exposures that cause direct effects on vegetation tend to be high concentrations (e.g., ppm range), or for long periods of time (days to weeks of continuous exposure). European standards have been established in response to a different exposure dynamic (longer term, lower concentration exposures versus point source exposures more common in North America). These standards are in the form of annual means, and protect vegetation from sub-acute (those that do not cause visible injury) exposures. They also are established to avoid long-term growth loss, decline of vigour, and changes in community composition.

Ozone (O₃) is an important pollutant that is toxic to plants and is known to interact with SO₂ and NO₂ in some cases. O₃ is not emitted directly, but forms in the atmosphere as a result of reactions between hydrocarbons and oxides of nitrogen in the presence of strong sunlight. O₃ is not expected to reach concentrations of concern for plants due to low formation rates at high latitude locations or at locations that do not have substantial sunshine. For that reason, it was not included in this analysis.



Particulates of concern in $PM_{2.5}$ primarily affect vegetation through acidification of the ecosystem addressed elsewhere in this report. While direct effects of acidified cloud water have been reported, no standards have been established for direct effects of $PM_{2.5}$ on vegetation, and so this assessment will focus on SO_2 and NO_2 . Table 4-1 shows the current objectives and standards in Canada, the US, and Europe.

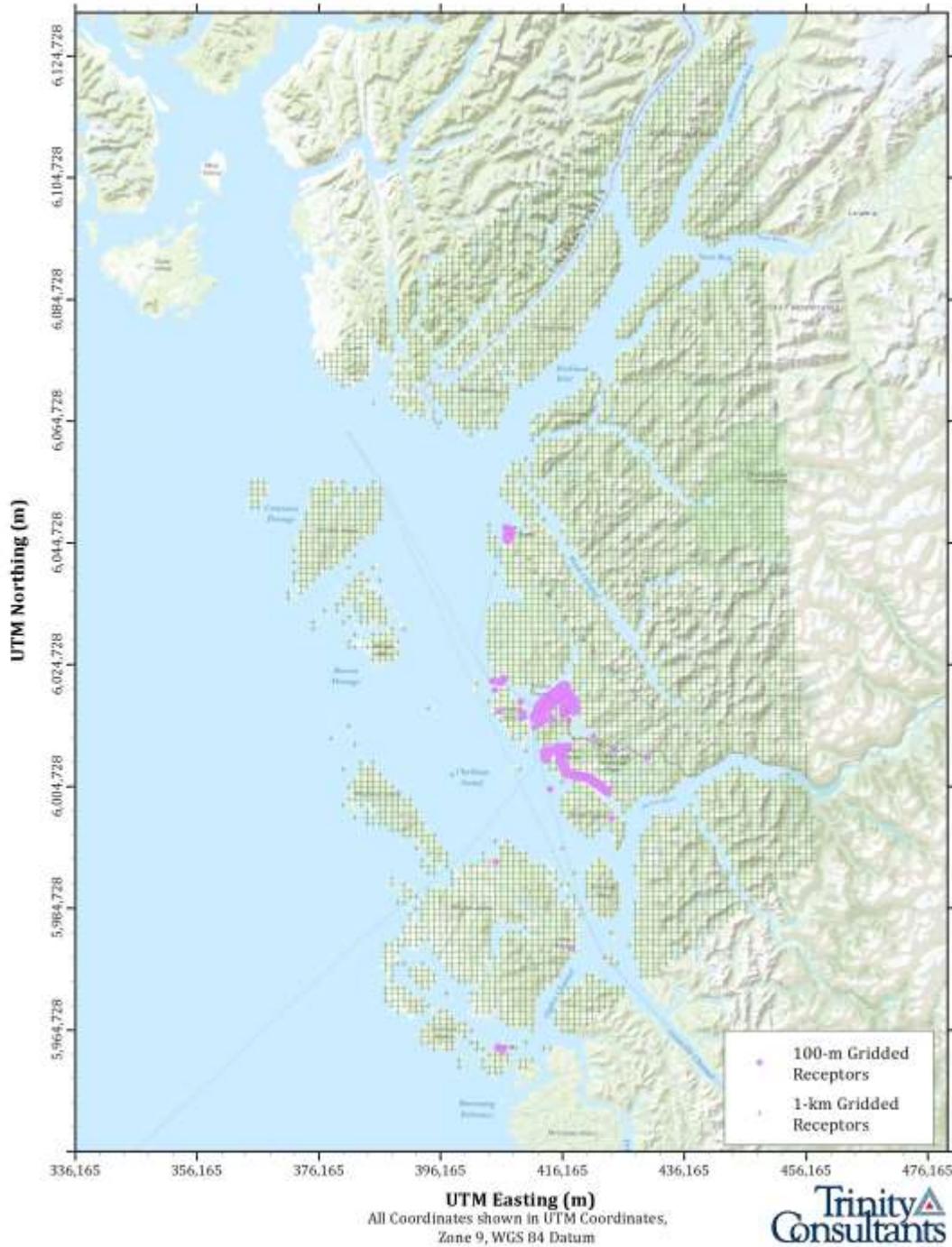


Figure 4-1: Receptors used in the vegetation assessment.

Table 4-1: Current objectives and standards.

Organization and Metric	SO ₂	NO ₂
<i>Environment Canada</i>		
Maximum Desirable	11 ppb annual average (30 µg/m ³); 57 ppb 24 hours (150 µg/m ³); 172 ppb 1 hour (450 µg/m ³)	32 ppb annual average (60 µg/m ³)
Maximum Acceptable	23 ppb annual average (60 µg/m ³); 115 ppb 24 hours (300 µg/m ³); 334 ppb 1 hour (875 µg/m ³)	53 ppb annual (100 µg/m ³); 106 ppb 24 hours (200 µg/m ³); 213 ppb 24 hours (400 µg/m ³)
Maximum Tolerable	306 ppb 24 hours (800 µg/m ³)	160 ppb 24 hours (300 µg/m ³); 532 ppb 1 hour (1,000 µg/m ³)
<i>US EPA</i>		
Annual Mean		53 ppb (100 µg/m ³)
3 hour average	500 ppb (1,310 µg/m ³ not to be exceeded more than once per year)	
<i>WHO</i>		
Annual mean	11 ppb for agricultural crops (30 µg/m ³) 7 ppb for forest vegetation (20 µg/m ³) 4 ppb for lichens (10 µg/m ³)	
<i>European Air Quality Standards</i>		
Annual Mean	7 ppb (20 µg/m ³) for vegetation	16 ppb (30 µg/m ³)

During photosynthesis, plants take up carbon dioxide from the air and release water vapour into the air through small pores (called stomata) in leaves or needles. This process is termed gas exchange. Stomata are sensitive to light and, in most plants, close during times of low light. Other conditions, such as drought or high or low temperature may cause full or partial stomatal closure as well. When stomata are closed very little gas exchange takes place, thus the uptake of pollutants is greatly diminished.

Both SO₂ and NO₂, if present in the atmosphere, are taken up during the process of gas exchange, so the flux of pollutant into leaves is determined by the concentration in the air and the rate of exchange between the leaf and the atmosphere. Because of that, exposures that take place in different seasons of the year, different times of the day, or under variable weather conditions can have different effects on the physiology of the plant. (Detailed analysis of the time series of predicted exposures is outside the scope of this study.) Repeated exposures below a threshold may cause unexpected effects if the exposures occur close in time or several times through the growing season. Similarly, exposures to high concentrations at times of the day when plants are not physiologically active may not cause injury. Effects of pollutant exposure may also accumulate through the growing season, or over multiple growing seasons, resulting in symptoms of chronic exposure. Therefore, we used vegetation thresholds and summary statistics in this analysis to account for variability and uncertainty, and to assess the likelihood of effects from both short- and long-term exposure.



Symptoms of exposure to NO₂ or SO₂ vary depending on the species of plant, the degree of exposure, and the pollutant. NO₂ at high concentrations may cause a bleaching of the leaf, turning the leaf from green to a lighter shade, or even to white. The exposure, if severe enough, may cause death of the leaf tissue. At higher exposures, SO₂ generally causes chlorosis (yellowing) or necrosis (death) of leaf tissue between the veins on broadleaf plants and tip chlorosis or necrosis on conifers or plants with blade shaped leaves. At lower exposures, it may cause a general chlorosis of broadleaf plants. Both pollutants have been reported to cause growth losses in agricultural plants and some forest trees if the exposures are of significant concentration and duration. Growth or yield losses may or may not be associated with visible injury of leaves. Standards and objectives have been established in an effort to avoid both visible injury to plants and growth reductions.

Reports of results of experimental exposures in the scientific literature help determine the range of sensitivity of plants to pollutants; however, there are few, if any, reports of controlled exposures of plants native the Prince Rupert area to NO₂ or SO₂. Sitka spruce has been studied due to its importance as a commercial plantation species in Europe. In the Liphook Experiments, Sitka spruce seedlings were exposed to SO₂ and ozone in an open-air fumigation system. After about 3.5 years of continuous exposure to 22 ppb SO₂, extension growth of shoots, but not basal diameter was increased. The authors postulate that the response may have been due to co-deposition of ammonium nitrogen from the atmosphere (Holland, et al., 1995). Shaw and McLeod (1995) reported increased concentrations of sulphur in needles Sitka spruce trees in the same experiment. Concentrations of foliar nitrogen were also increased.

Air pollutants may also interact with other stressors, such as insects or pathogens. If plants are placed under substantial stress, they may become more susceptible to attack, particularly by pests and pathogens related to decline diseases (rather than primary pests and pathogens).

This discussion and the methods described relate to direct effects of SO₂ and NO₂ on vegetation, including bryophytes and lichens. It is well known that both pollutants can cause indirect effects on vegetation through acidification processes discussed elsewhere in this report. Based on syntheses of the most recent North American and European literature (US EPA 2008, 2011; WHO 2000; European Environment Agency 2014), a set of metrics was selected to assess the likelihood of direct effects of SO₂ and NO₂ exposure on vegetation in the Prince Rupert airshed. We examined an annual averaging period as well as averaging periods of 1 and 3 hours (for SO₂). Since plants respond to a variety of exposure types (e.g., short-term, high concentration, long-term, low concentration), using a variety of averaging periods allows us to assess the likelihood of direct effects on vegetation due to a range of exposures. Vegetation may also respond to peak, rather than mean, concentrations. By evaluating the exceedance of thresholds at different averaging periods, we can assess whether exposures are likely to be acute (short term peak) or chronic (long term mean).

We also computed the same metrics using exposures during the growing season (April 15 – September 15). Although the frost-free period generally extends into October in Prince Rupert, photoperiod is decreasing and the level of physiological activity is likely restricted. Examining exposures during this period allows evaluation of likely effects of direct exposure since plants do



not generally respond to exposures outside the growing season and uptake of gaseous pollutants is not significant during periods of reduced light. On warm, sunny days outside the growing season, conifers may take up small amounts of pollutants, but given the climate conditions of Prince Rupert, gas exchange during those periods is unlikely to be significant. Lichens are exceptions, so we used an annual average to assess the likely effects on those life forms, as is done in Europe. We report exceedances of these thresholds during the entire year and display exceedances within the growing season as well. Finally, we computed metrics for “daylight hours”—7 AM to 7 PM—when physiological activity of photosynthesizing plants would be greatest.

Exposure statistics were calculated from the results of air quality dispersion modelling for each of the scenarios in this assessment. Total concentrations of NO_x have been reported as NO_2 , because thresholds for direct effects on vegetation are based on NO_2 exposure (and NO_2 is the most phytotoxic form of NO_x).

To assess the effects of SO_2 and NO_2 on vegetation receptors, the calculated exposure statistics were compared to thresholds of effect in a risk assessment framework (Table 4-2 to Table 4-7) after the methodology used for the KAA (ESSA et al. 2014). The threshold values used in the likelihood matrices were based on thresholds from the literature tailored by professional judgement to account for vegetation response and to reduce uncertainty associated with predicted air concentrations (e.g., daily, seasonal, weather-related) as described above.

In their 2008 synthesis of the literature, the US EPA reviewed hundreds of studies conducted to assess the effects of NO_2 on vegetation, and found no clear dose-response relationships. However, visible injury was considered to be unlikely at exposures of less than $360 \mu\text{g}/\text{m}^3$ for at least 100 hours. In the short term, concentrations of $1,800 \mu\text{g}/\text{m}^3$ for less than one day caused visible injury on some plants. WHO (2000) suggests, although they did not adopt the suggestion as a standard or guideline, that in Europe NO_2 exposures of $20 \mu\text{g}/\text{m}^3$ for 1 year, $200 \mu\text{g}/\text{m}^3$ for 1 day, or $1,000 \mu\text{g}/\text{m}^3$ for 1 hour establish a critical level, including when NO_2 occurs in combination with SO_2 . The European Directive of 2008 (EU 2008) suggests that annual means of $20 \mu\text{g}/\text{m}^3$ for SO_2 and $30 \mu\text{g}/\text{m}^3$ for NO_2 are appropriate as critical levels. WHO (2000) suggests a level (annual average) of $10 \mu\text{g}/\text{m}^3$ for SO_2 to protect lichen taxa.

There are limited studies of the effects of SO_2 and NO_2 in combination on plants. However, the research that has been done reported minor interactive effects at prolonged exposure (US EPA 2008), so interactive effects are not included in the risk matrix. It should also be noted that characteristics of exposure are likely to be different in Prince Rupert as compared to Europe given the configuration of sources. Additionally, levels of ozone (another phytotoxic pollutant) are likely to be greater in Europe and other parts of North America than in the Prince Rupert area and could figure into the reported response of vegetation to other pollutants in areas where it is of concern. As mentioned above, it is not expected to be significant in Prince Rupert and vicinity.

Table 4-2: Likelihood levels proposed for the risk assessment framework for vegetation and SO₂.

A – Almost Certain	B – Likely	C – Possible	D – Unlikely	E – Very Unlikely
Exposure of sensitive vegetation to >2,600 µg/m ³ for ≥1 hour during daylight hours of the growing season. Exposure of sensitive vegetation to 1,300 µg/m ³ for >3 hours on more than one occasion during daylight hours of the growing season.	Exposure of the most sensitive vegetation to 1,300 µg/m ³ for 3 hours during daylight hours of the growing season.	Exposure of the most sensitive vegetation to 650 µg/m ³ for >8 hours during daylight hours of the growing season. Exposure that exceeds 20 µg/m ³ annual average.	Exposure of the most sensitive vegetation to 650 µg/m ³ repeated daily during daylight hours of the growing season.	Exposure of vegetation to less than 1,300 µg/m ³ for 3 hours or 650 µg/m ³ for 8 hours during daylight hours of the growing season. Exposures to less than 10 µg/m ³ annual average.

Table 4-3: Consequence levels proposed for the risk assessment framework for vegetation for SO₂.

1 - Minor	2 - Medium	3 - Serious	4 - Major	5 - Catastrophic
Occasional symptoms of injury due to SO ₂ on leaves of the most sensitive species in the immediate vicinity of the industrial area.	Symptoms of SO ₂ injury extending beyond immediate vicinity of the industrial areas. Chronic symptoms (chlorosis/necrosis) resulting in unsightly appearance or indicating potential minor effects on growth.	Severe and repeated symptoms of SO ₂ injury on more than the most sensitive species, including species of economic or social importance. Symptoms of acute or chronic SO ₂ injury at remote monitoring locations.	Defoliation of trees and shrubs of high public importance at multiple locations due to SO ₂ .	Death of trees, shrubs, and forbs of high public importance at multiple locations due to SO ₂ exposures.

Table 4-4: Impact categories from the combined likelihood and consequence dimensions of the risk assessment framework for vegetation for SO₂.

Likelihood (definitions in Table 4-2)	Consequence (definitions in Table 4-3)				
	1 – Minor	2 – Medium	3 – Serious	4 – Major	5 – Catastrophic
A – Almost certain	Moderate	High	Critical	Critical	Critical
B – Likely	Moderate	High	High	Critical	Critical
C – Possible	Low	Moderate	High	Critical	Critical
D – Unlikely	Low	Low	Moderate	High	Critical
E – Very Unlikely	Low	Low	Moderate	High	High



Table 4-5: Likelihood levels proposed for the risk assessment framework for vegetation and NO₂.

A – Almost Certain	B – Likely	C – Possible	D – Unlikely	E – Very Unlikely
Exposure of sensitive vegetation to >1,800 µg/m ³ for 24 hours or more during the growing season. Exposure of sensitive vegetation to 400 µg/m ³ for >100 hours continuously on one or more occasions during the growing season.	Exposure of the most sensitive vegetation to 1,000 µg/m ³ for 24 hours during the growing season.	Exposure of the most sensitive vegetation to 300 µg/m ³ for >24 hours during the growing season. Exposure of sensitive vegetation to more than 30 µg/m ³ annual average.	Exposure of the most sensitive vegetation to 400 µg/m ³ for 8 hours repeatedly during daylight hours of the growing season. Exposure of the most sensitive vegetation to more than 20 µg/m ³ .	Exposure of vegetation to less than 30 µg/m ³ continuously during the growing season. Exposure of vegetation to less than 30 µg/m ³ annual average.

Table 4-6: Consequence levels proposed for the risk assessment framework for vegetation for NO₂.

1 - Minor	2 - Medium	3 - Serious	4 - Major	5 - Catastrophic
Occasional symptoms of injury due to NO ₂ on leaves of the most sensitive species in the immediate vicinity of the industrial area.	Symptoms of NO ₂ injury extending beyond immediate vicinity of the industrial areas. Chronic symptoms (chlorosis/necrosis) indicating potential growth effects.	Severe and repeated symptoms of NO ₂ injury on more than the most sensitive species, including species of economic or social importance. Symptoms of NO ₂ injury at remote monitoring locations.	Defoliation of trees and shrubs of high public importance at multiple locations due to NO ₂ .	Death of trees, shrubs, and forbs of high public importance at multiple locations due to NO ₂ exposures.

Table 4-7: Impact categories from the combined likelihood and consequence dimensions of the risk assessment framework for vegetation for NO₂.

Likelihood (definitions in Table 4-5)	Consequence (see definitions in Table 4-6)				
	1 – Minor	2 – Medium	3 – Serious	4 – Major	5 – Catastrophic
A – Almost certain	Moderate	High	Critical	Critical	Critical
B – Likely	Moderate	High	High	Critical	Critical
C – Possible	Low	Moderate	High	Critical	Critical
D – Unlikely	Low	Low	Moderate	High	Critical
E – Very unlikely	Low	Low	Moderate	High	High

4.2 Results

4.2.1 Vegetation of the Area

The vegetation of the Prince Rupert area is well characterized in the scientific literature, and in particular as a result of the HyP³ (“Hip-Cubed”) project, a multi-year ecosystem assessment



and experiment (Radcliffe et al. 1994; Banner et al. 2005). The area is part of the Coastal Western Hemlock zone, and further classified as the Very Wet Hypermaritime Subzone, Central Variant (CWHvh2). This classification extends from the coast to about 600 m in elevation and encompasses the study area of PRAS. It is an area of high rainfall, mild temperatures and low evapotranspiration (indicating low rates of gas exchange by plants). There is a surplus of rainfall during the growing season and where water occurs on the landscape likely plays a large role in the distribution of vegetation (lowlands and bogs versus uplands, for instance) (Banner et al. 2005).

The vegetation includes commercially productive forest, lower productivity forest, bog forests, bog woodlands, and blanket bogs. According to Banner et al. (2005), the three latter types are wetlands that cover 50% or more of the landscape and are a unique feature of the landscape (Radcliffe et al. 1994). The most productive forests occur on steep uplands.

Banner et al. (2005) report the major tree species to be western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), yellow cedar (*Cupressus nootkatensis*), shore pine (*Pinus contorta* v. *contorta*), Sitka spruce (*Picea sitchensis*), Pacific silver fir (*Abies amabilis*), mountain hemlock (*T. mertensiana*), and red alder (*Alnus rubra*). Shrubs in the understory may include salal (*Gaultheria shallon*), blueberry (*Vaccinium* sp.), and false azalea (*Menziesia ferruginea*). Herbs include bunchberry (*Cornus canadensis*), deer fern (*Blechnum spicant*), false lily-of-the-valley (*Maianthemum dilatatum*), heart-leaved twayblade (*Listera cordata*), and skunk cabbage (*Lysichiton americanus*). Mosses include lanky moss (*Rhytidiadelphus loreus*), step moss (*Hylocomium splendens*), common green sphagnum (*Sphagnum girgensohnii*), and large leafy moss (*Rhizomnium glabrescens*). The lichen flora of the area have been studied and characterized to some extent (P. Williston, BC MOE, pers. comm.). There is some anecdotal information available to document the response of lodgepole pine (*P. contorta* var. *latifolia*) (similar to shore pine) to SO₂, and there is an 18-year history of measurement of sulphur in western hemlock needles associated with the aluminum smelter at Kitimat, BC. Other than that, little is known about the effects of pollutants on these species other than that mentioned above.

Both red- and blue listed ecosystems occur in the subzone. Red-listed ecosystems are considered “imperiled provincially because of extreme rarity or because of some factor(s) making it especially vulnerable to extirpation or extinction.” Blue-listed ecosystems are more common but considered vulnerable to either large- or small-scale disturbance. Banner, et al. (2005) report 11 listed ecosystems in the CWHvh2 subzone, including both inland forest ecosystems and sea-spray shoreline forests. According to Banner et al (2005), no vascular plants reported from the area are currently listed. This conclusion should be verified within the proposed project area.

4.2.2 Potential Effects of SO₂ on Vegetation

Results of dispersion modelling of concentrations SO₂, compared to thresholds of concern for vegetation, are presented in Table 4-8 to Table 4-10. Locations with the maximum modelled concentrations listed in the tables are shown in Figure 4-2. The maximum concentration locations occur in unvegetated industrial areas. All scenarios resulted in similar profiles with regard to thresholds of concern. Some scenarios have identical results for comparisons of



interest and have been grouped to avoid duplication. This does not imply that the results of the scenarios were identical, only that the comparisons to thresholds of interest and the location of peak concentrations were the same. The highest concentrations are predicted to occur during night-time hours or close to sunset (2104 hours on day 231 and 2206 hours on day 197). Modelled concentrations of SO₂ in all scenarios have predicted daily peak concentrations for 1 or 3 hours well below those reported in the literature to cause visible injury to sensitive vegetation. Figure 4-3 shows the spatial extent of the daily peak 1-hour concentrations under the two bookend scenarios (A and F_R), representing the range of emission scenarios. The concentration isopleths indicate that concentrations decline rapidly from the maximum modelled concentration.



Table 4-8: Averaging periods and modelled concentrations for SO₂ under Scenario A, C, and F_R.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	US EPA Secondary Standards ^b (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location ^d
					Julian Day	Time	
1-hour	1st	547	547		103	2300	Receptor A
	2nd		547		232	0100	Receptor A
	4th		505		231	2000	Receptor A
3-hour	1st	413		1300	232	0100	Receptor A
	2nd	315			197	2200	Receptor A
Annual	Mean	27					Receptor B
Annual Growing Season ^c		32					Receptor B
Annual Growing Season Daylight ^c		23					Receptor B

a Modelled concentrations of 3-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include background concentrations corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations are provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 4.0 ppb = 10.7 µg/m³ for 1-hour and 3-hour averaging period; 1.5 ppb = 4.0 µg/m³ for the annual averaging period.

b Secondary National Ambient Air Quality Standard (NAAQS) define the levels that protect the public welfare from any known or anticipated adverse effects of a pollutant. The secondary standard for the 3-hour averaging period is not to be exceeded more than once per calendar year. Therefore, results are compared to the second high.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.

d A map showing the receptor locations is provided in Figure 4-2.



Table 4-9: Averaging periods and modelled concentrations for SO₂ under Scenario B and E.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	US EPA Secondary Standards ^b (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location ^d
					Julian Day	Time	
1-hour	1st	547	547		103	2300	Receptor A
	2nd		546		232	0100	Receptor A
	4th		505		231	2000	Receptor A
3-hour	1st	413		1300	232	0100	Receptor A
	2nd	315			197	2200	Receptor A
Annual	Mean	26					Receptor B
Annual Growing Season ^c		31					Receptor B
Annual Growing Season Daylight ^c		24					Receptor B

a Modelled concentrations of 3-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include background concentrations corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations are provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 4.0 ppb = 10.7 µg/m³ for 1-hour and 3-hour averaging period; 1.5 ppb = 4.0 µg/m³ for the annual averaging period.

b Secondary National Ambient Air Quality Standard (NAAQS) define the levels that protect the public welfare from any known or anticipated adverse effects of a pollutant. The secondary standard for the 3-hour averaging period is not to be exceeded more than once per calendar year. Therefore, results are compared to the second high.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.

d A map showing the receptor locations is provided in Figure 4-2.



Table 4-10: Averaging periods and modelled concentrations for SO₂ under Scenario D.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	US EPA Secondary Standards ^b (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location ^d
					Julian Day	Time	
1-hour	1st	547	547		103	2300	Receptor A
	2nd		547		232	0100	Receptor A
	4th		505		231	2000	Receptor A
3-hour	1st	413		1300	232	0100	Receptor A
	2nd	315			197	2200	Receptor A
Annual	Mean	26					Receptor B
Annual Growing Season ^c		31					Receptor B
Annual Growing Season Daylight ^c		24					Receptor B

a Modelled concentrations of 3-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include background concentrations corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations are provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 4.0 ppb = 10.7 µg/m³ for 1-hour and 3-hour averaging period; 1.5 ppb = 4.0 µg/m³ for the annual averaging period.

b Secondary National Ambient Air Quality Standard (NAAQS) define the levels that protect the public welfare from any known or anticipated adverse effects of a pollutant. The secondary standard for the 3-hour averaging period is not to be exceeded more than once per calendar year. Therefore, results are compared to the second high.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.

d A map showing the receptor locations is provided in Figure 4-2.



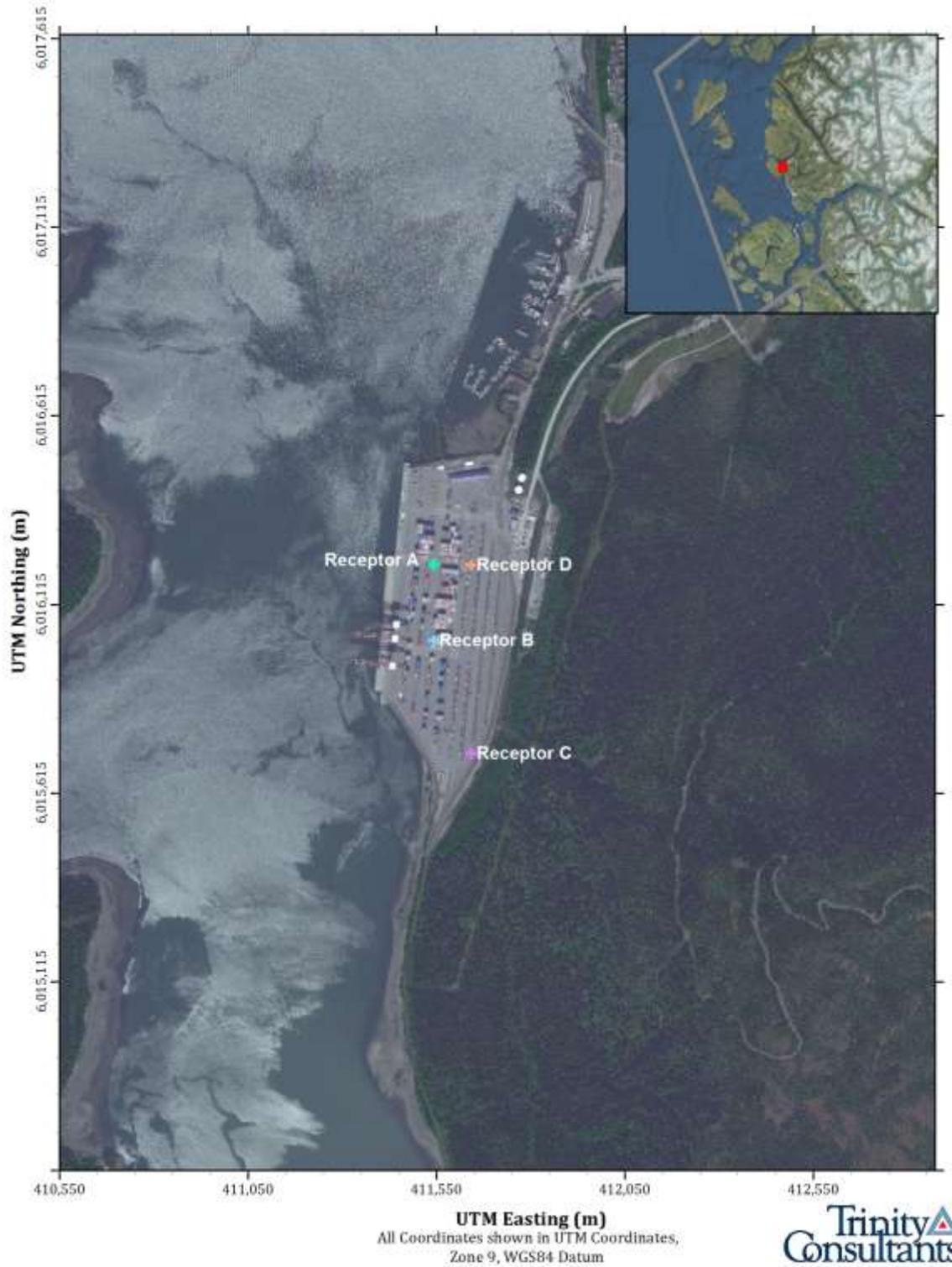


Figure 4-2: Location of receptors showing maximum modelled SO₂ concentrations.



Prince Rupert Airshed Study 99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average 2012 Meteorological Year

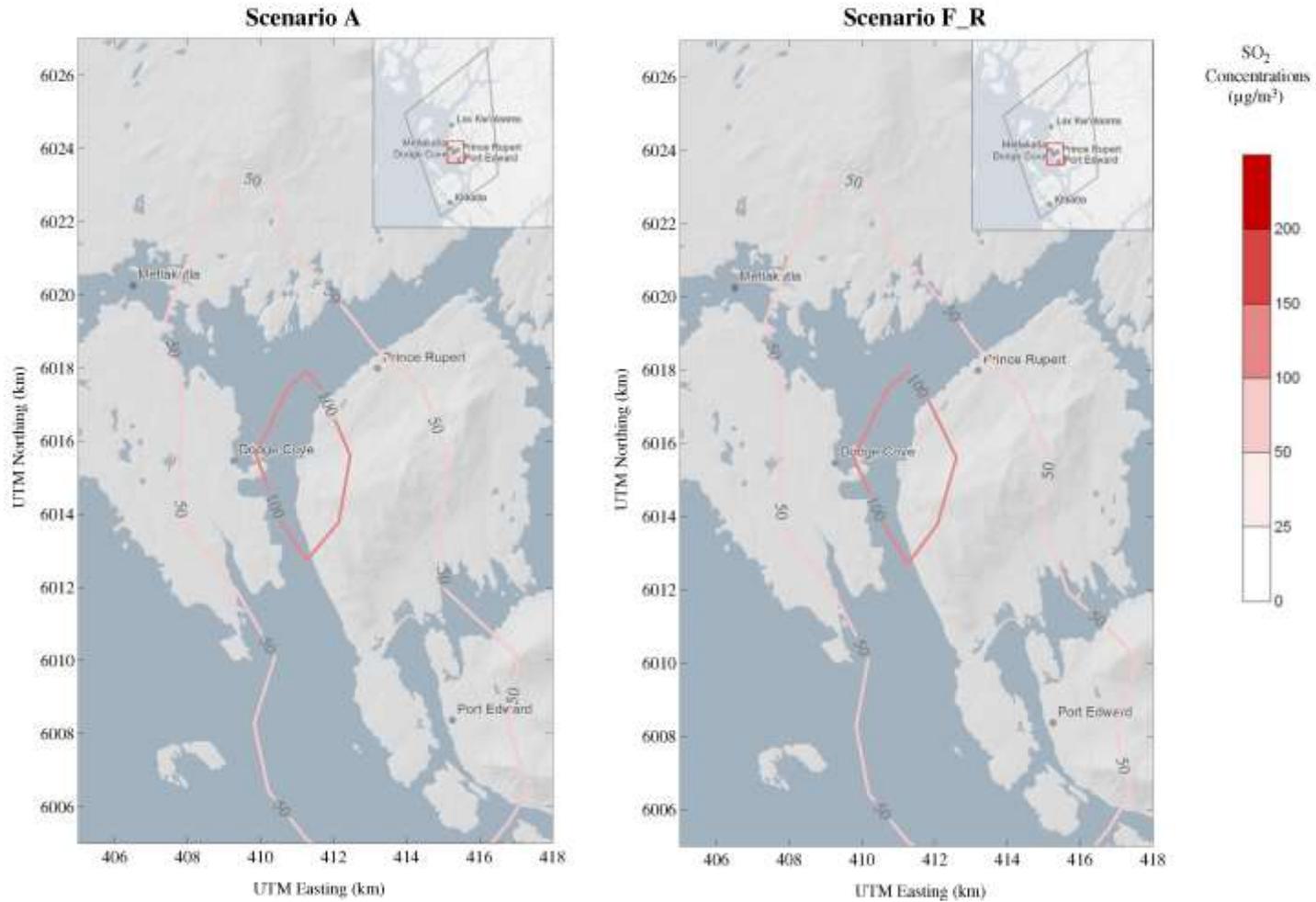


Figure 4-3: Scenario A and Scenario F_R, 99th percentile SO₂ concentrations, 1-hour average. The modelled SO₂ concentrations include a background concentration of 11 µg/m³, as discussed in Section 2.1.1.



The annual mean standard ($20 \mu\text{g}/\text{m}^3 \text{SO}_2$) established in Europe (European Environment Agency 2014) to be protective of vegetation, including lichens and mosses, is exceeded, as is the WHO guideline to protect lichen taxa of $10 \mu\text{g}/\text{m}^3 \text{SO}_2$ (WHO 2000). However, exceedance occurs in a very small area for the entire range of emission scenarios (see Figure 4-4 that illustrates modelled SO_2 concentrations for the bookend scenarios A and F_R). There is a recent report (Schirokauer et al. 2014) that suggests a critical level of about 3-33 $\mu\text{g}/\text{m}^3 \text{SO}_2$ (depending on hardwood or coniferous forest type) for lichen flora of SE Alaska. Modelled dispersion suggests that the lower end of that range would be exceeded in an area of perhaps 20 x 20 km. The upper end of the range would not be exceeded under any scenario modelled.

Based on the results of dispersion modelling for 2012, little or no effect on sensitive higher (vascular) vegetation would be expected under any scenario. If higher vegetation did respond, affected plants would likely be confined to the immediate area of the industrial development. No direct effects of SO_2 on vegetation, including lichens, would be expected at Lax Kw'alaams. Based on recently suggested critical levels for lichen taxa in SE Alaska and on established standards and guidelines from Europe, effects on sensitive lichen flora would likely be expected only within the confines of the $10 \mu\text{g}/\text{m}^3$ isopleth, to the point of maximum concentrations. These conclusions apply to all scenarios.



Prince Rupert Airshed Study SO₂ Concentrations, Annual Average 2012 Meteorological Year

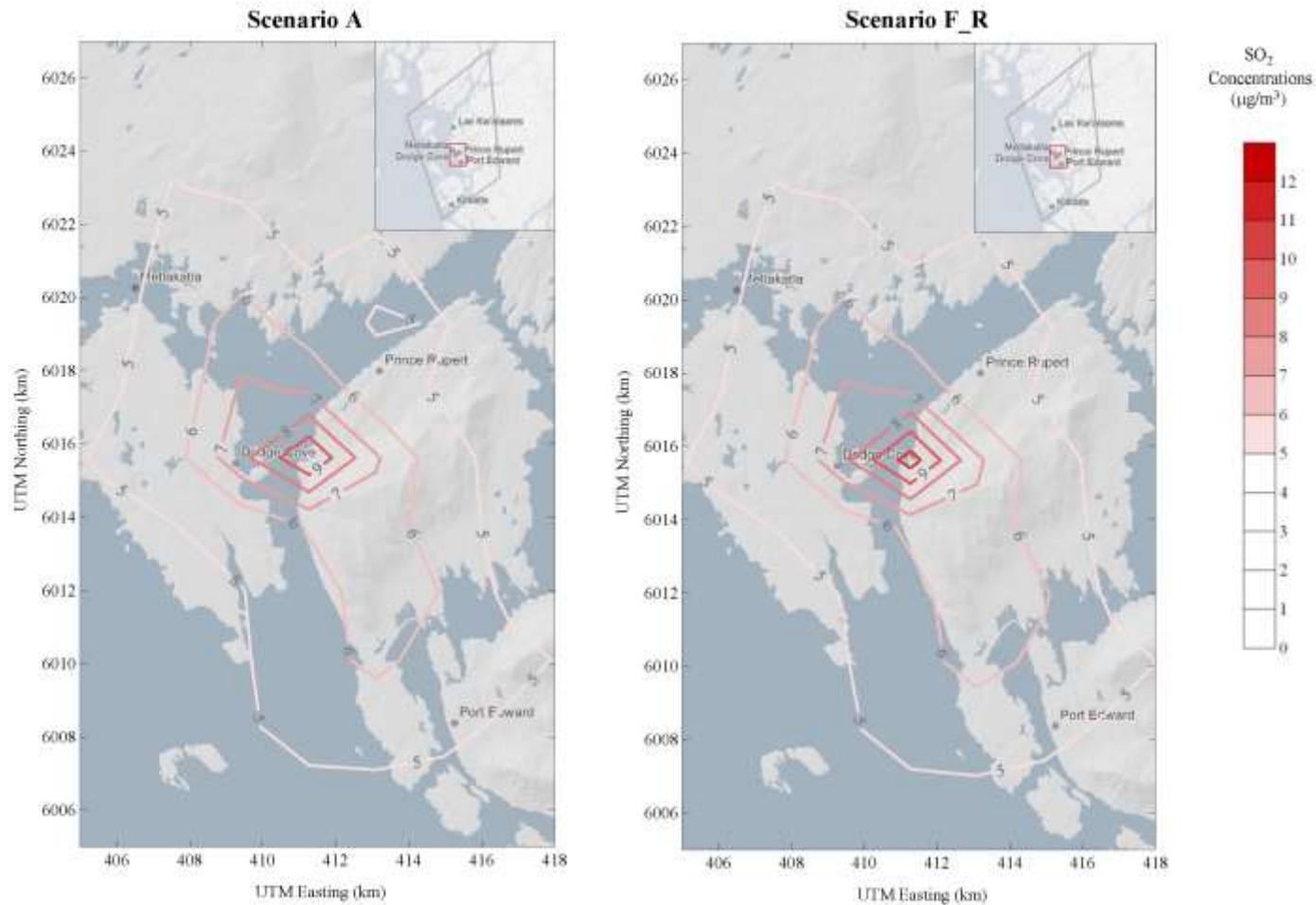


Figure 4-4: Scenario A and Scenario F_R, SO₂ concentration, annual average. The modelled SO₂ concentrations include a background concentration of 4 µg/m³, as discussed in Section 2.1.1.



4.2.3 Potential Effects of NO₂ on Vegetation

Modelled concentrations of NO₂ compared to thresholds of concern for vegetation are shown in Table 4-11 to Table 4-16. As opposed to SO₂, modelled maximum concentrations of NO₂ are quite high, reaching almost 2,500 µg/m³ for an hour in a few locations in the unvegetated industrial area (Figure 4-2). These concentrations are within the range that could cause visible injury to sensitive vegetation if present, and if exposed during a sensitive period (e.g., during the growing season and during the day). The highest concentrations reported here occurred during late evening or night-time hours when gas exchange activity is low.

The European standard of 30 µg/m³ annual average concentration of NO₂ is exceeded no more than once at any single receptor for all scenarios over all hours, including during the growing season. Multiple receptors show a single exceedance of the 30 µg/m³ threshold level. The receptor with the highest concentration of NO₂ was Receptor B (see Figure 4-2). Under all scenarios, the spatial extent of daily peak concentrations that exceed thresholds is confined to an area of about 10 x 10 km (Figure 4-5 compares the bookend scenarios, A and F_R). The annual average NO₂ concentration exceeds the 30 µg/m³ standard at one location under all scenarios. Under the worst case, the area where the annual average is exceeded is relatively small and restricted to the current industrial area (Figure 4-6 compares the bookend scenarios, A and F_R).

Based on the results of dispersion modelling for 2012, injury to sensitive higher (vascular) vegetation is possible in the immediate vicinity of the maximum receptor location. The spatial extent and severity of visible injury would likely be small based on the pattern of modelled concentrations for the worst-case scenario shown in Figure 4-5. Visible injury to vegetation due to NO₂ is very unlikely at Lax Kw'alaams. Results indicate a larger area of concern for potential effects on lichens, including near Lax Kw'alaams if results from Europe are applicable to the Prince Rupert area. The recent report from SE Alaska (Schirokauer et al. 2014) did not suggest a critical level for NO₂ in the region.

Table 4-11: Averaging periods and modelled concentrations for **NO₂** under Scenario A.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	European Critical Level ^b (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location ^d
					Julian Day	Time	
1-hour	1st	2481	2481		140	2300	Receptor A
	2nd		2311		200	2100	Receptor A
	8th		1792		173	2300	Receptor A
Annual	Mean	104		30			Receptor C
Annual Growing Season ^c		128		30			Receptor B
Annual Growing Season Daylight ^c		92					Receptor B

a Modelled concentrations of 1-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include a background concentration corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations were provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 13.0 ppb = 24.44 µg/m³ for the 1-hour averaging period; 3.0 ppb = 5.64 µg/m³ for the annual averaging period.

b Comparison to the WHO Guideline is not intended to provide conclusions related to impacts on the environment. The European Critical Level is intended for protection of vegetation.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.

d A map showing the receptor locations is provided in Figure 4-2.



Table 4-12: Averaging periods and modelled concentrations for NO₂ under Scenario B.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	European Critical Level ^b (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location ^d
					Julian Day	Time	
1-hour	1st	2481	2481		140	2300	Receptor A
	2nd		2311		200	2100	Receptor A
	8th		1790		173	2300	Receptor A
Annual	Mean	104		30			Receptor D
Annual Growing Season ^c		127		30			Receptor A
Annual Growing Season Daylight ^c		96					Receptor A

a Modelled concentrations of 1-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include a background concentration corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations were provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 13.0 ppb = 24.44 µg/m³ for the 1-hour averaging period; 3.0 ppb = 5.64 µg/m³ for the annual averaging period.

b Comparison to the WHO Guideline is not intended to provide conclusions related to impacts on the environment. The European Critical Level is intended for protection of vegetation.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.

d A map showing the receptor locations is provided in Figure 4-2.



Table 4-13: Averaging periods and modelled concentrations for **NO₂** under Scenario C.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	European Critical Level ^b (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location ^d
					Julian Day	Time	
1-hour	1st	2481	2481		140	2300	Receptor A
	2nd		2311		200	2100	Receptor A
	8th		1792		173	2300	Receptor A
Annual	Mean	105		30			Receptor C
Annual Growing Season ^c		128		30			Receptor B
Annual Growing Season Daylight ^c		93					Receptor B

a Modelled concentrations of 1-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include a background concentration corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations were provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 13.0 ppb = 24.44 µg/m³ for the 1-hour averaging period; 3.0 ppb = 5.64 µg/m³ for the annual averaging period.

b Comparison to the WHO Guideline is not intended to provide conclusions related to impacts on the environment. The European Critical Level is intended for protection of vegetation.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.

d A map showing the receptor locations is provided in Figure 4-2.



Table 4-14: Averaging periods and modelled concentrations for NO₂ under Scenario D.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	European Critical Level ^b (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location ^d
					Julian Day	Time	
1-hour	1st	2481	2481		140	2300	Receptor A
	2nd		2311		200	2100	Receptor A
	8th		1795		173	2300	Receptor A
Annual	Mean	104		30			Receptor C
Annual Growing Season ^c		127		30			Receptor B
Annual Growing Season Daylight ^c		95					Receptor B

a Modelled concentrations of 1-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include a background concentration corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations were provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 13.0 ppb = 24.44 µg/m³ for the 1-hour averaging period; 3.0 ppb = 5.64 µg/m³ for the annual averaging period.

b Comparison to the WHO Guideline is not intended to provide conclusions related to impacts on the environment. The European Critical Level is intended for protection of vegetation.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.

d A map showing the receptor locations is provided in Figure 4-2.



Table 4-15: Averaging periods and modelled concentrations for NO₂ under Scenario E.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	European Critical Level ^b (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location ^d
					Julian Day	Time	
1-hour	1st	2481	2481		140	2300	Receptor A
	2nd		2311		200	2100	Receptor A
	8th		1790		173	2300	Receptor A
Annual	Mean	106		30			Receptor C
Annual Growing Season ^c		129		30			Receptor B
Annual Growing Season Daylight ^c		97					Receptor B

a Modelled concentrations of 1-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include a background concentration corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations were provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 13.0 ppb = 24.44 µg/m³ for the 1-hour averaging period; 3.0 ppb = 5.64 µg/m³ for the annual averaging period.

b Comparison to the WHO Guideline is not intended to provide conclusions related to impacts on the environment. The European Critical Level is intended for protection of vegetation.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.

d A map showing the receptor locations is provided in Figure 4-2.



Table 4-16: Averaging periods and modelled concentrations for NO₂ under Scenario F_R.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	European Critical Level ^b (µg/m ³)	Maximum Date and Start Time All Receptors		Maximum Location ^d
					Julian Day	Time	
1-hour	1st	2482	2482		140	2300	Receptor A
	2nd		2311		200	2100	Receptor A
	8th		1795		173	2300	Receptor A
Annual	Mean	107		30			Receptor C
Annual Growing Season ^c		130		30			Receptor B
Annual Growing Season Daylight ^c		95					Receptor B

a Modelled concentrations of 1-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include a background concentration corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations were provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 13.0 ppb = 24.44 µg/m³ for the 1-hour averaging period; 3.0 ppb = 5.64 µg/m³ for the annual averaging period.

b Comparison to the WHO Guideline is not intended to provide conclusions related to impacts on the environment. The European Critical Level is intended for protection of vegetation.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.

d A map showing the receptor locations is provided in Figure 4-2.



**Prince Rupert Airshed Study
98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average
2012 Meteorological Year**

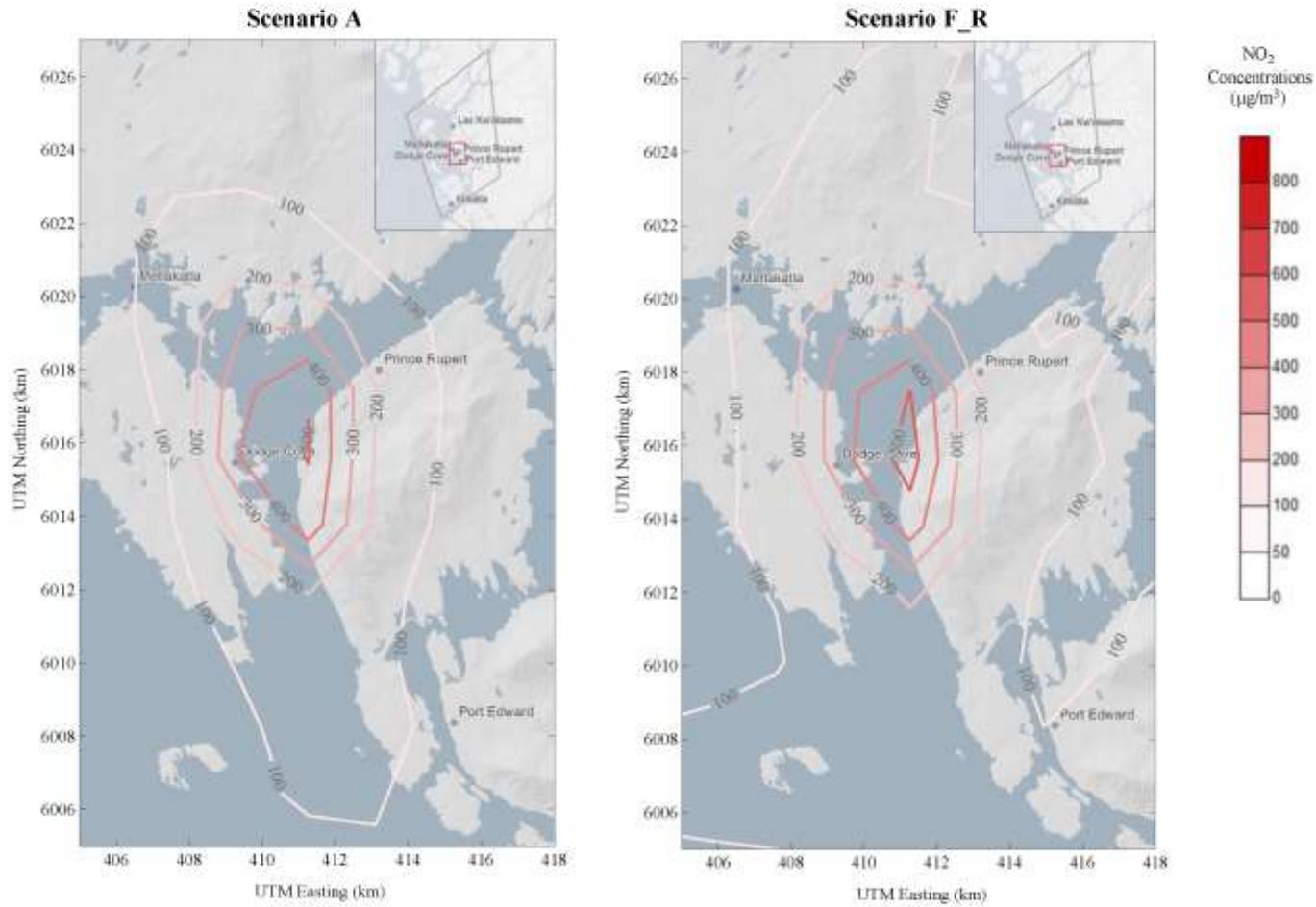


Figure 4-5: Scenario A and Scenario F_R, 98th percentile NO₂ concentration, 1-hour average. The modelled NO₂ concentrations include a background concentration of 24 µg/m³, as discussed in Section 2.1.1.



Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year

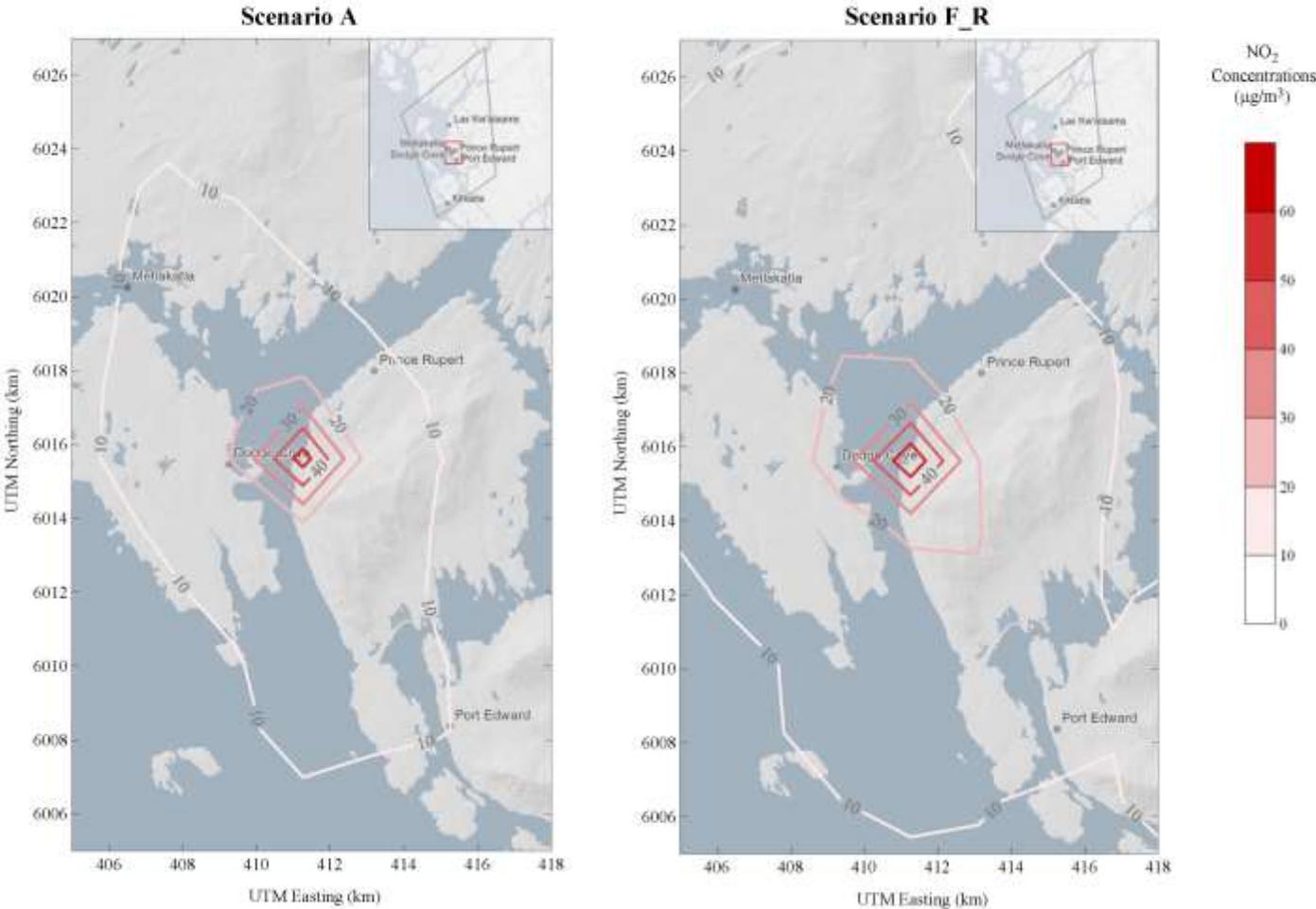


Figure 4-6: Scenario A and Scenario F_R, NO₂ concentration, annual average. The modelled NO₂ concentrations include a background concentration of 5.6 µg/m³, as discussed in Section 2.1.1.



4.2.4 Risk Categorization of Results

Based on results and interpretation of modelled air concentrations of SO₂ in this study, the impact assessment is classified as D-Unlikely and 1-Minor, resulting in a Low risk, as shown in Table 4-17. Potential effects on lichen flora are likely to occur in an area bounded by an annual mean concentration of 10-20 µg/m³. However, the quantitative effect on lichens is unknown and would depend on the sensitivity of the species present. If effects occur, the diversity, abundance, and distribution of lichens could be affected.

Table 4-17: Impact assessment from the combined likelihood and consequence dimensions of the risk assessment framework for vegetation for SO₂.

Likelihood (definitions in Table 4-2)	Consequence (definitions in Table 4-3)				
	1 – Minor	2 – Medium	3 – Serious	4 – Major	5 – Catastrophic
A – Almost certain	Moderate	High	Critical	Critical	Critical
B – Likely	Moderate	High	High	Critical	Critical
C – Possible	Low	Moderate	High	Critical	Critical
D – Unlikely	Low	Low	Moderate	High	Critical
E – Very Unlikely	Low	Low	Moderate	High	High

Based on results and interpretation of modelled air concentrations of NO₂ in this study, the impact assessment is classified as C-Possible and 2-Medium, resulting in a Moderate risk as shown in Table 4-18. Potential effects on lichen flora are likely to occur in an area bounded by an annual mean concentration of 30 µg/m³. However, the quantitative effect on lichens is unknown and would depend on the sensitivity of the species present. If effects occur, the diversity, abundance, and distribution of lichens could be affected. It is also probable that there would be a shift in the composition of the lichen community, favouring lichen species that respond positively to high nitrogen inputs versus those that do not.

Table 4-18: Impact assessment from the combined likelihood and consequence dimensions of the risk assessment framework for vegetation for NO₂.

Likelihood (definitions in Table 4-5)	Consequence (see definitions in Table 4-6)				
	1 – Minor	2 – Medium	3 – Serious	4 – Major	5 – Catastrophic
A – Almost certain	Moderate	High	Critical	Critical	Critical
B – Likely	Moderate	High	High	Critical	Critical
C – Possible	Low	Moderate	High	Critical	Critical
D – Unlikely	Low	Low	Moderate	High	Critical
E – Very Unlikely	Low	Low	Moderate	High	High



4.3 Main Sources and Implications of Quantitative Scientific Uncertainty

There are three primary sources of uncertainty in the analysis of the modelled scenarios and possible plant response. Uncertainty associated with dispersion modelling is discussed elsewhere in this document, however with respect to plant response, two issues arise. First, only one meteorological year was modelled, thus it is possible that conditions in other years could cause exposures to higher concentrations for greater periods of time, thereby increasing the probability of direct effects on vegetation. There is also uncertainty associated with the modelling of pollutant dispersion itself. In both cases, using threshold metrics that are conservative, as are the Canadian objectives and the European standards (see Table 4-1), with respect to exposures that have been reported to injure vegetation, provides a margin of safety in an attempt to accommodate the uncertainty in estimation of exposures.

The lack of knowledge about the sensitivity of plants in the Prince Rupert area to SO₂ and NO₂ is another source of uncertainty. Unlike the Kitimat area (ESSA et al. 2014), vegetation inspections have not been conducted over several decades. Neither has the area been exposed to industrial emissions that historically were greater than modelled here. There is also a potential for chronic effects on plants, particularly perennial plants, from repeated years of exposure. However, there is little reason to suspect that the inherent sensitivity of the vegetation in the area differs substantially from what is reported in the literature. The sensitivities of the lichen taxa are unknown, but may be presumed similar to that reported for Europe and SE Alaska.

The interaction of pollutant emissions with other stresses introduces a third source of uncertainty. The literature indicates that exposure of plants to SO₂ may alter their susceptibility to attack by certain insects or pathogens. In general, studies under controlled conditions would indicate that exposures in excess of what are predicted here would be required to cause such interactions. Little is known about the interaction of NO₂ with biotic stress factors. The scientific literature also documents indirect effects on vegetation due to deposition of acidifying pollutants addressed elsewhere in this report. There is little known about the response of plants that are stressed from soil conditions to additional direct pollutant exposure, other than from those related to nutrient deficiencies in agricultural crops. So, for instance, the potential direct effects of SO₂ or NO₂ on plants in an ecosystem where S or N critical loads have been exceeded are unknown. We believe the applicable air quality guidelines and standards should provide a margin of safety in estimation of effects.

4.4 Recommendations on Impact Assessment Guidance

Several activities are suggested as a result of this analysis. A baseline survey of vegetation is key to documenting the composition, distribution, health, and vitality of the plant communities and ecosystems. HyP³ (Banner et al. 2005) is an excellent starting point and further work should be coordinated with that effort to assure continuity and comparability, and perhaps extend the results. The survey should build on the present knowledge of the lichen flora and its distribution,



with particular attention to the report of Schirokauer et al. 2014 since they provide both background data and a quantitative assessment of effects of air quality on lichens.

A second activity would be to assess and establish baseline knowledge of the chemical content of foliage. These data provide a potential method of biomonitoring the presence of pollutants like S from SO₂ that may be useful in comparing the dispersion of the pollutants to what was modelled. Additionally, monitoring of other elemental concentrations, such as in Schirokauer et al. 2014, may provide understanding of indirect effects on vegetation, perhaps mediated by soil processes.

A vegetation monitoring and assessment program should also be designed for implementation in the event that industrial development proceeds. Such a program would provide periodic assessment of the condition of vegetation and could document problems should they begin to develop. It would also document the condition of vegetation in the area as affected by disease, insect infestations, or cultural conditions (frosts, drought, excess rainfall, etc.).

These monitoring and assessment programs should be coordinated with air monitoring to validate the spatial distribution of pollutant concentrations projected to occur through dispersion modelling.



5 Soils and Terrestrial Ecosystems

5.1 Methods

5.1.1 Assessment Approach

Anthropogenic emissions of sulphur (S) and nitrogen (N) oxides result in acidic deposition that can potentially acidify forest soils and negatively impact tree health owing to an increase in dissolved aluminum (Al) in soil solution. Additionally, N is an essential nutrient that is often limiting to forests, as such, an increase in N deposition can lead to N leaching and changes in plant community composition, which is referred to as eutrophication. In terrestrial ecosystems, lichens are typically considered the most sensitive indicator of elevated atmospheric N concentrations.

Critical loads are widely used to evaluate the potential risk of both acidification and eutrophication. When assessing the risk of acidification, critical load models assume that all S deposition is leached from soils and can therefore contribute to acidification. However, some of the N that is deposited can be retained in soils or vegetation, or can be emitted back to the atmosphere; as such, only excess N contributes to acidification. Critical load assessments are based on an endpoint known as the critical chemical limit that is considered potentially harmful to the receptor ecosystem (e.g., forests). With respect to eutrophication, two approaches are commonly used. One is based upon estimating the amount of N that can be deposited without exceeding an acceptable nitrate leaching concentration in soil, while the other uses an empirical approach that is based upon past observations relating N deposition to ecological impacts such as changes in plant species diversity.

In this assessment, the risk of acidification and eutrophication (nutrient N) to forest, shrubland and wetland (receptor) ecosystems in the Prince Rupert study domain was assessed using a critical loads approach following internationally accepted methods (UNECE 2004). The assessment of risk was based on the area and magnitude of critical load exceedance, i.e., where deposition is in excess of the critical load.

- Empirical critical loads of acidic and nutrient N deposition on terrestrial ecosystems were evaluated using the Skokloster (UNECE 2004) and empirical N (Bobbink and Hettelingh 2010) classifications, respectively, following the BC Ministry of the Environment 'critical load screening chart' (BC MOE 2014).
- Mass balance critical loads of acidity (S and N) and nutrient N were determined for natural terrestrial habitats covering up to 82% of the terrestrial study area. The determination of critical loads of acidity incorporated base cation weathering rates derived from the Skokloster classification, owing to the limited soils data for the region.
- Average accumulated exceedance of critical loads was determined under a range of modelled anthropogenic S and N emissions scenarios for receptor ecosystems in every 1 km × 1 km grid across the study domain. The areal proportion of exceedance was estimated with reference to an '*effects domain*', defined as the receptor ecosystem area



enclosed by the 15.0 meq/m²/yr modelled anthropogenic S and N deposition isopleth under the highest emissions scenario.

5.1.2 Environmental Data

The determination and mapping of critical loads³⁵ (acidity and eutrophication) for terrestrial ecosystems (Figure 5-1) incorporated point observations³⁶ and continuous digital (mapped) coverages for a range of environmental data in the study region (Table 5-1). A wide range of regional data sets (e.g., atmospheric deposition, meteorology, hydrology [soil percolation], land cover [coverage of receptor ecosystems], soils and geology) are required to determine critical load model input parameters, e.g., base cation weathering rates can be derived from digital soil maps, or determined from point observations and mapped across the region (see ESSA et al. 2014). In the Prince Rupert study area, detailed digital soil maps were not available; as such, bedrock geology was used as an indicator of soil parent material to define acid sensitivity and weathering rate following the Skokloster classification (UNECE 2004).

³⁵ A critical load is defined as 'a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge' (Nilsson and Grennfelt 1988).

³⁶ Point observations were only used to evaluate soil base cation weathering rates at sites where soil mineralogical observations were available (n = 18; see Appendix 3.2 in Volume 2 of this report).



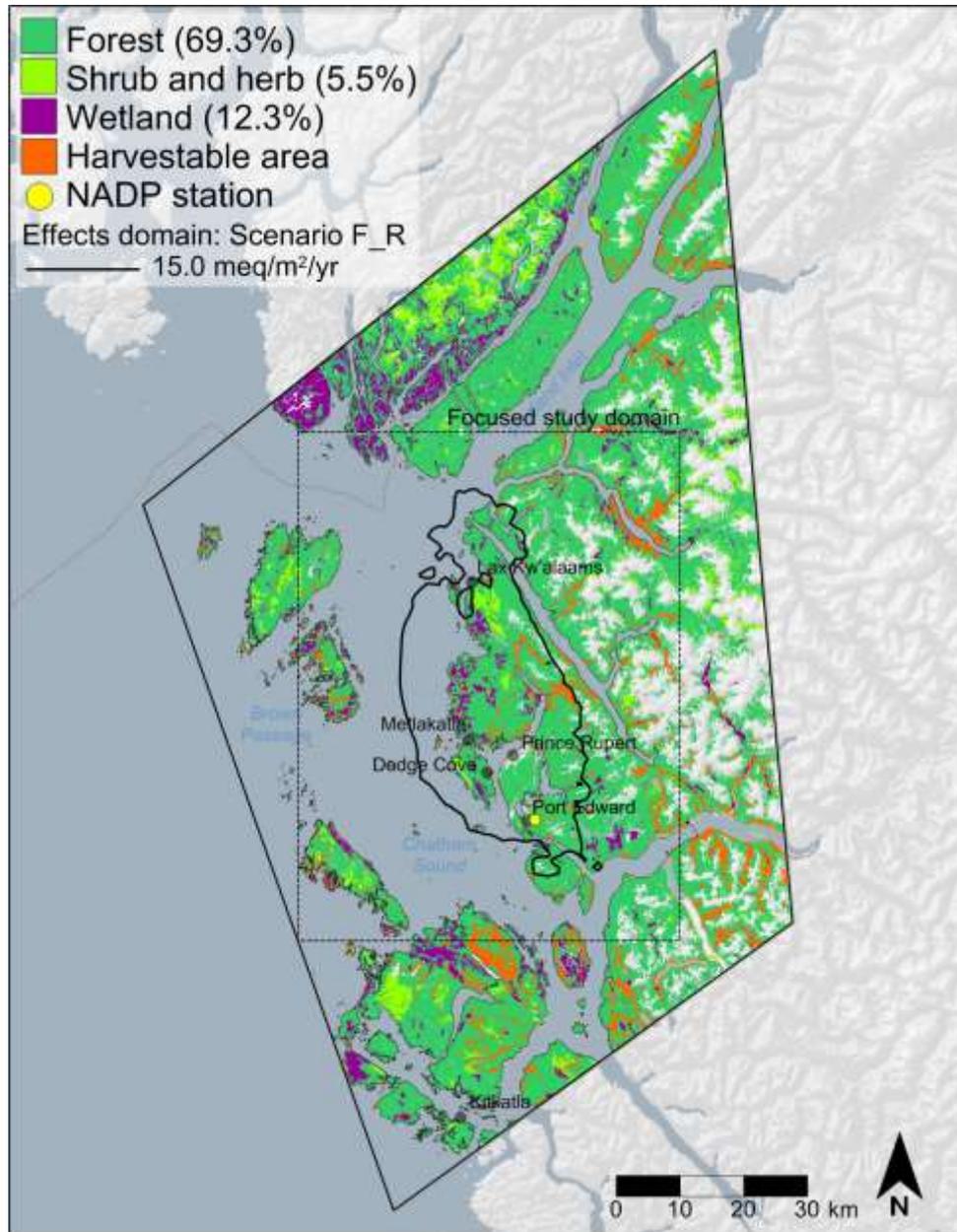


Figure 5-1: Map of the Prince Rupert Airshed Study area depicting the coverage of the terrestrial ecosystem (soils) assessment (diamond shaped outline 10,969 km² [terrestrial 6,275 km²]). Critical load of acidity was assessed for forest (coniferous, deciduous and mixed), shrub and herb, and wetland (bog) ecosystems (82% of the terrestrial study area). Critical load of eutrophication was assessed for all natural ecosystems (99% of the terrestrial study area). The area receiving ≥ 15.0 meq/m²/yr modelled sulphur and nitrogen deposition owing to anthropogenic emissions under Scenario F_R (defined as the 'effects domain') is also shown. A focused study domain (dotted rectangle) encompassing the effects domain was defined for the visual presentation of results (see Section 5.2). The location of the National Atmospheric Deposition Program (NADP) wet precipitation monitoring station is also shown (yellow filled circle). Map projection: Universal Transverse Mercator (UTM) Zone 9 (WGS-84).

Table 5-1: Environmental data sets (site-specific observations and digital [mapped] coverages) used for the determination of critical loads (acidity and eutrophication) for terrestrial ecosystems in the Prince Rupert Airshed Study.

Data	Description and source
Soil maps	A. Soil Landscapes of Canada (1:100 000 scale). Source: Canadian Soil Information Service [sis.agr.gc.ca/cansis/nsdb/slc/index.html]. B. BC Soil Mapping (1:50 000 scale). Source: BC Ministry of Environment [www.env.gov.bc.ca/esd/distdata/ecosystems/Soil_Data/SOIL_DATA_FGDB].
Soil chemistry and geochemistry	A. Soil Sample Sites and Soil Analyses: BC Soils Information System. Source: BC Ministry of Environment [http://www.env.gov.bc.ca/soils/provsoil]. B. Supplemental site-specific observations of soil chemistry and geochemistry from existing studies as provided by the BC Ministry of Environment. C. Provincial Geochemical Database: Geochemical data for stream and lake sediments. Source: BC Ministry of Energy and Mines [www.empr.gov.bc.ca/Mining/Geoscience/Geochemistry].
Geology	A. Bedrock Geology (Version: 2.2, October 2013). Source; BC Ministry of Energy and Mines [www.empr.gov.bc.ca/mining/geoscience/bedrockmapping/pages/bcgeomap.aspx]. B. EcoGeo (scale 1:250 000; provincial map derived from bedrock geology and quaternary sediments layer). Source: BC Ministry of Environment.
Elevation	Digital Elevation Model (scale: 1:20 000). Source: BC Ministry of Environment.
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) [www.climatewna.com].
Precipitation chemistry	Wet-only precipitation chemistry at Port Edward. Source: National Atmospheric Deposition Program [nadp.sws.uiuc.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	A. Biogeoclimatic zones (scale: 1:20 000), i.e., regions characterized as having specific climate, soil and vegetation communities (Meidinger and Pojar 1991). B. The British Columbia Watershed Atlas of aquatic-related features, e.g., streams, lakes, wetlands, obstructions, dams, etc (scale: 1:50 000). Source: BC Ministry of Environment. C. Ministry of Forestry VRI. D. Landsat 1999–2004. E. Cutblock data 2013.
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).



5.1.3 Critical Loads

Critical loads of acidification and eutrophication (nutrient N) for terrestrial ecosystems in the Prince Rupert Airshed Study area were estimated using the steady state mass balance (SSMB) and nutrient mass balance (NMB) models, respectively (UNECE 2004). The assessment focused on natural habitats covering up to 82% of the terrestrial study area (forest, shrubland and wetland [receptor] ecosystems; Figure 5-1). Nutrient N was also assessed for all natural ecosystems (99% of terrestrial area) using empirical critical loads (Bobbink and Hettelingh 2010). Further, the potential effects of acidic and nutrient deposition were initially evaluated using empirical approaches following the BC Ministry of Environment ‘critical load screening chart’ (BC MOE 2014). The screening criteria were developed to determine if critical load analysis is required to assess the impacts of acidic deposition.

The acidifying impact of S and N define a critical load function (CLF) incorporating the most important biogeochemical processes that affect long-term soil acidification (UNECE 2004). The function is defined by three quantities (see Table 5-2: Equations 5-1 to 5-4): the maximum critical load of S ($CL_{max}(S)$); minimum critical load of N ($CL_{min}(N)$); and the maximum critical load of N ($CL_{max}(N)$). Similarly, the critical load of nutrient N for forested ecosystems is derived from the balance of long-term sources and sinks of N (see Table 5-2: Equation 5-5). The level of protection for the chosen receptor ecosystem (e.g., forests or wetlands) is specified via critical ANC³⁷ leaching (acidification [see Table 5-2: Equation 5-2]) and acceptable nitrate leaching (nutrient N [see Table 5-2: Equation 5-5]). Habitat-specific empirical critical loads of nutrient N ($CL_{emp}(N)$) were based upon the current state-of-knowledge following Bobbink et al. (2010), Bobbink and Hettelingh (2010), Pardo et al. (2011) and Blett et al. (2014).

Table 5-2: Critical load mass balance models for the assessment of acidification and eutrophication of forested ecosystems; see Table 5-3 for a description of model parameters and data sources.

Critical load	Equation	Number
$CL_{max}(S)^a$	$CL_{max}(S) = BC_{dep} - Cl_{dep} + BC_w - BC_u - ANC_{le(crit)}$	Eqn (5-1)
	Where [for mineral soils] ³⁸	Eqn (5-2a)
	$ANC_{le(crit)} = -Q^{\frac{2}{3}} \cdot \left(1.5 \cdot \left(\frac{BC_w + BC_{dep} - BC_u}{(Bc : Al)_{crit} \cdot K_{gibb}} \right) \right)^{\frac{1}{3}} - 1.5 \cdot \left(\frac{BC_w + BC_{dep} - BC_u}{(Bc : Al)_{crit}} \right)$	
	Or [for organic soils]	Eqn (5-2b)
	$ANC_{le(crit)} = -0.5 \cdot \left(\frac{BC_w + BC_{dep} - BC_u}{(Bc : H)_{crit}} \right)$	
$CL_{min}(N)^a$	$CL_{min}(N) = N_i + N_u$	Eqn (5-3)

³⁷ Acid Neutralising Capacity (ANC). The most common approach is based on a critical molar Bc:Al ratio as an indicator of damage to plant fine roots; in general most chemical criteria incorporate aluminium concentration as the indicator of damage.

³⁸ Equation 5-2 depends on the chosen chemical criteria, a molar Bc:Al was selected under the Prince Rupert Airshed Study.



Critical load	Equation	Number
$CL_{max}(N)^a$	$CL_{max}(N) = CL_{min}(N) + CL_{max}(S) / (1 - f_{de})$	Eqn (5-4)
$CL_{nut}(N)^b$	$CL_{nut}(N) = CL_{min}(N) + N_{le(acc)} / (1 - f_{de})$	Eqn (5-5)

^a Critical loads of acidity ($CL_{max}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$) were determined for forest (coniferous, deciduous and mixed), herb, shrub and wetland ecosystems (area = 5,120 km²). Exceedance was determined as the proportion (%) of the effects domain, which is defined as the receptor ecosystem area enclosed by the 15.0 meq/m²/yr modelled S and N deposition isopleth under Scenario F_R (586 km²).

^b Critical loads of nutrient N ($CL_{nut}(N)$) were determined for forest (coniferous, deciduous and mixed), herb and shrub ecosystems (area = 4,350 km²). Exceedance was determined as the proportion (%) of the effects domain, which is defined as the receptor ecosystem area enclosed by the 15.0 meq/m²/yr modelled S and N deposition isopleth under Scenario F_R (513 km²).

Five critical loads variables were determined and mapped across the Prince Rupert study area: $CL_{max}(S)$, $CL_{min}(N)$, $CL_{max}(N)$, $CL_{nut}(N)$ and $CL_{emp}(N)$. The required model inputs for the mass balance models (Table 5-3) were obtained from existing environmental data sets (Table 5-1) and literature values (e.g., UNECE 2004, Bobbink and Hettelingh 2010). The final mapped resolution was consistent with the modelled deposition scenarios (1 km × 1 km, see Section 2), i.e., critical load variables were estimated as the area-weighted average of all receptor ecosystems in each 1 km × 1 km grid square across the study domain.

Table 5-3: Description of input parameters and their data sources (see Table 5-2) required to determine critical loads of acidity and eutrophication for terrestrial ecosystems in the Prince Rupert Airshed Study.

Critical load	Parameter	Description	Data source
$CL_{max}(S)$	BC^*_{dep}	Non-marine base cations ($BC = Bc + Na^+$ (sodium), $Bc = Ca^{2+}$ (calcium) + Mg^{2+} (magnesium) + K^+ (potassium)) deposition.	Precipitation concentrations (NADP [three regional stations] and Emili and Price, 2013).
	Cl^*_{dep}	Non-marine chloride deposition; it is assumed that non-marine chloride is negligible in the study area.	–
	BC_w	Base cation weathering rate estimated using the Skokloster classification (Appendix 3, Volume 2 of this report), modified for temperature: $BC_w = Skokloster(meq/m^2/yr) \cdot \exp\left(\frac{A}{281} + \frac{A}{281+T}\right)$ where T (°C) is the average annual (soil) temperature and A = 3600 K.	Table 5-1 (bedrock geology); Sverdrup (1990), Hornung et al. (1995), Aherne and Farrell (2000), UNECE (2004).
	Bc_u	Base cation removal in harvested biomass based on Annual Allowable Cut (AAC) and literature values for tree species (Western Hemlock) base cation (Ca^{2+} , Mg^{2+} and K^+) concentrations.	ESSA Technologies (updated from ESSA et al. 2013, 2014).



Critical load	Parameter	Description	Data source
	Bc:Al _(crit)	For mineral soils, the critical molar base cation to aluminum ratio is the chemical criterion associated with ecosystem damage. Following the KAA, Bc:Al = 1.0 for coniferous forests and Bc:Al = 6.0 for deciduous and mixed.	ESSA et al. (2014), Sverdrup and Warfinge (1993).
	Bc:H _(crit)	For organic soils (which do not contain aluminium), the critical molar base cation to proton ratio has been proposed. The default value for Bc:H is 0.3 × Bc:Al ratio ^a (mol mol ⁻¹).	Aherne et al. (2001); UNECE (2004)
	Q	Long-term annual soil percolation or runoff.	Table 5-1 (hydrology).
	K _{gibb}	Gibbsite equilibrium constant: mineral soil= 950 m ⁶ /eq ² .	ESSA et al. (2014); UNECE (2004).
CL _{min} (N)	N _i	Long-term nitrogen immobilization based on soil organic matter content: mineral soil = 5 meq/m ² /yr; organic soil = 7.1 meq/m ² /yr (based on average from ESSA et al. 2014).	ESSA et al. (2014); UNECE (2004).
	N _u	Nitrogen removal in harvested biomass based on Annual Allowable Cut (AAC) and literature values for tree species (Western Hemlock) concentrations of nitrogen.	ESSA Technologies (updated from ESSA et al. 2013, 2014).
CL _{max} (N)	f _{de}	The fraction of atmospherically deposited nitrogen that is denitrified based on soil type and its moisture status: mineral soil = 0.35; organic soil = 0.8 meq/m ² /yr (based on average from ESSA et al. 2014).	ESSA et al. (2014); UNECE (2004).
CL _{nut} (N)	N _{le(acc)}	Acceptable nitrogen leaching is the chemical criterion associated with ecosystem damage. Default values range between 0.2–0.4 mg N/L. Set to 0.2 mg N/L (14.3 µeq/L) × Q	Table 5-1 (hydrology); ESSA et al. (2014); UNECE (2004).

^a The default critical chemical limit assumes a cubic relationship between aluminium dissolution and hydrogen concentration (i.e., following gibbsite aluminium); as such, the Bc:H ratio is set to a third of the Bc:Al ratio.

Critical loads of acidity (S and N) and nutrient N were determined for forested ecosystems on mineral soils, covering approximately 64% of the Prince Rupert study area (Figure 5-1: derived from land cover classified as coniferous, deciduous and mixed forest or previously forested). Mapped forest area was delineated into 1 km × 1 km grids aligned with the modelled deposition grid, and the proportion of coniferous, deciduous and mixed forest recorded for each grid. Additionally, critical loads of acidity were determined for shrub (on mineral soil) and wetlands (on organic soils), covering approximately 17% of the terrestrial study area. The total number of receptor grids was 7,445, covering an ecosystem area of 5,120 km² (not all grids had 100% receptor coverage); critical loads of acidity and eutrophication (Table 5-2) were estimated for receptor ecosystems in each 1 km × 1 km grid across the study area (see Figure 5-1) by combining existing mapped input parameters (Table 5-3) with derived parameters, e.g., soil base cation weathering rate.

Non-marine base cation wet deposition (BC*_{dep}) was set at 2.1 meq/m²/yr across the study area based on annual average observations during 2014 at two National Atmospheric Deposition Program (NADP) precipitation chemistry monitoring stations (Port Edward [BC24; see Figure 5-1] and Lakelse Lake [BC23]). This is consistent with estimated background S (10 meq/m²/yr) and N (5 meq/m²/yr) deposition across the study area (Appendix 3, Volume 2 of this report). Owing to limited soil data, soil base cation weathering (BC_w) was derived by allocating mapped bedrock types to Skokloster classes (n = 5) based on rock mineralogical composition. The



Skokloster classification groups minerals that control weathering into five weathering rate ranges (Appendix 3, Volume 2 of this report), the mid-point of each range was used in the current study to represent soil base cation weathering for the upper 50 cm of mineral soil (a comparison with weathering rates estimated at soil observation points in Prince Rupert and against regional maps in the KAA is given in Appendix 3, Volume 2 of this report). A base cation weathering of 12.5 meq/m²/yr was allocated to organic soils following the soil type – texture approximation method (UNECE 2004). Further, the temperature-dependence of weathering was modelled using an Arrhenius-factor (Sverdrup and Warfvinge 1993). The determination of base cation uptake (Bc_u) and runoff (or soil percolation; Q) followed ESSA et al. (2014), while other parameters such as N immobilisation and denitrification fraction were assigned default values for mineral and organic soil types (see Table 5-3), which were consistent with the Kitimat Airshed Emissions Effects Assessment (KAA) (ESSA et al. 2014).

Long-term (1960–1990³⁹) annual runoff was obtained from the province-wide Distributed Climate Water Balance Model (Moore et al. 2012; data provided by Joel Trubilowicz, Department of Geography, University of British Columbia) on a 0.4 km x 0.4 km grid over the study area (Figure 5-2). The Distributed Climate Water Balance Model uses input data on monthly precipitation and temperature for each grid cell from the ClimateBC gridded data set (Spittlehouse 2006), and tracks changes over time in snowpack, soil moisture, and runoff, using different procedures for glaciers, non-glacier land and surface water. Moore et al. (2012) compared their model's runoff predictions to 226 unregulated catchments against Water Survey of Canada data, and found a mean absolute error of 25.4%; more than half of the streams had errors of less than 20%.

Empirical Critical Loads: The BC Ministry of Environment 'critical load screening chart' (BC MOE 2014) outlines an empirical approach to determine if critical load analysis is required to assess the impacts of acidic deposition. Accordingly, this study employed the screening procedure as a 'first step' assessment. Empirical critical loads for acidity are based solely on the Skokloster classification, which represents the buffering capacity of receptor ecosystems to acidic deposition (Appendix 3, Volume 2 of this report). Empirical critical loads for N ($CL_{emp}(N)$) were derived from observations of detrimental responses to an ecosystem or ecosystem component under N deposition; this level of annual deposition is set as the critical load. Empirical critical loads for N published in the peer-reviewed literature were based on measurements from numerous gradient studies, field experiments, or long-term monitoring sites, and are typically synthesized as ranges for broader ecosystem or habitat classifications (Bobbink et al. 2010; Pardo et al. 2011; Blett et al. 2014). Land cover classes (Figure 5-1) within the study area⁴⁰ were assigned the lower end of the range from published empirical critical loads for N associated with the most relevant ecosystem types reported by Bobbink et al. (2010), Pardo et al. (2011), and Blett et al. (2014) (Table 5-4). When more than one potential ecosystem type was reported for a land cover classification, the lowest $CL_{emp}(N)$ was chosen (Table 5-4).

³⁹ Represents the baseline (reference) normal period for climate data used in the ClimateBC model (Spittlehouse 2006).

⁴⁰ There is a paucity of published empirical critical loads for western Canada, as such, critical load ranges for habitats in Europe and western US were used.



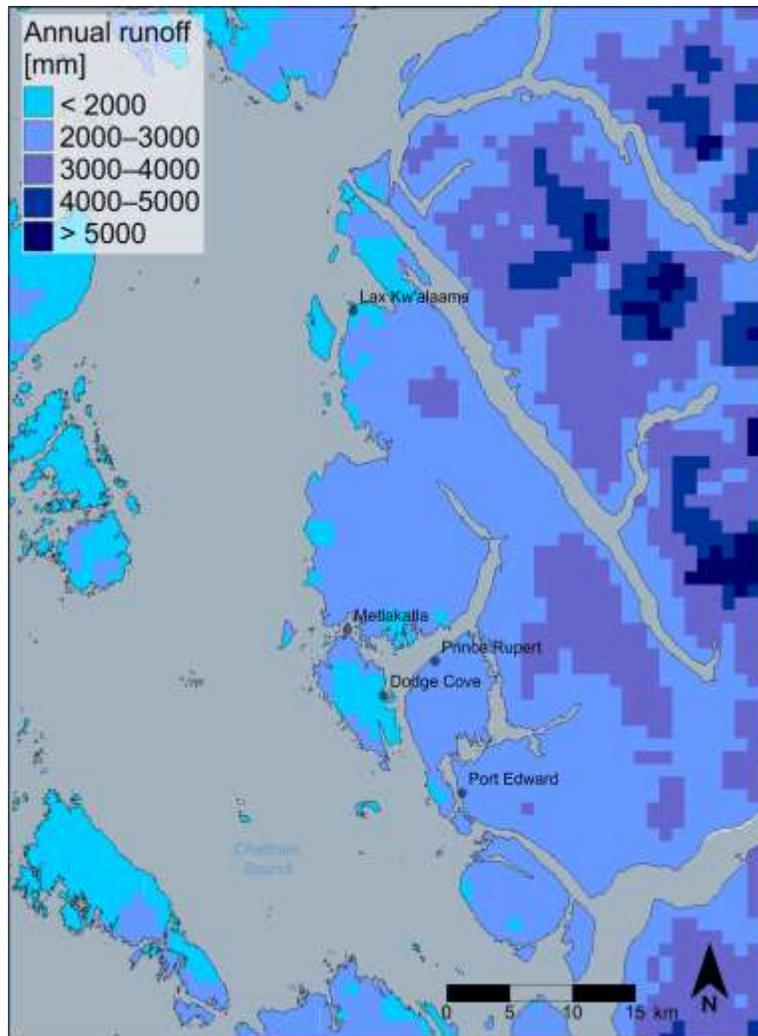


Figure 5-2: Long-term (1960-1990) annual runoff (mm) estimated by the Distributed Climate Water Balance Model (Moore et al. 2012); model outputs on a 0.4 km x 0.4 km grid were summarized on a 1 km x 1 km grid over the study area.

A study by Geiser et al. (2010) suggested that $CL_{emp}(N)$ could be as low as 19.2 meq/m²/yr (2.7 kg N/ha/yr) based on community changes in epiphytic macro-lichen communities in western Oregon and Washington forests. However this $CL_{emp}(N)$ was considered applicable to low (440 mm) precipitation areas (Geiser et al. 2010). In areas with median (1,860 mm) precipitation, a $CL_{emp}(N)$ of 35.7 meq/m²/yr (5 kg N/ha/yr) was reported, and in high (4,510 mm) precipitation areas, a $CL_{emp}(N)$ of 65.7 meq/m²/yr (9.2 kg N/ha/yr) was suggested (Geiser et al. 2010). Consequently, to protect lichen communities in coniferous forests in the study area, a $CL_{emp}(N)$ of 35.7 meq/m²/yr (5 kg N/ha/yr) was chosen based on a synthesis of multiple studies (Bobbink et al. 2010; Pardo et al. 2011; Blett et al. 2014). A $CL_{emp}(N)$ of 35.7 meq/m²/yr (5 kg N/ha/yr) represents the low end of the range for the majority of habitat or ecosystem types in the study area (Table 5-4); as such, a $CL_{emp}(N)$ of 35.7 meq/m²/yr (5 kg N/ha/yr) was applied to all ecosystems. Empirical critical loads were estimated for natural habitats covering 99% of the terrestrial study domain; developed land, and snow and ice land cover classes were not included in the assessment.

Table 5-4: Land cover classes (see Figure 5-1), reported values (ranges) of empirical critical loads for nutrient nitrogen ($CL_{emp}(N)$) for related habitat or ecosystem types^a, and selected $CL_{emp}(N)$ for the Prince Rupert study area (given in kg N/ha/yr and meq/m²/yr).

Land cover	Habitat or ecosystem type and reported $CL_{emp}(N)$ ranges (kg N/ha/yr) ^b	Area (km ²) ^c	Area (%)	$CL_{emp}(N)$ (kg N/ha/yr [meq/m ² /yr])
Coniferous forest (dense, open and sparse); Cut blocks	Coniferous Forests Northwest: 10–15 Marine West Coast Forests: 5 Spruce Forests: 5–7	3972.3	63.3	5 [35.7]
Deciduous forest (dense, open and sparse)	Deciduous Forests: 10–15	8.7	0.1	5 [35.7] ^d
Mixed forest (dense, open and sparse)	Temperate Forests Northwest: 10–15 Marine West Coast Forests: 5	11.2	0.2	5 [35.7]
Herb (dense, open and sparse)	Alpine / Subalpine Grassland: 5–10	3.0	0.0	5 [35.7]
Shrub low (dense, open and sparse); Shrub tall (dense, open and sparse)	Arctic, Alpine and Subalpine Scrub Habitats: 5–15	315.1	5.0	5 [35.7]
Rock/Rubble; Exposed land; Unclassified	Moss and Lichen Dominated Mountain Summits: 5–10	1138.5	18.1	5 [35.7]
Wetland (herb, shrub and treed)	Raised and Blanket Bogs: 5–10 Poor Fens: 10–20	787.2	12.5	5 [35.7]

^a Source: Bobbink et al. (2010), Pardo et al. (2011), and Blett et al. (2014).

^b Empirical critical loads for nutrient nitrogen ($CL_{emp}(N)$) are reported in the literature in units of kg N/ha/yr, which is converted to meq/m²/yr as 1 kg N/ha/yr = 7.1 meq/m²/yr.

^c Empirical critical loads of nutrient N ($CL_{emp}(N)$) were determined for 99% of the terrestrial study area (6236 km²). Exceedance was determined as the proportion (%) of the effects domain, which is defined as the receptor ecosystem area enclosed by the 15.0 meq/m²/yr modelled S and N deposition isopleth under Scenario F_R (608 km²).

^d The low end of the critical load range for deciduous forests is 71.4 meq/m²/yr (10 kg N/ha/yr); however, a $CL_{emp}(N)$ of 35.7 meq/m²/yr (5 kg N/ha/yr) was also applied to deciduous forest for consistency with other habitats (and given its low coverage (0.1%)).

5.1.4 Critical Limits and Exceedance

Critical Chemical Criteria. The most widely used acidification threshold linking soil chemical status and plant response is a critical⁴¹ molar base cation (Bc) to aluminium ratio; sodium is excluded as it does not protect plant roots against aluminium toxicity. A soil solution critical molar Bc:Al ratio = 1.0⁴² within the top 50 cm (the principal rooting zone) was chosen to be conservatively protective of the dominant tree species (*Tsuga heterophylla*, western hemlock) in the region (Sverdrup and Warfvinge 1993). In areas dominated by deciduous (or mixed) forests a critical Bc:Al ratio = 6.0 within the top 50 cm was chosen to ensure protection of the more sensitive deciduous tree species, such as *Populus tremuloides* (quaking aspen). Note that the limit for *Populus tremula* (Sverdrup and Warfvinge 1993) was used as the limit for the protection of *Populus* species native to British Columbia such as *Populus tremuloides* and *Populus*

⁴¹ Refers to the critical limit which is the most unfavourable value for the chemical criterion, i.e., the critical chemical criterion for protection of structure and function of the chosen receptor ecosystem.

⁴² A range of critical values has been proposed which depends on plant species (see Sverdrup and Warfvinge 1993). The most widely used critical chemical criterion is Bc:Al = 1.0, as such it was used under the Prince Rupert Airshed study.



trichocarpa. For consistency, a Bc:H ratio was used as the indicator of damage to plant species on organic soils (as organic soils do not contain aluminium). The recommended default critical ratio for Bc:H is $0.3 \times \text{Bc:Al}$ ratio⁴³ (UNECE 2004). The average critical load for each 1 km × 1 km grid was determined by weighting the critical load estimate for each receptor ecosystem (forest, shrub and wetland) by their areal coverage. Notably, a range of chemical indicators of acidification has been proposed for forest ecosystems (see Table 5-5); while the molar Bc:Al ratio is the most widely used criterion (see Cronan and Grigal 1995 for support), it has also been criticized (Løkke et al. 1996); as such, several studies have used alternative or multiple chemical criteria (Aherne et al. 2001; Hall et al. 2001; Reinds et al. 2008; ESSA et al. 2014). The uncertainty in predicted exceedance associated with the choice of critical chemical criteria was evaluated under the KAA (ESSA et al. 2014). While critical loads varied under each chemical criteria, the predicted exceedance did not change the risk rating. Acceptable N leaching is the chemical criterion associated with ecosystem damage under (mass balance) nutrient N deposition in forested ecosystems; acceptable N leaching was set to 0.2 mg N/L in all forest types to protect against nutrient imbalances (UNECE 2004).

Table 5-5: Link between air pollution impacts, chemical indicators and critical limits (ecological thresholds; UNECE 2004) for terrestrial ecosystems. Ecological thresholds given are typical values that vary depending on ecological and environmental conditions, and desired level of protection.

Impact	Ecological Response	Chemical Indicator	Critical Limit (Ecological Threshold)	
Acidification	<ul style="list-style-type: none"> ▪ Decreased forest growth ▪ Increased susceptibility to disease ▪ Decreased soil nutrient status ▪ Loss of soil structural integrity ▪ Increased export of toxic metals 	Molar Bc:Al or molar Ca:Al ratio	<1.0 mol/mol ^a	Indicator of damage to plant fine roots
		Molar Bc:H ratio	< $0.3 \times \text{Bc:Al}$ ^b	Indicator of damage to plant species on organic soils
		Soil solution Al ³⁺ (Al)	<0.2 eq/m ³	Indicator of damage to plant fine roots
		Soil solution pH	<4.0–4.2	Mobilisation of toxic metals and damage to plant roots
		Al mobilisation (p)	<2 eq/eq	Indicator of depletion of secondary Al phases and soil structural changes
		Soil base saturation	<10%	Indicator of the soil acid status and nutrient deficiencies
Nutrient enrichment	<ul style="list-style-type: none"> ▪ Nutrient imbalances ▪ Elevated nitrogen leaching ▪ Loss of sensitive plant species ▪ Increase in invasive plants ▪ Increased tree mortality 	Nitrogen leaching	<0.2 mg N/L	Indicator of elevated nitrate leaching, nutrient imbalances and vegetation changes
		Nitrogen deposition	>5–10 kg N/ha/yr ^b	Indicator of shift in plant species composition (see Table 5-4)

^a Bc:Al = 1.0 mol/mol is the most commonly used critical limit but values depend on species (see Sverdrup and Warfvinge 1993).

^b 35.7-71.4 meq/m²/yr.

⁴³ A Bc:H ratio = 0.3 was used for all organic (wetland) soils in the study area, based on $0.3 \times \text{Bc:Al}$ ratio = 1.0.



Exceedance of Critical Load. Exceedance of critical loads of acidity and nutrient N was estimated under a range of modelled S and N emissions scenarios (A to F_R: see Section 2). All critical load exceedance calculations included an estimated background deposition for S (10 meq/m²/yr) and N (5 meq/m²/yr) owing to transboundary emission sources (see ESSA et al. 2014). Exceedance for a given S and N deposition pair is the sum of the S and N deposition reductions required to reach the critical load function (CLF) by the ‘shortest’ path (Figure 5-3). The computation of the exceedance function followed the methodology described by UNECE (2004). In some instances, S deposition (or N) must be reduced to achieve non-exceedance (see coloured zones in Figure 5-3) The proportional area of exceedance was defined as the mapped receptor area under exceedance relative to an ‘effects domain’, which was defined as the area receiving ≥ 15.0 meq/m²/yr modelled S and N deposition owing to anthropogenic emissions under Scenario F_R⁴⁴.

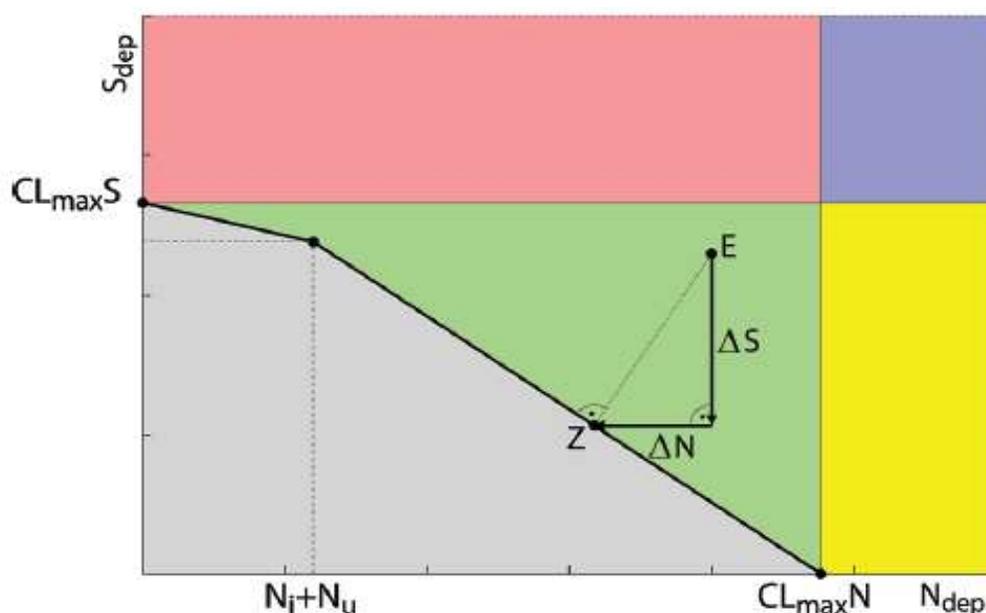


Figure 5-3: Piece-wise critical load function (CLF) for sulphur (S) and acidifying nitrogen (N) as defined by soil properties (thick black line), and the terrestrial system ANC is kept above the critical level. For a given deposition pair (N_{dep} , S_{dep}) the critical load exceedance is calculated by adding the N and S deposition reductions needed to reach the CLF via the shortest path (E→Z): $Ex = \Delta S + \Delta N$. The grey area below the CLF denotes deposition pairs resulting in non-exceedance of critical loads. If a deposition pair is located in the green area (such as E), non-exceedance can be achieved by reducing N or S deposition (or both); in the pink (or yellow) area S_{dep} (or N_{dep}) must be reduced to achieve non-exceedance; and in the blue area both N_{dep} and S_{dep} must be reduced. Source: Posch et al. (2014), CLF for aquatic systems.

Risk Assessment Framework. A rating of risk was assigned to each emission scenario based on the area and magnitude of exceedance under acidification and eutrophication assessments.

⁴⁴ Effects domain: $CL_{acidity} = 586$ km², $CL_{nut}(N) = 513$ km² and $CL_{emp}(N) = 608$ km².



The BC Ministry of Environment determined the exceedance thresholds between the risk categories, primarily based on the areal extent of exceedance (with respect to the ‘effects domain’); see Table 5-6. The magnitude of exceedance was also considered, and if areal extent was dominated by uniform low levels of exceedance, i.e., <10 meq/m²/yr, then the risk rating was modified (lower); however this situation did not occur.

Table 5-6: Risk categories and definitions for the terrestrial ecosystem receptors.

Low	No exceedance, or an areal exceedance of critical loads of acidity and (or) critical loads of nutrient nitrogen ^a ≤0.05%: emissions scenarios expected to have no, or negligible, areal impact. ^b
Moderate	Areal exceedance of critical loads of acidity and (or) critical loads of nutrient nitrogen ≤2.5%: emissions scenarios expected to have an impact, but of a magnitude or spatial extent considered to be acceptable. ^c
High	Areal exceedance of critical loads of acidity and (or) critical loads of nutrient nitrogen >2.5% and ≤5%: emissions scenarios expected to have an impact of a magnitude or spatial extent considered to be unacceptable; ^c further investigation is needed into the implications of the assumptions in this scoping-level assessment to determine if reducing uncertainties and refining assessment inputs lowers the risk category.
Critical	Areal exceedance of critical loads of acidity and (or) critical loads of nutrient nitrogen >5%: scenarios expected to have an impact of a magnitude or spatial extent, considered to be extremely unacceptable ^c ; further investigation could be made into the implications of the assumptions in this scoping-level assessment to determine if reducing uncertainties and refining assessment inputs lowers the risk category, but would be unlikely to reduce the impact sufficiently to be considered acceptable ^d .

^a Critical loads of nutrient nitrogen were assessed using mass balance (CL_{nut}(N) and empirical (CL_{emp}(N)) approaches; assignment of risk was based on the approach with the highest exceedance.

^b Areal exceedance was estimated as a proportion of the ‘effect domain’, i.e., receptor area receiving ≥15.0 meq/m²/yr modelled sulphur and nitrogen deposition owing to anthropogenic emissions under Scenario F_R.

^c “Acceptability” of impacts depends on one’s values, and is ultimately a policy decision.

^d Exceedance is defined as damage to plant fine roots under acidification and a shift in plant species composition under nutrient nitrogen (see Table 5-5).

5.2 Results

5.2.1 Critical Loads of Acidity and Nutrient Nitrogen

The potential impact of acidic (S and N) deposition depends on the sensitivity of the receptor ecosystem (e.g., forest soils) and the magnitude of atmospheric deposition. The BC Ministry of the Environment ‘critical load screening chart’ (BC MOE 2014) delineates 7.5 kg SO₄²⁻/ha/yr (15.6 meq/m²/yr) and 5 kg N/ha/yr (35.7 meq/m²/yr) as broad deposition thresholds of concern leading to potential impacts on natural ecosystem health. Under emissions Scenario F_R (the highest S and N oxide emissions scenario), the threshold SO₄²⁻ (sulphate) and N deposition isopleths were centred around Kaien and Digby islands encompassing an area of approximately 250 km² and 100 km², respectively (Figure 5-4). Under the ‘critical load screening chart’, deposition in excess of the thresholds indicates that a critical load analysis for acidity, using a steady-state mass-balance model and an empirical critical load assessment for nutrient N, is required.



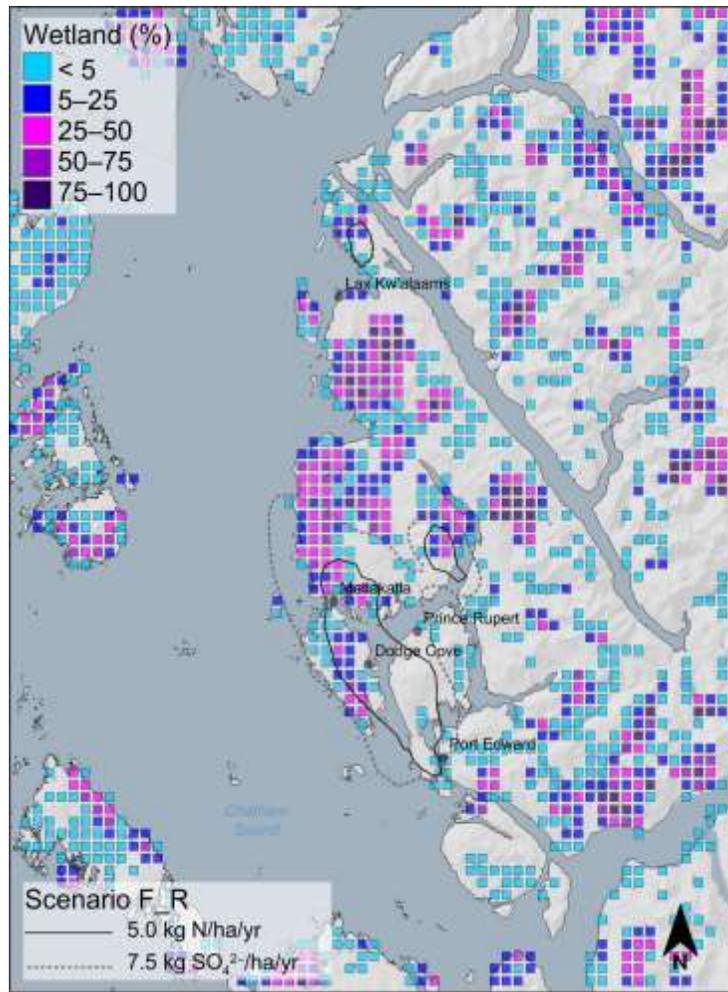


Figure 5-4: Isopleths showing regions with potential effects of acidic (7.5 kg SO₄²⁻/ha/yr; 15.6 meq/m²/yr) and nutrient (5.0 kg N/ha/yr; 35.7 meq/m²/yr) deposition on terrestrial ecosystems under emissions Scenario F_R (following BC Ministry of the Environment 'critical load screening chart'). The location and coverage of wetland (bog) ecosystems (proportion of 1 km x 1 km grids) in the Prince Rupert study area are also shown. Wetland coverage was compiled for several data sources: Vegetation Resource Inventory (VRI) 2013; BC Freshwater Atlas 2008; Baseline Thematic Mapping (BTM) 1992; BC Terrestrial Ecosystem Information System (TEIS); Global Land Cover 2000 (GLC-2000; bioval.jrc.ec.europa.eu).

Base cation weathering rate (sum of calcium, magnesium, potassium and sodium weathering) is an important factor for critical load, as it represents long-term buffering capacity against acidic deposition. Base cation weathering rate was estimated to range from 19.4 meq/m²/yr to 393.1 meq/m²/yr (average: 76.2 meq/m²/yr) in the top 50 cm of soil (CV⁴⁵ = 36%). Average regional base cation weathering was higher than was found for the KAA (Table 5-7) (ESSA et al. 2014; see also Appendix 3, Volume 2 of this report). In general, however, weathering rates were similar to those in other acid sensitive regions in Canada: 3-13 meq/m²/yr Nova Scotia (Whitfield

⁴⁵ Coefficient of Variation (CV) is estimated as the standard deviation divided by the mean multiplied by 100 (%).

et al. 2006); 58-446 meq/m²/yr Quebec (Houle et al. 2012); 21-79 meq/m²/yr Ontario (Koseva et al. 2010); and 19-351 meq/m²/yr British Columbia (Mongeon et al. 2010). The highest base cation weathering rates were predicted to be north of Prince Rupert (Figure 5-5). The lowest weathering rates were northwest of Prince Rupert, extending north from Digby Island, and almost completely enveloped by the 7.5 kg SO₄²⁻/ha/yr deposition isopleth under Scenario F_R. An area of 35.5 km² was predicted to receive acidic (S) deposition greater than the predicted weathering rate (approximately 14% of the SO₄²⁻ deposition isopleth; Figure 5-5), indicating sensitive soils and potential impacts from acidic deposition.

Table 5-7: Average regional characteristics and critical loads under the Prince Rupert Airshed Study compared with the Kitimat Airshed Assessment (ESSA et al. 2014).

Parameter	Prince Rupert Airshed Study	Kitimat Airshed Assessment
Study domain	10,969 km ²	6,777 km ²
Terrestrial area	6,274 km ²	5,378 km ²
Temperature	5.8°C	4.6°C
Soil percolation or runoff(Q)	2851 mm	2046 mm
Base cation weathering (BC _w)	76.2 meq/m ² /yr	56.6 meq/m ² /yr
Base cation deposition (BC* _{dep})	2.1 meq/m ² /yr	5.7 meq/m ² /yr
Base cation harvest removal (BC _u)	26.9 meq/m ² /yr	7.0 meq/m ² /yr
Maximum critical load of sulphur (CL _{max} (S))	193.6 meq/m ² /yr	181.1 meq/m ² /yr
Minimum critical load of nitrogen (CL _{min} (N))	12.3 meq/m ² /yr	10.7 meq/m ² /yr
Maximum critical load of nitrogen (CL _{max} (N))	322.3 meq/m ² /yr	294.0 meq/m ² /yr
Critical load of nutrient nitrogen (CL _{nut} (N))	75.5 meq/m ² /yr	57.9 meq/m ² /yr



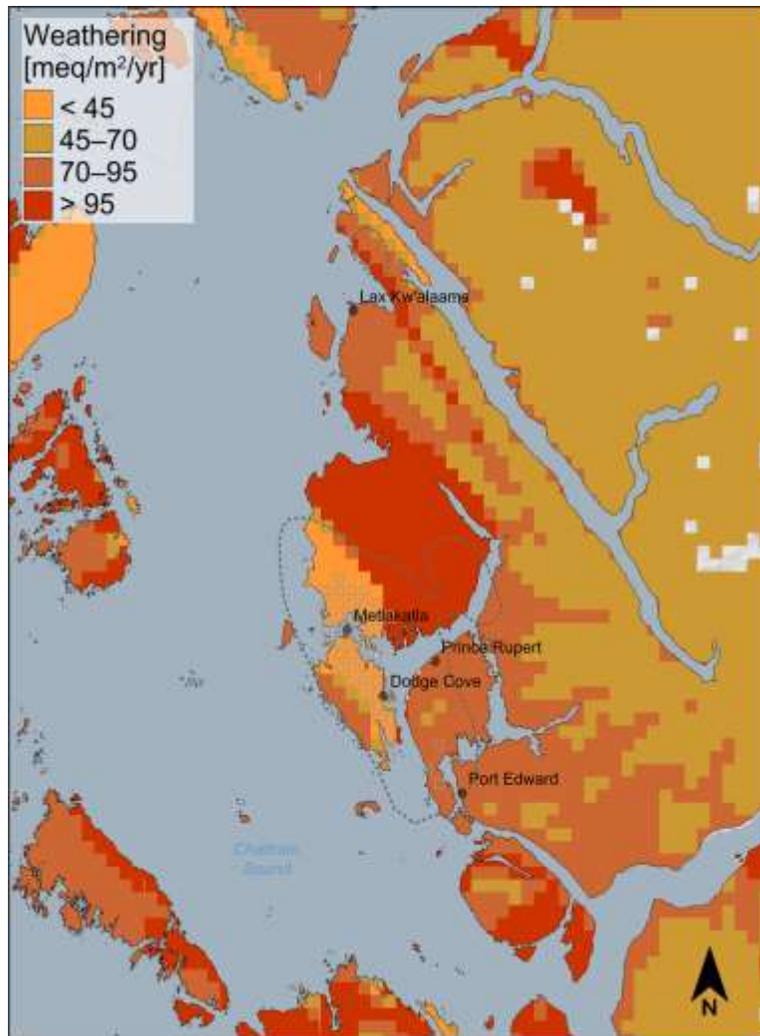


Figure 5-5: Mapped soil base cation weathering ($\text{meq/m}^2/\text{yr}$) based on the Skokloster classification (see Appendix 3, Volume 2 of this report). Regions receiving modelled anthropogenic sulphur deposition greater than $7.5 \text{ kg SO}_4^{2-}/\text{ha}/\text{yr}$ ($15.6 \text{ meq/m}^2/\text{yr}$) under emissions Scenario F_R are denoted by the dotted isopleth. Receptor ecosystems ($1 \text{ km} \times 1 \text{ km}$ grid cells) outlined in grey, indicate grids where atmospheric acidic input (sulphur) is greater than the weathering rate ($n = 54$ grids; receptor area = 35.5 km^2).

Modelled long-term runoff in the study area (Q ; Figure 5-2 and Table 5-3) derived from the Distributed Climate Water Balance Model (Moore et al. 2012) ranged from 1,500 mm to $> 5,000$ mm, with an average of 2,850 mm ($\text{CV} = 36\%$). Runoff in the Prince Rupert Study area was higher and less variable than what was found for the KAA (Table 5-7). The high values reflect the high precipitation in the study area. Runoff was used to estimate the critical ANC leaching and acceptable N leaching, which incorporate the chemical criteria or indicators of damage (see Table 5-3 and Table 5-5). As such, previous studies have noted that high runoff will lead to high critical loads suggesting regional insensitivity to the chosen chemical indicator of damage (Reinds et al. 2008).

Regional base cation harvest removal was notably higher (>3.5 times⁴⁶) in the current study compared with the KAA (Table 5-7). Removal of base cations in harvested biomass makes soils more sensitive to acidic deposition, because it reduces base cations available to exchange with incoming hydrogen ions, an important mechanism of neutralizing acidity. Assuming that all of the Annual Allowable Cut will be harvested is a conservative assumption, since it leads to greater removal of base cations and therefore greater soil sensitivity to acidification (harvest assumptions are explained further in Section 6.1.1.3). In contrast to base cation harvest removal, non-marine base cation wet deposition was approximately 60% lower.

The spatial pattern of $CL_{max}(S)$ was not similar to base cation weathering (BC_w) other than an area of low $CL_{max}(S)$ extending north from Digby Island (compare Figure 5-5 and Figure 5-6). Average $CL_{max}(S)$ was significantly greater in magnitude across the region ($\times \sim 2.5$) than BC_w owing to the dominance of the $ANC_{le(crit)}$ term, which was 1.7 times the average weathering rate (see Table 5-2: Equations 5-1 and 5-2). In regions with high runoff, a critical chemical criterion based on a Bc:Al ratio = 1.0 incorporated into the leaching term will result in high critical loads (compared with weathering rates); all chemical criteria incorporated into leaching terms will show the same pattern (Table 5-2 and Table 5-5). Despite differences in average regional critical load model inputs, the estimated critical loads of acidity were similar to the KAA, e.g., $CL_{max}(S)$ was 193.6 meq/m²/yr and 181.1 meq/m²/yr, respectively (Table 5-7). Overall, much of the study region including peatlands is considered to have moderate to high critical loads of acidity, and consequently have moderate to low sensitivity to acidic deposition.

⁴⁶ This suggests higher forest growth rates in the current study area compared with Kitimat. However, the difference may be driven by the limited data for TSAs, TFLs, and community forests.



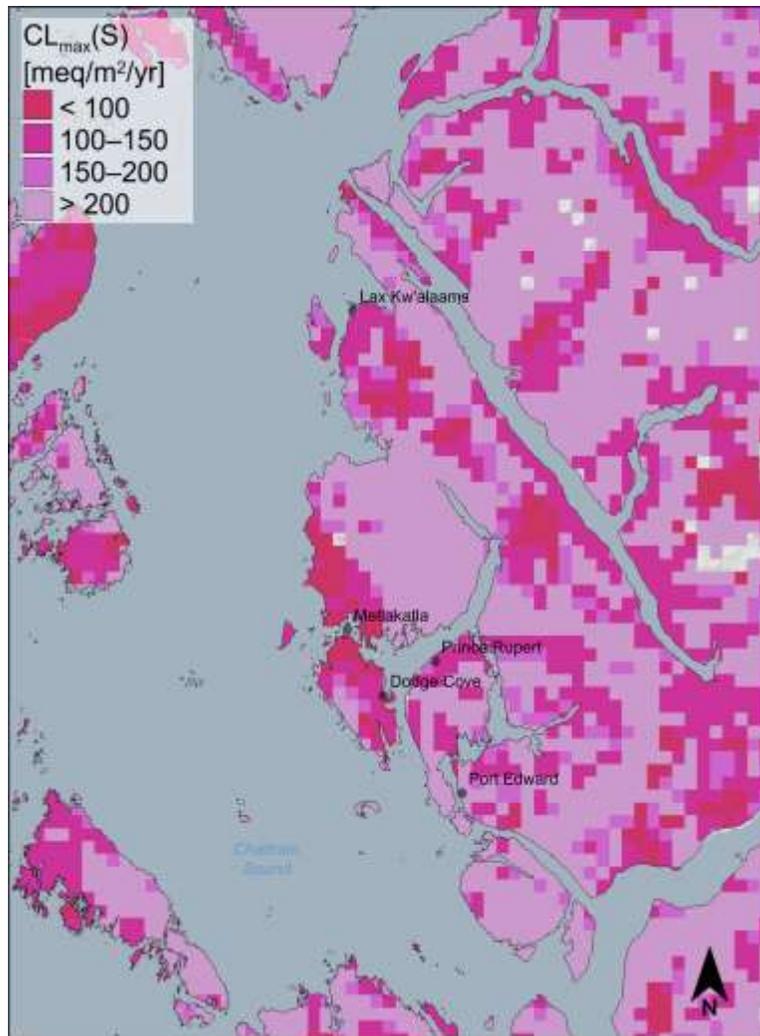


Figure 5-6: Maximum critical load of sulphur ($CL_{max}(S)$) for forest, shrubland and wetland ecosystems (see Figure 5-1) in the Prince Rupert study area based on the Steady State Mass Balance (SSMB) model (see Table 5-2). The mapped values for $CL_{max}(S)$ refer to the area-weighted average critical load for all receptor ecosystems in each 1 km × 1 km grid.

Critical loads for nutrient N were low, with $CL_{nut}(N)$ estimated to be <100 meq/m²/yr across 91% of the mapped receptor (forest and shrub) ecosystems. Some of the lowest values, $CL_{nut}(N) < 50$ meq/m²/yr, were predicted on Digby Island (Figure 5-7). Empirical N, $CL_{emp}(N)$, was set to one value for all natural ecosystems across the study area (Table 5-4), which was 35.7 meq/m²/yr (5 kg N/ha/yr). In comparison, the average $CL_{nut}(N)$ was approximately double at 75.5 meq/m²/yr (10.6 kg N/ha/yr). Mapped habitats were assigned the lowest $CL_{emp}(N)$ values from the range reported for each ecosystem type in the study area; the mid-point of the range would result in greater correspondence with estimated $CL_{nut}(N)$ and may be more appropriate for the region. However, the lowest value was selected as a conservative approach to mapping $CL_{emp}(N)$ in this study, in the absence of research on N impacts in the region.

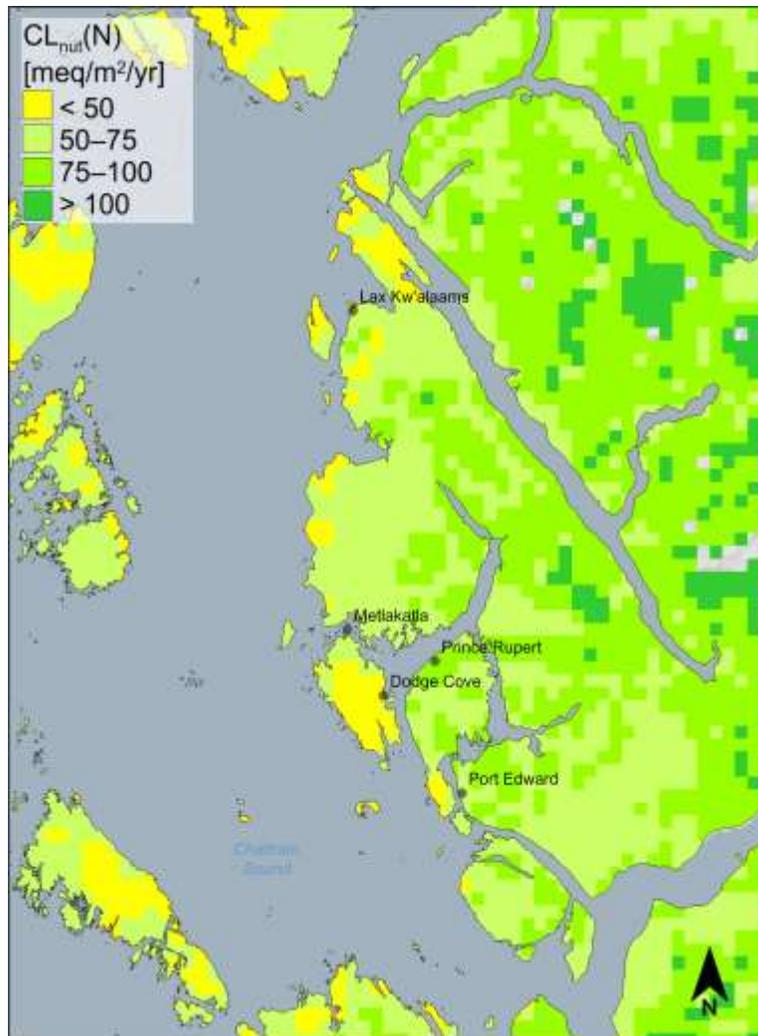


Figure 5-7: Critical load of nutrient nitrogen ($CL_{nut}(N)$) for forest and shrubland ecosystems (see Figure 5-1) in the Prince Rupert study area based on the Nutrient Mass Balance (NMB) model (see Table 5-2). The mapped values for $CL_{nut}(N)$ refer to the area-weighted average critical load for receptor ecosystems in each 1 km x 1 km grid.

5.2.2 Exceedance of Critical Loads for Scenarios A through F_R

Exceedance of critical loads of acidity and nutrient N was estimated under a range of S and N oxide emissions scenarios (A to E and F_R: see Section 2). Under these emissions scenarios, maximum S deposition ranged from 78.8-100.7 meq/m²/yr (Scenarios B, C and F_R) and maximum N deposition ranged from 108.8-134.7 meq/m²/yr (Scenario B to F_R).

Critical Loads of Acidity (Sulphur and Nitrogen): The area of the receptor ecosystems (forest, shrub and wetland) exceeded under the six emissions scenarios was low, ranging from 4.04 km² (Scenario B) to 10.27 km² (Scenarios C and F_R). Only Scenarios C and F_R had >10 km² predicted to be exceeded (Table 5-8). The greatest areal exceedance (Scenarios C and F_R) represented <2% of the mapped receptor ecosystem within the effects domain (586 km²).

Average predicted exceedance was also low, <25 meq/m²/yr under all emissions scenarios (the highest magnitude was estimated under Scenario F_R), indicating that a small area of receptor ecosystems will receive acidic deposition somewhat in excess of their critical load (Table 5-8; e.g., 6.3 km² with exceedance >20 meq/m²/yr under Scenario F_R). The exceeded area was located at the north end of Digby Island and Metlakatla⁴⁷ (Figure 5-9). Under all emissions scenarios, S exceedance was greater than N exceedance (Table 5-8). Nonetheless, all exceeded receptor grids (1 km × 1 km) require S or N reductions to achieve non-exceedance, e.g., under Scenario F_R, 18 grids require S or N reductions (see green region in Figure 5-3 and see ‘white grids’ in Figure 5-9).

Table 5-8: Exceedance of the Critical Load Function (CLF: see Figure 5-3) for acidification (defined by CL_{max}(S), CL_{min}(N) and CL_{max}(N)) of forest, shrubland and wetland ecosystems (see Figure 5-1).

Scenario	A	B	C	D	E	F_R
Risk category ^a						
Average exceedance (meq/m ² /yr)	23.78	13.70	21.79	16.11	16.83	24.44
Average exceedance S (meq/m ² /yr)	15.28	8.80	13.99	10.39	10.88	15.66
Average exceedance N (meq/m ² /yr)	8.50	4.90	7.80	5.72	5.95	8.78
Exceeded area (%) ^b	1.46	0.69	1.75	0.72	1.18	1.75
Exceeded area (km ²) ^c	8.57	4.04	10.27	4.21	6.88	10.27
Exceeded area >10 meq/m ² /yr (km ²)	7.26	1.85	7.26	2.27	4.21	7.26
Exceeded area >20 meq/m ² /yr (km ²)	4.58	0.63	5.35	0.68	1.85	6.34

^a Risk category based on exceedance area (%).

^b Exceeded area presented as a proportion (%) of the effects domain, which is defined as the receptor ecosystem area enclosed by a 15.0 meq/m²/yr modelled sulphur and nitrogen deposition isopleth under Scenario F_R (586 km²).

^c Exceeded area is also given as the area (km²) with > 10 and > 20 meq/m²/yr exceedance; this provides a qualitative assessment of uncertainty, i.e., areas with exceedance > 10 meq/m²/yr have a higher risk of negative impacts (as indicated by the critical limit).

Critical Loads of Nutrient Nitrogen: Under all scenarios, the exceeded area was much greater (>4 times) for empirical critical loads (CL_{emp}(N)) compared with the nutrient mass balance (CL_{nut}(N); Table 5-9). The CL_{nut}(N) exceeded area ranged from 4.97 km² to 23.54 km² compared to 19.57 km² to 93.82 km² for CL_{emp}(N) under Scenarios B to F_R (Table 5-9). Under Scenario F_R, exceedance of CL_{nut}(N) was primarily predicted along the south east of Digby Island and the west of Kaien Island (Figure 5-9). Notably, only two 1 km × 1 km grids exceeded both acidity and mass balance nutrient N. In contrast, large areas of Kaien and Digby Islands and further north were predicted to exceed CL_{emp}(N) under Scenario F_R (Figure 5-9, Table 5-9). The greatest proportional areal exceedance was 4.0% for CL_{nut}(N) and 16.1% for CL_{emp}(N) (Scenario F_R) of the mapped receptor ecosystem within the effects domain.

⁴⁷ Exceeded grid squares are predicted on the Metlakatla First Nations reserve lands; as such this may have relevance to tradition land use including plant harvesting (as opposed to direct impacts to human health).



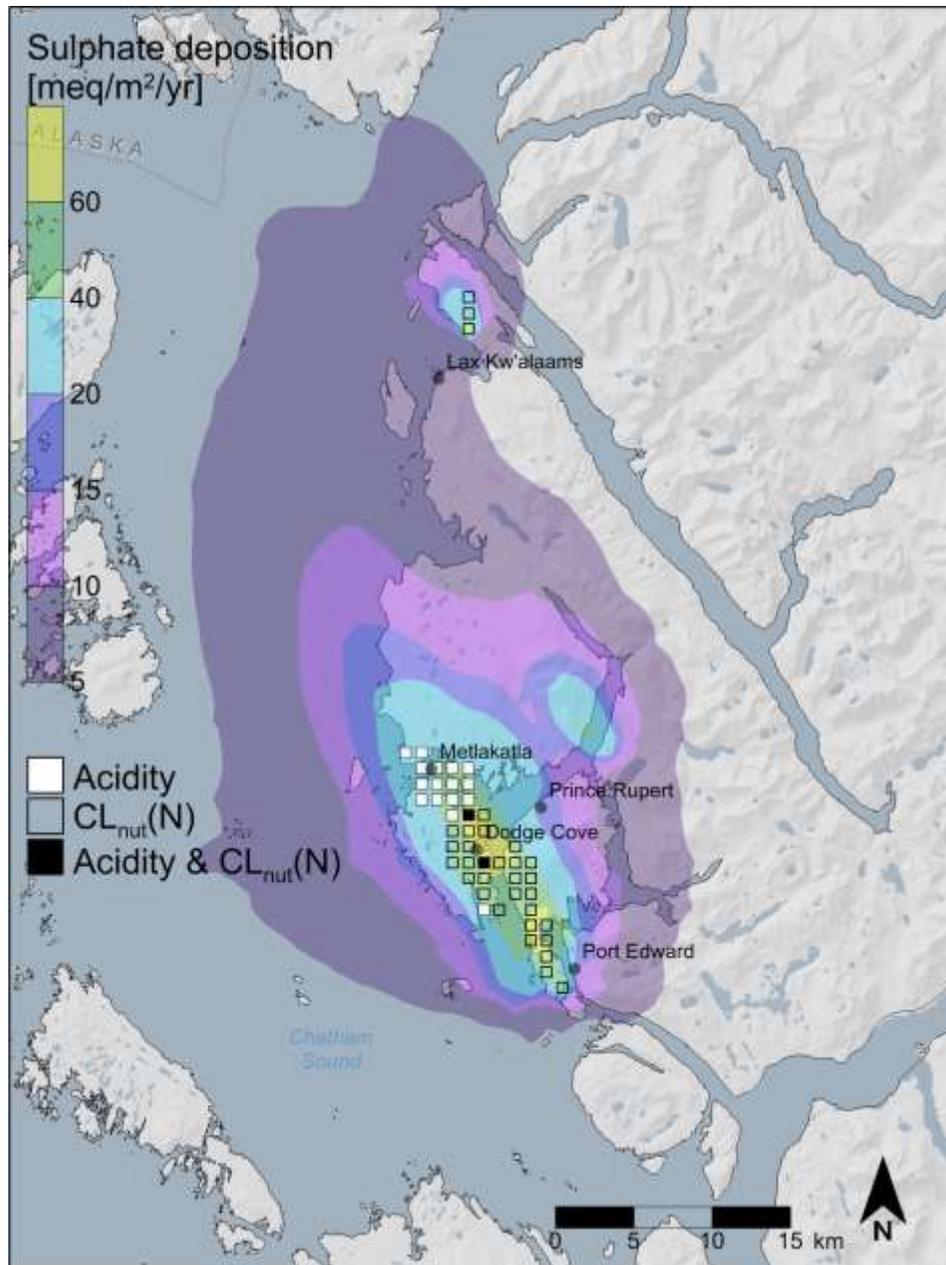


Figure 5-8: Location of receptor ecosystems with predicted exceedance of critical loads of acidity (white-filled 1 km × 1 km grid squares; n = 18) and nutrient nitrogen (black outlined 1 km × 1 km grid squares; n = 33) under emissions Scenario F_R. Black-filled squares indicate 1 km × 1 km grids with exceedance of acidity and nutrient nitrogen (n = 2). Modelled total sulphur deposition under Scenario F_R is also shown.

Table 5-9: Exceedance of critical load of nutrient nitrogen ($CL_{nut}(N)$) for forest ecosystems on mineral soil (see Figure 5-1) and empirical nutrient nitrogen ($CL_{emp}(N)$) for terrestrial habitats (see Table 5-4), respectively in the study area.

Scenario	A	B	C	D	E	F_R
Risk category ^a						
$CL_{nut}(N)$ exceedance (meq/m ² /yr)	9.73	7.36	10.92	10.73	10.40	19.03
$CL_{nut}(N)$ exceeded area (%) ^b	2.79	0.97	3.52	1.50	1.42	4.02
$CL_{nut}(N)$ exceeded area (km ²)	14.28	4.97	18.03	7.70	7.26	23.54
Risk category ^a						
$CL_{emp}(N)$ exceedance (meq/m ² /yr)	13.54	11.37	14.56	12.81	11.91	16.07
$CL_{emp}(N)$ exceeded area (%) ^b	9.18	3.22	10.36	4.79	7.70	15.44
$CL_{emp}(N)$ exceeded area (km ²)	55.79	19.57	62.95	29.10	46.80	93.82

^a Risk category based on $CL_{nut}(N)$ and $CL_{emp}(N)$ exceeded area (%).

^b Exceeded area presented as a proportion (%) of the effects domain, which is defined as the receptor ecosystem area enclosed by the 15.0 meq/m²/yr modelled sulphur and nitrogen deposition isopleth under Scenario F_R ($CL_{nut}(N)$: 513 km²; $CL_{emp}(N)$: 608 km²).

Overall Risk: Based on these exceedance values the impact of Scenarios B and D was considered to be Moderate to High, i.e., scenarios expected to have an impact, of a magnitude, or spatial extent considered to be unacceptable; whereas the impact of emissions Scenarios A, C, E and F_R were considered to be Moderate to Critical, i.e., scenarios expected to have an impact, of a magnitude, or spatial extent, that is considered potentially extremely unacceptable. The risk ranking is primarily based on nutrient N impacts. It is important to note that a critical risk rating indicates unacceptable areal exceedance (>5% of the effects domain) based on the chosen critical load (see Table 5-4). In this study, exceedance with respect to empirical nutrient N indicates an increased risk for change in epiphytic macro-lichen species composition. However, this does not preclude an increased risk for composition shifts in N-sensitive vascular plants (see Bobbink et al., 2010, and Pardo et al., 2011 for further details on the impacts of N deposition on plant species).



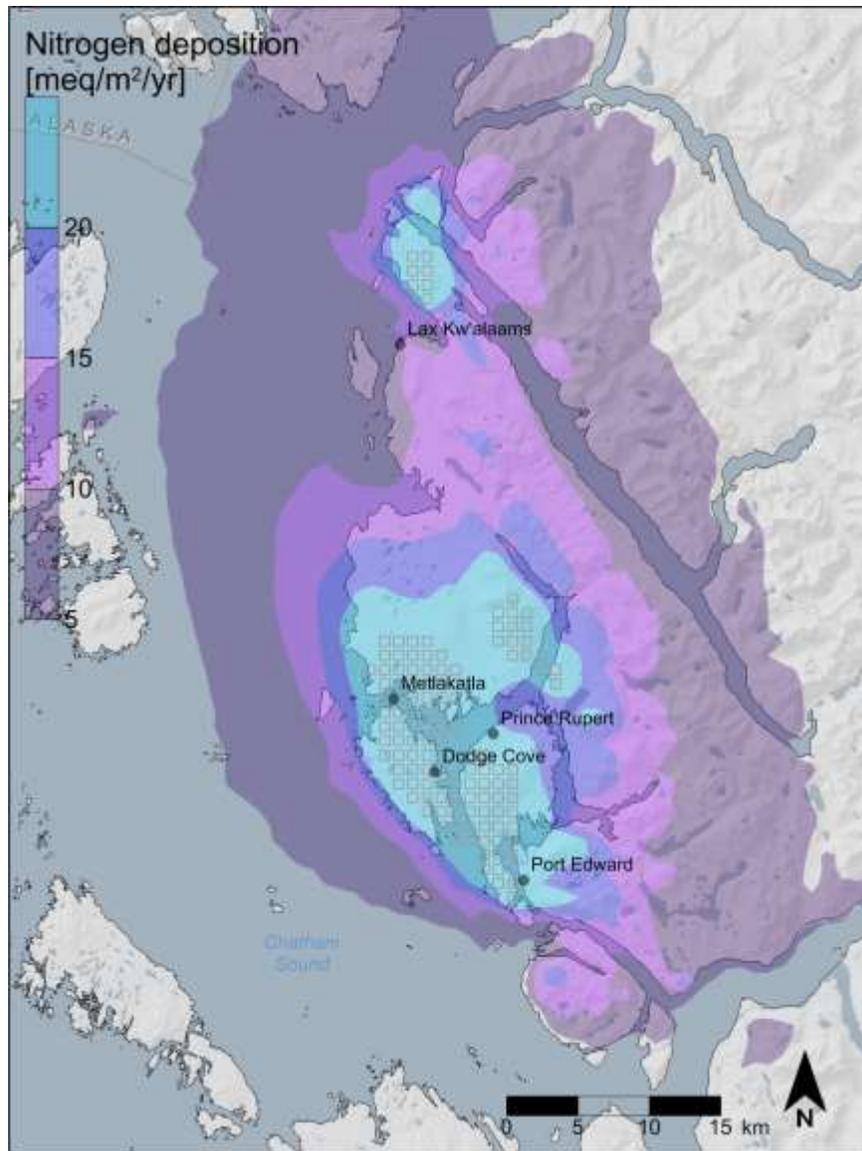


Figure 5-9: Location of receptor ecosystems with predicted exceedance of empirical critical loads of nitrogen (grey-outlined 1 km x 1 km grid squares; n = 126) under modelled total nitrogen deposition (Scenario F_R). Empirical critical loads for nutrient nitrogen were set at 35.7 meq/m²/yr (5 kg N/ha/yr; see Table 5-4) for all natural ecosystems.

5.3 Main Sources and Implications of Quantitative Scientific Uncertainty

The predicted level of exceedance is subject to uncertainty associated with model input parameters (Table 5-3), i.e., parametric uncertainty. In general, parametric uncertainty does not bias the predicted level of exceedance in either direction. The principle sources of uncertainty that could have a potentially large impact on predicted critical load or exceedance in this study were as follows:

1. **Atmospheric Deposition.** The areal extent of exceedance and the associated scenario risk rating were primarily driven by the predicted (modelled) N deposition. Similarly, predicted acidity exceedance required reductions in N deposition to achieve non-exceedance. As such, the correspondence between CALPUFF-modelled and observation-based air concentration and deposition should be evaluated; this applies to all receptor assessments (surface waters, vegetation and human health).
2. **Critical Chemical Criteria.** Empirical N critical loads were set to the low end of recommended ranges; if set to the mid-point of the range, exceedance would be greatly reduced. Further evaluation of regionally appropriate $CL_{emp}(N)$ values is required, especially given that $CL_{emp}(N)$ is primarily responsible for the high level of areal exceedance (and associated critical risk rating). Additionally, the suitability of a Bc:H ratio for organic soils should be further evaluated.
3. **Soil Weathering.** There are limited soil data (e.g., organic matter, texture, bulk density, mineralogy) for the region. As such, base cation weathering rate was based (ranked) on bedrock geology. It is semi-quantitative, at the resolution of the mapped geology bedrock units. Additional soil data would allow for evaluation of the semi-quantitative approach, or development of observation-based weathering rate maps for the region. Mineralogical data available at seven locations (with 18 sites) suggest higher weathering rates than estimated under the Skokloster classification (see Appendix 3, Volume 2 of this report).

5.4 Recommendations on Impact Assessment Guidance

It is recommend that impact assessments should include:

- Regional air concentration or deposition monitoring, to confirm the magnitude and spatial extend of the predicted (modelled) deposition, specifically atmospheric N owing to its dominant role in critical load exceedance. Monitoring may include passive approaches.
- Vegetation surveys to document plant species, including lichens and mosses. Further, it is recommended to potentially establish long-term vegetation monitoring plots depending on the (literature) sensitivity of plant species, including lichens, to N deposition.
- Soil sampling and geochemical analysis for regions receiving >7.5 kg $SO_4^{2-}/ha/yr$ modelled deposition, i.e., regions with deposition potentially in excess of their critical load of acidity. While some data already exist (see Appendix 3, Volume 2 of this report), only three locations in the study (under the 7.5 kg $SO_4^{2-}/ha/yr$ isopleth) have soil mineralogical data.



6 Aquatic Ecosystems

6.1 Methods

The following sections describe the methods and data used for the assessment of potential acidification and eutrophication in the lakes of the PRAS area. The overall approach was based on recent similar work conducted for Kitimat Airshed Emissions Effects Assessment (KAA) (ESSA et al. 2014a) and the KMP SO₂ Technical Assessment (STAR) (ESSA et al. 2013). The methods were consistent with the recent guidance on studies of aquatic acidification and eutrophication published by the BC Ministry of Environment on June 25, 2015 (BC MOE, 2015). We assessed the potential for acidification for each lake based on their critical loads of acidity, as calculated using two steady state models: (1) the Steady State Water Chemistry (SSWC) model (Henriksen et al. 2002); and (2) the First-order Acidity Balance (FAB) model (Henriksen and Posch 2001; Aherne et al. 2004; UNECE 2004; Posch et al. 2012). A critical load (CL) is defined as “a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge” (Nilsson and Grennfelt 1988, cited in Henriksen et al. 2002). The calculated critical loads were compared to S and N deposition estimates in order to assess the capacity of the aquatic ecosystems in the study area to withstand (buffer) the effects of acid deposition. We estimated the potential for exceedance of these critical loads (i.e., deposition values greater than CL values) for each lake under each emission and deposition scenario.

Additionally, we calculated the expected change in pH of the sampled lakes using a modification of the ESSA-DFO model (Marmorek et al. 1990; ESSA et al. 2013, pg. 247-249). The use of the modified ESSA-DFO model is an important supplement to the SSWC and FAB models, since it provides an estimate of pH changes for all lakes, not merely the risk of having a lake fall below pH 6.0. A change in lake pH from 6.5 to 6.0 could also be biologically significant. Studies of acidification impacts on biota in Sweden (Fölster et al. 2007) provided a protective standard for the protection of surface waters, namely that lakes should be maintained within 0.4 pH units of their original, pre-industrial pH₀.

Finally, we assessed the risk of eutrophication for the lakes in the study area using empirical critical loads for nutrient-N and comparing them with expected N deposition levels. The eutrophication assessment was conducted at two spatial scales: (1) for the 35 sampled lakes; and (2) for all of the lakes in the PRAS area with a surface greater than 1 ha (i.e., 859 lakes in total, including both the Canadian and Alaskan portions of the study area).

Results of exceedances of critical loads and expected changes in pH were combined in an integrative risk assessment for the freshwater ecosystems in the PRAS area (described in Section 6.1.3). The PRAS risk assessment framework was based on the approach developed by MOE for the KAA. Since there are fewer than half as many sampled and analyzed lakes in the PRAS compared to the KAA (35 versus 80), the risk categories in the PRAS are coarser, and represent slightly different percentages of the sampled and analyzed lakes in each risk category.



6.1.1 Environmental Data

6.1.1.1 Water Quality Data

The study team used two data sets for the aquatic ecosystem assessment:

4. **Data set 1 (DS1)** is comprised of 30 lakes sampled by Environment Canada (EC) in September 2014 following standard methods for sample collection and handling (P. Shaw, pers. comm., 27 February 2015). The samples were analyzed at the Pacific Environmental Science Centre (EC's regional analytical laboratory in North Vancouver) following data quality procedures similar to those described in Strang et al. (2010).
5. **Data set 2 (DS2)** includes seven lakes sampled in August 2014 by AECOM for the Prince Rupert LNG (PRLNG) project. One lake (Alwyn Lake) was also sampled as part of DS1, and was therefore not included in the combined data set. These samples were analyzed at Maxxam Analytics laboratory in Burnaby BC.

Thus the complete sample (DS1 and DS2) was 36 lakes. As discussed in Section 6.2.1, one of these lakes (Lake AD-SW7 from DS2) was excluded from the analysis based on data quality considerations, so that 35 lakes were analyzed in this study.

The location of these lakes is shown in Figure 6-1. Note that there are gaps in coverage in the northern and the interior part of the PRAS study area, and also on various islands. There are 787 lakes with an area greater than 1 ha within the Canadian portion of the PRAS study area, and 72 such lakes within the Alaska portion of the study area, for a total of 859 lakes greater than 1 ha in the study area.

The sampled lakes tended to be larger (median lake area of 12.45 ha) than the overall population of 859 lakes >1 ha in the study area (median lake area of 2.65 ha). As shown in Figure 6-2, the frequency distribution of sampled lake areas is greater (shifted to the right) than the frequency distribution for the overall population of lakes. The sampled lakes are biased towards larger lakes, and are likely to have less variability in Acid Neutralizing Capacity than the overall population of lakes (i.e., the sample will not capture either the most acid-sensitive or the least acid-sensitive lakes), as was found by Sullivan et al. (1990) when they compared a sample of Adirondack lakes >4 ha with a sample of lakes >1 ha.



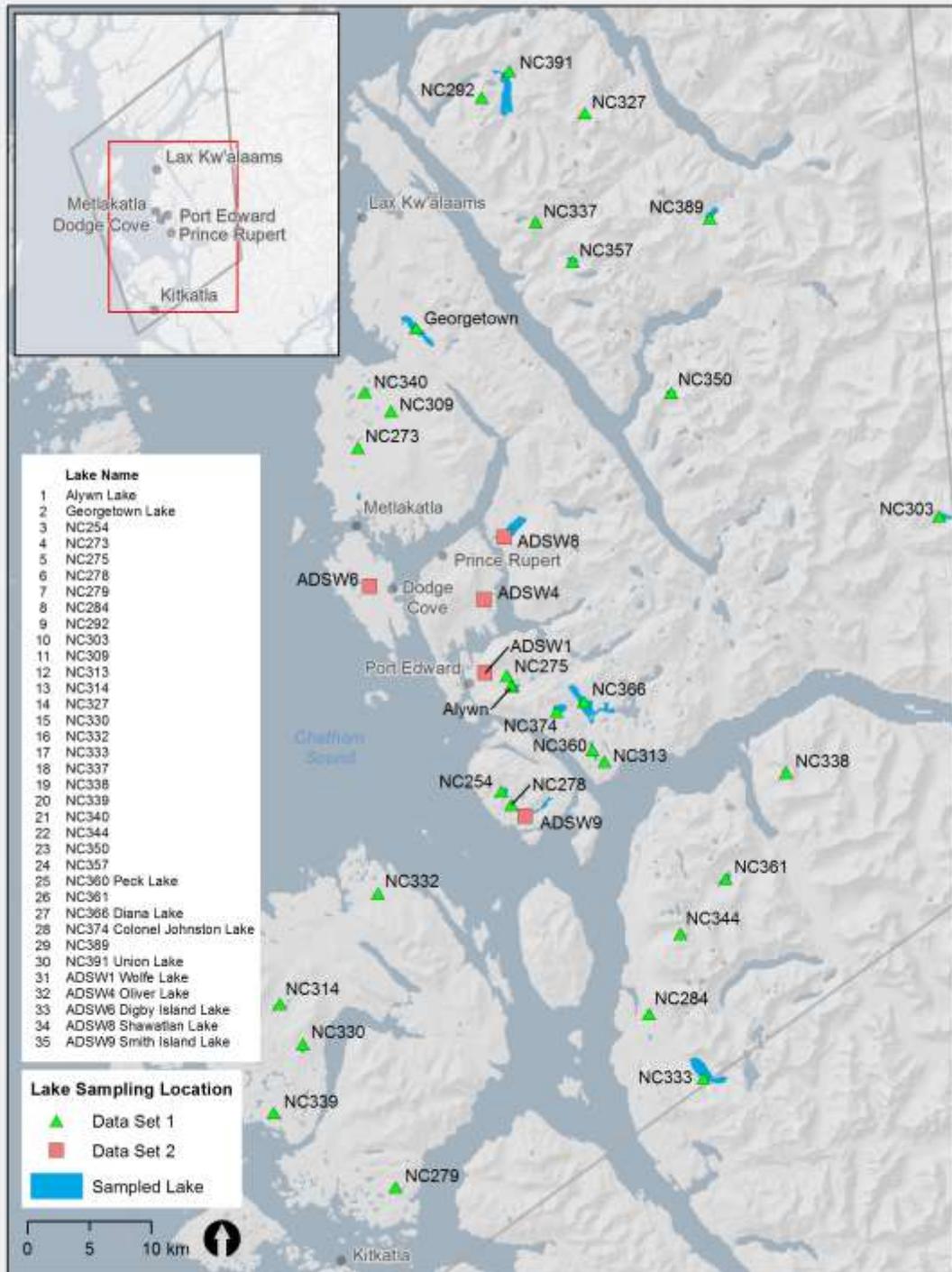


Figure 6-1: Map of the study area showing the 36 lake samples used in the analysis. Lakes sampled by Environment Canada (DS1) are labelled with “NC” and lakes sampled by Prince Rupert LNG are coded by “AD” (DS2).



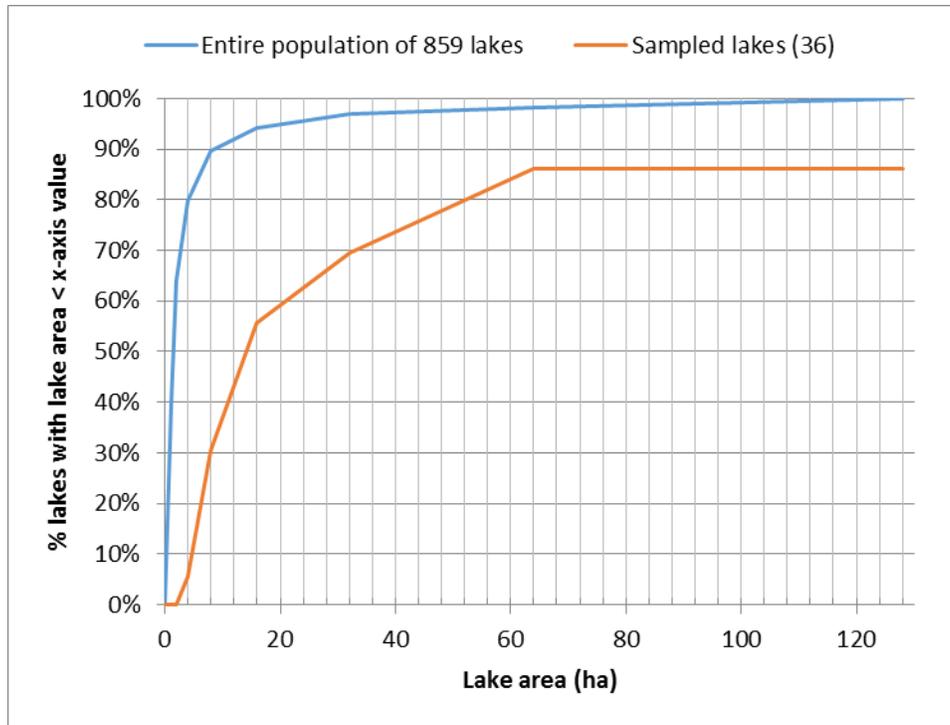


Figure 6-2: Cumulative frequency distributions of lake areas for: a) all 859 lakes in the PRAS study area that are greater than 1 ha in size; and b) the 36 sampled lakes. Five of the sampled lakes (Shawatlan, Diana, Georgetown, NC391, NC333) are larger than 130 ha, and therefore do not show up on this graph.

Sampling criteria for DS1 followed those applied previously by Environment Canada in lake selection for coastal BC and described in Strang et al. (2010). These include the following: (i) poorly weatherable bedrock geology; (ii) lake surface areas greater than 4 ha; and (iii) random selection of lakes within lake area classes, with minor adjustment to ensure good spatial coverage. The area of interest for lake selection for sampling in 2014 spanned the region from Douglas Channel to Kitsault. As described in Strang et al. (2010), catchment lithology (bedrock geology) was determined from the digital geology map of BC (1:250,000 BC Ministry of Energy, Mines and Petroleum Resources). Dominant rock types were grouped into five weathering categories from very low weathering (1) such as granite and diorite, to very high weathering (5) such as limestone and other (P. Shaw, pers. comm., 27 February 2015). Selections were restricted to lakes underlain by bedrock of weathering classes 1 or 2. From this target population, lakes with an area greater than 4 ha were randomly selected from five lake area classes: 4 – 10 ha; 10 – 50 ha; 50 – 100 ha; 100 – 500 ha; and >500 ha.

Surface waters in DS2 included lakes or streams representative of the regional study area and/or used by people (Patrick Williston, pers. comm., 26 February, 2015). The lakes in DS2 include one on Digby Island, one on Smith Island, one at Metlakatla, the backup drinking water source for Port Edward (Shawatlan Lake), a lake that supplies drinking water for Prince Rupert, Wolfe Lake/Creek (in an area of high deposition), and Kaien Island Creek.



Given the mix of criteria used to choose these 36 lakes, the gaps in coverage, and the bias towards larger lakes, the combined data set cannot be considered to be a statistically representative sample of all lakes within the Prince Rupert Airshed Study area. While it is straightforward in this study to compute the percent of sampled lakes and percent of sampled lake area with characteristics of interest (e.g., CL exceedance), there is much more uncertainty in estimating these metrics for the entire population of lakes in the study area. Further lake sampling is required to fill data gaps within the PRAS effects domain area receiving the greatest amount of acidic deposition (as shown in Figure 5-4). In the STAR (ESSA et al. 2013), the sampled population of lakes included all lakes larger than 1 ha in the portion of the STAR study area receiving more than 10 kg/ha/yr of total deposition, as well as all lakes larger than 1 ha within the two most sensitive Acid Sensitivity Classes (even if outside the higher deposition zone).

6.1.1.2 Water Quality Data Preparation and Quality Analysis

Data sets DS1 and DS2 included measurements for the following parameters:

- **Standard water quality parameters:** dissolved oxygen, conductivity (only for DS1), total dissolved solids, temperature, turbidity.
- **Major anions:** chloride, fluoride, nitrate, bicarbonate, carbonate, sulphate.
- **Major cations:** calcium, magnesium, sodium, potassium, ammonium, hydrogen (pH).
- **Metals** (only for DS2): aluminum, manganese, iron (potentially contributing to charge balance).
- **Fixed end point alkalinity** (or Total Alkalinity): as determined by titration to a fixed end point of pH 4.5.
- **Dissolved organic carbon:** used to estimate the concentration of organic anions, an indicator of influence from wetlands and vegetation on water quality.

As was done for the KAA and STAR studies, the data were organized and analyzed using a spreadsheet format, linking worksheets and formulas for QA/QC, and for application of the SSWC, FAB and modified ESSA-DFO models. We applied the following principles in preparing the water chemistry data for subsequent analyses:

- Field duplicates were not used (their purpose is for the analytical labs to ensure proper QA/QC but not to provide additional precision for those sites).
- Lab pH measurements were used instead of field pH, as they better reflect true ecological exposure integrated across fluctuations throughout each day (based on variation of dissolved CO₂), whereas field pH captures a particular moment within that fluctuation. Lab pH measurements provide much more reliable estimates of the functional relationship between pH and ANC (see Figure 6–1 in Landers et al. 1987), which is an important component in determining the critical ANC, a key assumption of the critical load assessment.
- For each ion, the concentration of dissolved ions was used rather than the concentration of total ions, which may include particulate forms.
- For ions below the analytical detection limit (DL), the concentration was assumed to be 0.5*DL, though this assumption made little difference to any of the calculations as these concentrations were so low.



- Lab measurements of cations and anions were converted from units of mg/L to units of µeq/L based on the atomic or molecular weight of each constituent, and its charge (e.g., 1 mg/L of [SO₄⁻²] is equivalent to 20.82 µeq/L).
- The concentration of organic anions was determined using the method of Oliver et al. (1983) assuming an average charge density of 7.5 µeq/mg of dissolved organic carbon (DOC) for the lakes of DS2, based on previous work (STAR and KAA; J. Aherne, Trent University, pers. comm., October 2012), and of 5.5 for the lakes of DS1, as this assumption yielded the best charge balance (explained further in Section 6.2.1.2).

In addition to the above considerations, we assessed the quality of the data (Section 6.2.1) using two methods:

- We assessed the charge balance for all of the sampled lakes in DS1 and DS2 (see ESSA et al. 2013, Section 8.6.3.2 for details of rationale and procedure).
- For DS1 only, we compared the measured conductivity for each sample to a calculated estimate of conductivity based on the ion concentrations (see ESSA et al. 2013, Section 8.6.3.2 for details of rationale and procedure). We could not apply this comparison to DS2 because conductivity was not measured in these lakes.

The **Gran Acid Neutralizing Capacity (Gran ANC)** is the capacity of a solution to neutralize strong acids and is usually determined by titration to the inflection point of the pH-alkalinity titration curve. This parameter was not available for either DS1 or DS2. Both data sets did however have estimates of **Total Alkalinity** (fixed end point titration to pH 4.5). For development of a titration curve (used both to determine a Critical Gran ANC for use in the SSWC model, and to apply the modified ESSA-DFO model), we converted Total Alkalinity into estimates of Gran ANC based on the following regression, developed in the Kitimat Airshed Assessment (ESSA et al. 2013, pg. 276, R²=0.999):

$$Gran\ ANC = \frac{Total\ Alkalinity - 11.59}{1.01}$$

Eqn (6.1)

While we did explore using other methods for estimating Gran ANC based on Charge Balance Alkalinity (i.e., Hemond 1990; Lyderson et al. 2004) we found that these approaches resulted in much greater variability around a titration curve of pH versus ANC due to imperfect charge balance in many of the samples. We found that it was more scientifically defensible to use a single independent variable to estimate Gran ANC (i.e., Total Alkalinity via the above regression equation) than to use the combination of major cations, major anions, and DOC as predictors of Gran ANC.

6.1.1.3 Data Inputs for Critical Load Modelling

Other data are required by the SSWC and FAB models. The following sections briefly describe these additional data sources.



Watershed areas: We defined watershed area using the approach applied in the KAA. Upstream watersheds for each sampled lake were defined primarily using the 1:20K [Freshwater Atlas Fundamental Watersheds](#). However, because the Freshwater Atlas watersheds do not use lake outflows as natural pour points to define the watershed boundaries, watershed polygons often encompass lakes and result in an area of watershed downstream of the lake. We therefore used flow direction calculated from the Canadian Digital Elevation Data 1:50K digital elevation model (DEM) to identify areas downstream of the lake, and removed them from the Freshwater Atlas watershed polygons. We used the 1:20K Freshwater Atlas stream network to enforce drainage within the DEM, and ESRI's hydrology toolset within ArcMap to define the upstream/downstream areas around the lake outflow. This approach, used in the KAA, is an improvement over the earlier methodology applied in the STAR, increasing the accuracy of the area calculations. Watershed area is an important attribute because it is needed to calculate area-weighted averages of deposition estimates and runoff estimates for the upstream watershed area of each lake.

Average runoff: Average annual runoff values for the period 1960-1990 were estimated by Joel Trubilowicz (Ph.D. candidate at UBC) for the entire study area on a 0.4 km x 0.4 km grid. These estimates were calculated via application of the Distributed Climate Water Balance Model described in Moore et al. (2012). We then used them to calculate area-weighted estimates of runoff within the upstream watershed area or catchment of each lake. Runoff modelling is described in Section 5.2.1. Figure 6-3 shows the estimates of runoff for the whole PRAS area, together with the locations of sampled lakes.

Land cover: The FAB model requires estimates of the areas of grass/heath-land, forested land, peat land (considered equivalent to wetlands) and bare rock within each lake catchment. The fraction of peat land/wetland can be used to estimate the rate of de-nitrification (Posch et al. 1997, as explained in Henriksen and Posch (2001) and UNECE (2004)). Land use and land cover classifications were produced using a combination of provincial and national data sets available from GeoBC and GeoBase, as described in Appendix 4.2 in Volume 2 of this report. Land cover was estimated using two methods: Method A based on the Vegetation Resource Inventory (VRI) and data from the Freshwater Atlas; and Method B including information from Baseline Thematic Mapping. Method A was used for the standard analyses throughout this report, while Method B serves as part of a sensitivity analysis to explore the effects of uncertainty in the data.



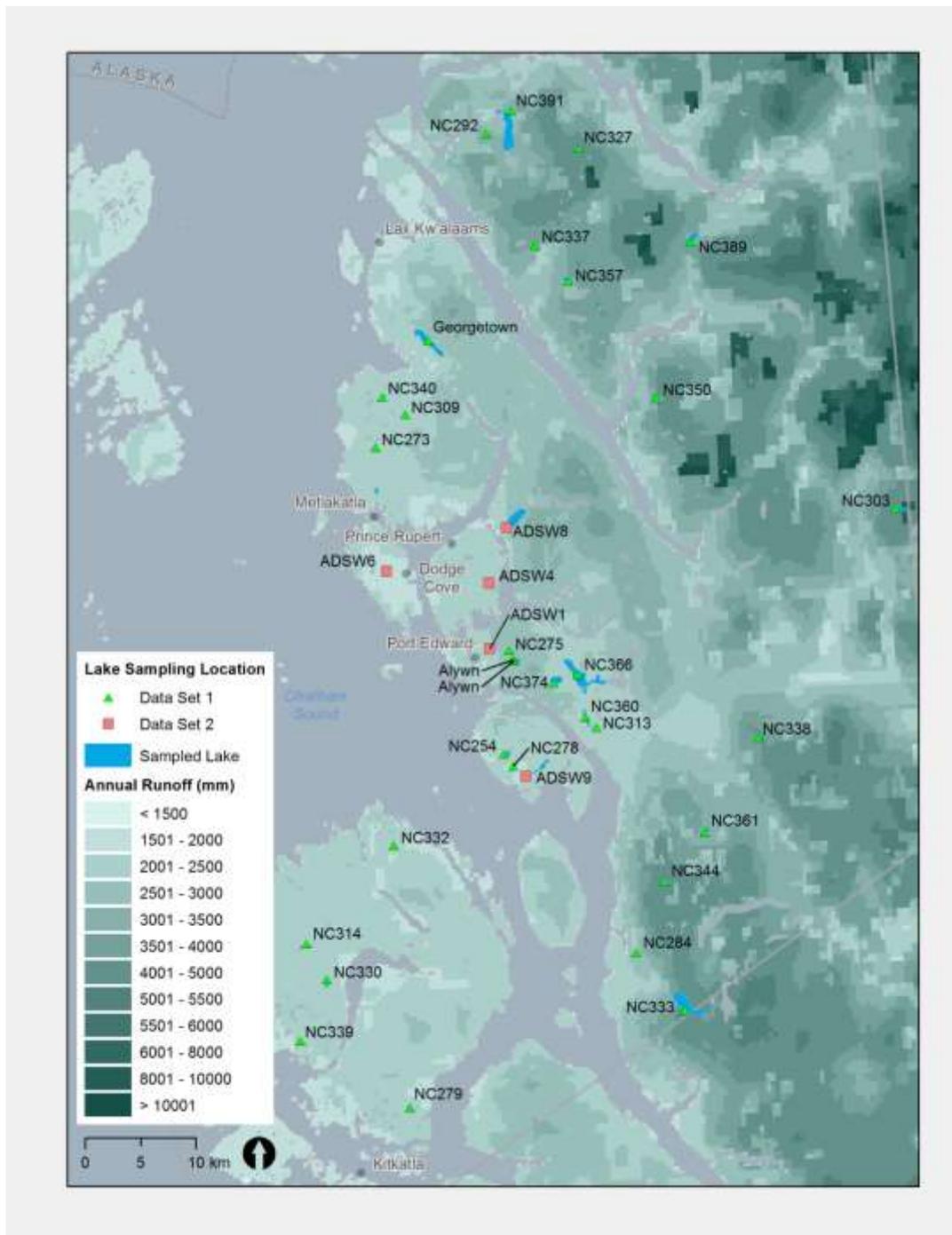


Figure 6-3: Estimated average annual runoff (mm) across the study area, for the period from 1960 to 1990. Source: J. Trubilowicz, UBC, based on applying the model developed by Moore et al. (2012).

Removal of Base Cations and Nitrogen by Forest Harvesting: Long-term, steady state removals were estimated using a two-step process, and the same general approach as described in the STAR (ESSA et al. 2013, pg. 208-209):



1. We estimated the long-term, steady state rate of biomass removal due to harvest. The PRAS study area is almost completely within a single Timber Supply Area (North Coast TSA), with a minor amount of area in the Nass and Kalum TSA and in TFL 1. Data were gathered from the publicly available layers of base data (e.g., acquired through GeoBC) and estimates of harvest rates (e.g., from the Timber Supply Reviews (TSR) for each TSA). As for the KAA, we allocated predicted harvest within the TSAs and TFL to the study area based on its proportional overlap with the TSAs' and TFL's spatial extent. Harvest estimates were not available either by species or in a spatially explicit manner. We therefore approximated the spatial distribution of harvesting within each polygon by removing areas in which forestry operations would not occur (non-THLB, alpine and other non-forested regions, parks, reserves, agricultural and developed areas, as determined by land-use data from GeoBC). When this still resulted in a total harvested area that was too large (i.e., exceeded the predicted extent of harvesting based on estimates of rates in the TSAs), we limited allocations to areas with recent cutblocks or with dense coniferous forest. After this overall net-down of forest, we had no harvestable area in the Nass TSA; 86% of the harvestable area was in the North Coast TSA. As we did for the STAR and KAA, we made the precautionary assumption of the maximum rate of removal of base cations from forest harvesting, based on the annual allowable cut (AAC). Also, like the STAR and KAA, we assumed that the main harvested species was hemlock and used the same conversion factors for converting volume to biomass.
2. We converted the estimates of exported biomass (i.e., removals) to estimates of exported base cations and nitrogen by applying estimates of nutrient concentration (i.e., per unit of biomass). We used the same nutrient concentration estimates as for the STAR and KAA to maximize efficiency and enable comparability among assessments. After extensive searching and outreach to experts during the STAR and KAA, we are confident that these data represent the best available information on nutrient concentration that is applicable to BC coastal conifer forests.

Deposition of S, N, S+N: As for the KAA, Trinity Consultants provided deposition outputs from CALPUFF including S, N, and S+N, at points spread 1 km apart across the large study area, consistent with the spatial resolution used in the KAA, with additional points at the centre of each sampled lake (see Section 2 of this report). Area averaged deposition values were used for the acidification risk analysis and values of N deposition at the lake centroids were used for the eutrophication risk analysis. We converted N and SO₄ deposition estimates from kg/ha (provided by CALPUFF) to meq/m² (as required for calculations in SSWC and FAB models).

6.1.2 Analysis of Lakes Acidification: Critical Loads, Exceedance Maps and Risk Classification

Our analysis of aquatic ecosystems for the PRAS followed the approach used for the KAA and STAR, applying the SSWC and the FAB models to calculate critical loads of acidity and their respective exceedances for each deposition scenario. Figure 6-4 shows the flow of information and the inter-connections of the analysis performed throughout these two models. The overall process included the following steps:

1. We examined the statistical and spatial distributions of total alkalinity, Gran ANC, charge balance, and pH to determine the sensitivity of the sampled lakes to acidification (see



Section 6.2.2 of the KAA, ESSA et al. 2014a). We also compared the spatial pattern of pH values in the sampled lakes with stream pH values from [Geoscience BC](#).

2. We evaluated the dominant anions (>50% of total anions) and influential anions (>25% of total anions) to determine the likely causes of current pH values less than 6.0, as described in Sections 8.6.3.3 and 9.4.1.2.3 of Volume 2 of the STAR (ESSA et al. 2013), and Section 6.2.2 and Appendix 20 in the KAA report (ESSA et al. 2014a).
3. We applied the SSWC model to all lakes included in the analysis because it is required as an input to the FAB model (see Figure 6-4). A detailed description of the SSWC approach is included in Appendix 4.1 (Volume 2 of this report).
4. We then applied FAB (see model description in Appendix 4.2 (Volume 2 of this report) to the 35 lakes in the combined data set to estimate surface water CLs for S and N deposition (see Figure 6-5), as described in UNECE (2004, cited as CLRTAP 2004 in the RFP), Aherne et al. (2002, 2004), and Henriksen and Posch (2001), ensuring that all inputs were consistent with those used for the soil CL model (Steady State Mass Balance) (see Section 5, and also Appendix 4.2 in Volume 2 of this report for a description of data inputs to CL models).
5. We derived a critical load function (CLF) using the FAB model for each modelled lake using combinations of S and N CLs.
6. We created a map plotting CL_{max} (S) for all sampled lakes in the study area and a similar map showing CL_{max} (N).
7. We used lake-specific CLFs to estimate N exceedance, S exceedance, and total exceedance of CLs for each lake (lines ΔN , ΔS and $\Delta N + \Delta S$, respectively in Figure 6-5).
8. We displayed the total exceedance in map form for each emission scenario using the same base map as the CL map in step 5.
9. We assessed potential changes in the pH of the lakes under the different scenarios, using the ESSA-DFO model (see Appendix 4.3 in Volume 2 of this report).
10. We conducted a sensitivity analysis of lakes acidification for various critical ANC values (see Appendix 4.4 in Volume 2 of this report for a description of the sensitivity analysis).
11. We conducted an assessment of the potential risk of eutrophication using the approach presented in Section 6.1.4.
12. We compared the relative performance of different emission scenarios in tabular form, using a consistent set of performance measures.
13. We summarized the level of risk to surface waters associated with each scenario, based on a risk assessment framework described below in Section 6.1.3.



Model Flow

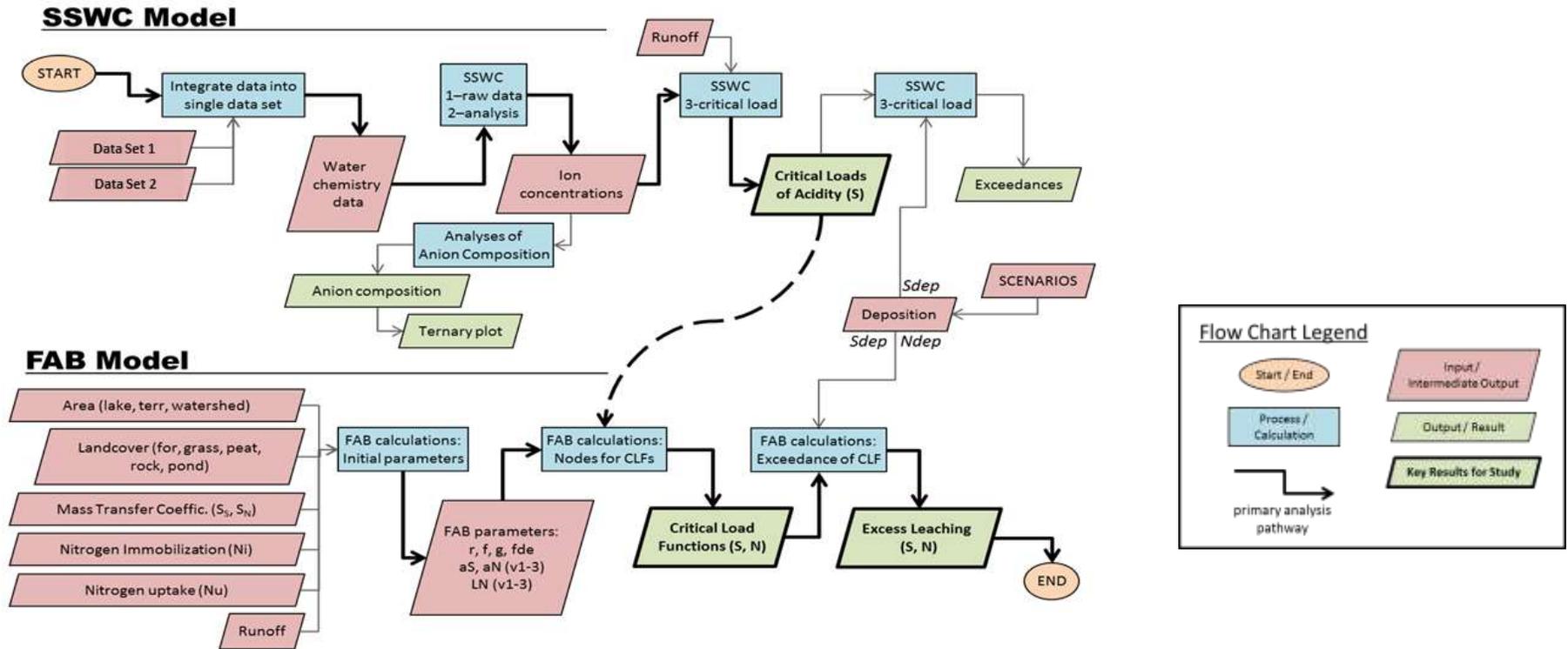


Figure 6-4: Schematic representation of the flow of analyses required to calculate the critical loads and exceedances for the sampled lakes in the study area using the SSWC and FAB models.



The three main models used for this assessment – SSWC, FAB and ESSA-DFO – are described in greater detail in Appendix 4 (Volume 2 of this report), and briefly discussed in the following sections.

The Steady-State Water Chemistry (SSWC) model: The SSWC is an empirical model for calculating critical loads of acidity in aquatic ecosystems (lakes or streams) and the amount (if any) by which these critical loads might be exceeded under scenarios of increased deposition from emissions. The principle behind this model is that the acid load reaching water bodies should not exceed the non-marine, non-anthropogenic base cation inputs plus sources and sinks in the catchment, minus a buffer to protect selected biota from being damaged UNECE (2004).

The SSWC model is described in detail by Henriksen and Posch (2001), Henriksen et al. (2002) and UNECE (2004). For the PRAS analysis, we have closely followed the approach described in Henriksen et al. (2002). The core components of SSWC, as well as any deviations from the original approach that have been introduced to accommodate the particularities in the data of the 35 sampled lakes, are presented in Table 6-1. Table 6-2 lists the parameters used in the equations presented in Table 6-1.

Table 6-1: Core components of the SSWC model.

Component	Equation applied	Modifications relative to Henriksen et al. (2002), if applied in this study
Critical load of acidity	$CL(A) = BC^*_0 - ANC_{limit}$	ANC_{limit} is lake-specific and varies with DOC
Original non-marine base cations	$BC^*_0 = BC^*_t - F \times (SO_4^*_t - SO_4^*_0)$	Does not include ΔNO_3 since current $[NO_3]$ were extremely low in all lakes (generally not detectable)
F-factor	$F = \sin\left(\frac{\pi \cdot Q \cdot [BC^*]_t}{S}\right)$	As in Henriksen et al. (2002)
Original non-marine sulphate	$[SO_4^*]_0 = [SO_4^*]_t - [SO_4^*]_{exp}$	Alternate calculation (see text)
Exceedance of acidity	$Ex(A) = S^*_{dep} + N_{leach} - CL(A)$	As in Henriksen et al. (2002)

Table 6-2: Parameters used in the SSWC model^a.

Parameter	Units	Description
CL(A)	meq/m ² /yr	Critical load of acidity
ANC _{limit}	meq/m ² /yr	Critical ANC limit
Q	m/yr	Runoff
F	(no units)	F-factor
S	meq/m ² /yr	Base cation flux at which F=1.0
Ex(A)	meq/m ² /yr	Exceedance of acidity
S* _{dep}	meq/m ² /yr	Total deposition of non-marine sulphate
N _{leach}	meq/m ² /yr	Nitrogen leaching
BC* _t	meq/m ² /yr	Current, non-marine base cations
[BC*] _t	µeq/L	



Parameter	Units	Description
BC^*_0	meq/m ² /yr	Original, non-marine base cations
$[BC^*]_0$	µeq/L	
BC^*_t	meq/m ² /yr	Current, non-marine base cations
$[BC^*]_t$	µeq/L	
$SO_4^*_t$	meq/m ² /yr	Current, non-marine sulphate
$[SO_4^*]_t$	µeq/L	
$SO_4^*_0$	meq/m ² /yr	Original, non-marine sulphate
$[SO_4^*]_0$	µeq/L	
$SO_4^*_{exp}$	meq/m ² /yr	Expected non-marine sulphate
$[SO_4^*]_{exp}$	µeq/L	

^a Note: The terms SO_4 and BC are sulphate and base cation fluxes per unit area within the watershed (meq/m²/yr), while $[SO_4]$ and $[BC]$ are lake or stream concentrations of sulphate and base cations in µeq/L. Substantial portions of the SSWC model track these ions as concentrations rather than fluxes. Concentrations can be converted to fluxes by multiplying by annual runoff in m (e.g., $BC_t = Q \times [BC_t]$), since 1 µeq/L = 1 meq/m³.

The First-order Acidity Balance (FAB) model: The FAB allows the simultaneous calculation of critical loads of acidifying sulphur (S) and nitrogen (N) deposition and their exceedances. The critical load of acidity, as calculated by the SSWC model, is used as an input to the FAB model. Additionally, the FAB model takes into account catchment processes in terrestrial soils, such as uptake, immobilisation, and denitrification, and the in-lake retention of S and N.

To estimate critical loads and exceedances using the FAB model, we followed the approach described in Aherne et al. (2002). Under this model, a Critical Load Function (CLF), as illustrated in Figure 6-5, is built for each lake. The CLF defines the critical load for every pair of N and S deposition values, (N_{dep} , S_{dep}). Therefore, the FAB model does not result in a single critical load value for each lake; rather, each combination of sulphur and nitrogen deposition results in a pair of critical load values, $CL_{max}(N)$ and $CL_{max}(S)$, for each acidifying component.



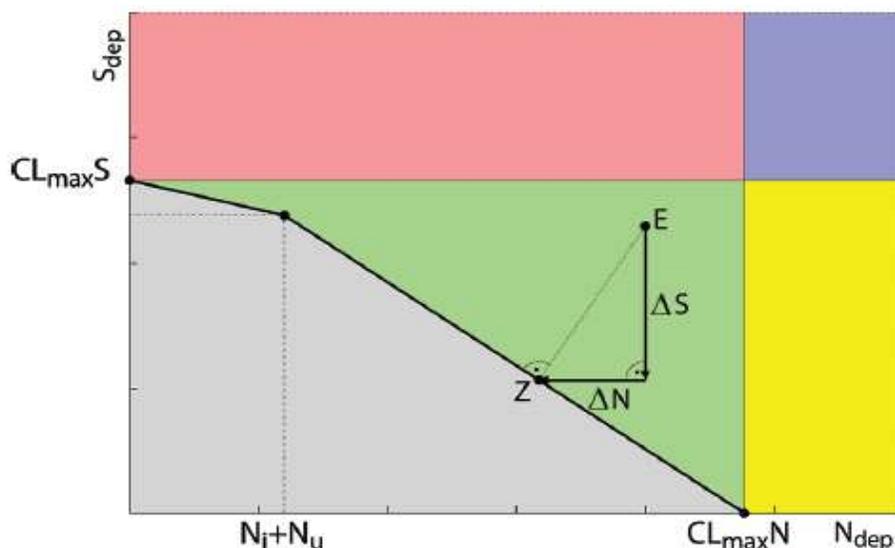


Figure 6-5: Piece wise critical load function (CLF) for S and acidifying N as defined by soil or catchment properties (thick black line), for a terrestrial system or for one lake and its catchment. The gray-shaded area below the critical load function defines deposition pairs (N_{dep} , S_{dep}) for which there is no exceedance, and the terrestrial system or lake's ANC is kept above the critical level. For a given deposition pair (N_{dep} , S_{dep}) the critical load exceedance is calculated by adding the N and S deposition reductions needed to reach the CLF via the shortest path (E→Z): $Ex = \Delta S + \Delta N$. The gray area below the CLF denotes deposition pairs resulting in non-exceedance of critical loads. If a deposition pair is located in the green area (such as E), non-exceedance can be achieved by reducing N or S deposition (or both); in the red (yellow) area S_{dep} (N_{dep}) has to be reduced to achieve non-exceedance; and in the blue area both N_{dep} and S_{dep} have to be reduced. Source: Posch et al. (2012), Figure 5.7 in UNECE (2004) and associated text.

The modified ESSA-DFO model: The modified ESSA-DFO model is based on a lake chemistry model described in Marmorek et al. (1990). We modified the original model as part of an approach to predicting the eventual steady state ANC and pH of lakes for the STAR and KAA assessments. For the PRAS, we used the modified model to estimate the original, pre-industrial, pH values of the sampled lakes as well as the eventual steady state ANC and pH under the various emission scenarios. The modified ESSA-DFO model, as applied to the PRAS lakes, predicts the change in Acid Neutralizing Capacity (ΔANC) as follows:

$$ANC_{\infty} = ANC_t + \Delta ANC_{FUTURE} \tag{Eqn (6.2)}$$

$$\Delta ANC_{FUTURE} = (-1) * [(1-F) * (\Delta S_{DEP}) + (1-F_N) * (\Delta N_{DEP})] / Q \tag{Eqn (6.3)}$$

Where:

- ΔS_{DEP} and ΔN_{DEP} are the modelled deposition values (meq/m²/yr) for S and N, respectively, for the various PRAS emission scenarios. Because the simulation of PRAS emission scenarios did not include background values of S and N deposition, and because the current ANC already reflects the effects of background deposition, we



estimated the change in ANC due to the net increase in S and N deposition predicted for each scenario.

- F (F-factor) = proportion of incoming acidity neutralized by cation exchange (related to current base cations by a sine function, as shown in Table 6-1).
- F_N is the fraction of N deposition neutralized in the watershed. To reflect the fact that catchments retain more N than S, we set $F_N = F * [CL_{max}(N)/CL_{max}(S)]$, while ensuring that F_N remained bounded between 0 and 1.

We estimated each lake's original, pre-industrial pH (pH_0) in the absence of any deposition by setting $S_{DEPSCEN}$ and $N_{DEPSCEN}$ to zero in Equation 6.3. We then used the titration curve described in Section 6.1 of this report (newly developed for KAA and PRAS lakes) to estimate the future steady state pH (pH_{∞}) associated with ANC_{∞} .

6.1.3 Exceedance Maps and Risk Classification

The goal of the risk assessment is to make defensible conclusions on the level of impact, based on both the proportion of lakes with CL exceedance, and the magnitude of exceedance. Following the same approach that was used in the KAA study, a combination of models was applied to assess both CL exceedance (SSWC and FAB models) and potential pH change (modified ESSA-DFO model). This creates four possible categories of biological concern for each lake (Table 6-3), ranging from no concern (CL not exceeded, pH change not biologically significant) to high concern (CL exceeded and biologically significant pH change). Category 3 in the table is somewhat counter-intuitive (i.e., CL not exceeded but $\Delta pH \geq 0.3$). This reflects the fact that, although the SSWC/FAB and ESSA-DFO models use some common inputs (e.g., runoff, lake sulphate concentrations, and deposition), SSWC and FAB are primarily driven by current base cation concentrations, whereas the modified ESSA-DFO model is primarily driven by Gran ANC. Using two complementary models is a precautionary approach.

For the 80 sampled lakes in the KAA, MOE developed a precautionary risk assessment procedure based on both CL exceedance (from the SSWC and FAB models) and the predicted change in lake pH (from the ESSA-DFO model), as summarized in Table 6-3. MOE used a similar approach for the PRAS risk assessment so results will be comparable to those from the KAA, making both assessments regionally informative. However there were several differences between the KAA and PRAS: 1) fewer lakes were sampled and analyzed lakes in the PRAS (35) than in the KAA (80), 2) most sampled lakes in the KAA were within the effects domain whereas most sampled lakes in the PRAS were outside of the effects domain; and 3) PRAS lakes were not selected using the same criteria as those in the KAA. These differences led MOE to apply a similar risk assessment approach to that used for soils in Table 5-6 to generate risk categories (expressed as percentages of lakes) very similar to the KAA. The risk categories for the KAA and PRAS are as follows:

- In the KAA, the Low risk category was indicated by 0 analyzed lakes with a $\Delta pH \geq 0.3$ (all analyzed lakes are in category 1 in Table 6-3, i.e., none exceed CL or have $\Delta pH \geq 0.3$). BC MOE assumes the same criterion for the PRAS – that all analyzed lakes need to be in category 1 of Table 6-3 for the Low risk category to be applicable. Table 5-6 (risk



criteria for soils) assumes that a Low risk category is <0.05% of soils exceeding a threshold of concern, which is also equivalent to zero lakes.

- In the KAA, the Moderate risk category was indicated by 1 or 2 lakes with $\Delta\text{pH} \geq 0.3$ (in categories 3 or 4 in Table 6-3), corresponding to **1.25% to 2.5%** of the 80 lakes analyzed in the KAA. For the PRAS, BC MOE follows the soils' criterion of < 2.5% of receptors exceeding a threshold of concern. This risk category translates to 1 analyzed lake with these attributes (1 lake represents **2.86%** of the 35 lakes analyzed in the PRAS, and is the nearest whole number to the equivalent soils criterion).
- In the KAA, the High risk category was indicated by 3 to 5 sampled lakes with $\Delta\text{pH} \geq 0.3$ (in categories 3 or 4 in Table 6-3), corresponding to **3.75% to 6.25%** of the 80 lakes analyzed in the KAA. For the PRAS, BC MOE follows the soils criterion of < 5% of receptors exceeding a threshold of concern. This risk category translates to 2 analyzed lakes with these attributes (2 lakes represent **5.71%** of the 35 lakes analyzed in the PRAS, the nearest whole number to the equivalent soils criterion).
- In the KAA, the Critical risk category was indicated by 6 or more lakes with $\Delta\text{pH} \geq 0.3$ (in categories 3 or 4 in Table 6-3), representing **7.5%** or more of the 80 lakes sampled and analyzed in the KAA. For the PRAS, BC MOE follows the soils criterion of $\geq 5\%$ of receptors exceeding a threshold of concern. This category corresponds to 3 or more analyzed lakes (3 lakes represent **8.6%** of the 35 lakes analyzed in the PRAS, the nearest whole number to the equivalent soils criterion).

Table 6-3: Lake categories of biological concern defined by MOE for use in the KAA (Source: ESSA et al. 2014a, pg. 153).

SSWC/FAB	Modified ESSA-DFO Model	
	pH change <0.3	pH change >0.3
CL exceeded	2. Low concern (CL exceeded but pH change not biologically significant)	4. Highest concern (CL exceeded and biologically significant pH change)
CL not exceeded	1. No concern (CL not exceeded and pH change not biologically significant)	3. Intermediate concern (CL not exceeded but biologically significant pH change)

Sample size is not an issue for the assessment of eutrophication risk, because in addition to an **intensive** analysis for the 35 sampled lakes (with average deposition accurately estimated based on the watersheds of these lakes), we can apply the empirical approach to an extensive analysis of all 859 lakes greater than 1 ha in size within the PRAS area (using estimated deposition at the centroids of these lakes). For the extensive analysis of eutrophication, BC MOE applied a risk assessment categorization similar to that used for soils in Table 5-6 (i.e., Critical if more than 43 lakes show CL exceedance ($\geq 5\%$), High if between 21 and 43 lakes show CL exceedance (2.5 to 5%), Moderate if between 1 and 21 lakes show CL exceedance (0.1% to 2.5%), and Low if zero lakes show CL exceedance).

6.1.4 Analysis of the Risk of Lake Eutrophication

Algal production and thus risk of eutrophication is determined by the supply of inorganic phosphorus ($\text{PO}_4\text{-P}$), also known as soluble reactive phosphorus (SRP), and dissolved inorganic nitrogen (DIN) (Wetzel 2001). In coastal lakes, these two nutrients tend to be present



in very low concentrations, producing a condition known as co-limitation, which is particularly prevalent in coastal lakes of British Columbia, including those on the north coast (Stockner and MacIsaac 1996).

Critical loads for nutrient N for aquatic ecosystems in the PRAS area were determined by empirical methods, which have strong support in the scientific literature (e.g., Bobbink et al. 1992; Grennfelt and Thörnelöf 1992; Bobbink et al. 1996; Bobbink et al. 2003; Achermann and Bobbink 2003; Bobbink and Hettelingh 2010; de Wit and Lindholm 2010).

The approach used to determine nutrient-N critical loads (CLs) and exceedances in the lakes of the study area consisted of the following steps:

1. We classified the sampled lakes as either *oligotrophic* (all lakes not classified as dystrophic) or *dystrophic* (lakes with pH <6 and with organic anions forming more than 50% of the total anions).
2. We used the empirically-based CLs reported in the International Cooperative Programme (ICP) Waters report *Nutrient enrichment effects of atmospheric N deposition on biology in oligotrophic surface waters* (de Wit and Lindholm 2010), based on the type of lake:
 - a. 5-10 kg N/ha/yr for permanent, temperate, oligotrophic lakes.
 - b. 3-5 kg N/ha/yr for permanent, temperate, dystrophic lakes.

The ICP Waters report further refines the empirical critical loads developed by Bobbink and Hettelingh (2010) based on their extensive literature review of the effects of N deposition on phytoplankton, benthic algae, macrophytes, and invertebrates. The Bobbink and Hettelingh (2010) workshop assessed empirical critical loads for a broad range of terrestrial and aquatic ecosystems, whereas the ICP Waters report focuses specifically on lakes, for which it provides similar but somewhat narrower ranges on estimates of critical limits (i.e., 5-10 kg N/ha/yr for oligotrophic lakes in de Wit and Lindholm (2010) vs. 3-10 in Bobbink and Hettelingh (2010)). The reliability of the estimated critical loads is evaluated according to a similar scale in both reports, building upon earlier work (Bobbink et al. 1996; Achermann and Bobbink 2003; Bobbink et al. 2003). de Wit and Lindholm (2010) conclude that the “critical loads for the alpine, boreal, temperate and Atlantic catchments is (sic) supported by a number of published papers from very different regions, focused on different organisms and employing different methods and are evaluated as ‘reliable’”. Such evaluation reflects the highest level of confidence. The critical loads for dystrophic lakes “should receive the medium grade of reliability, ‘quite reliable’” (de Wit and Lindholm 2010).

3. For each type of lake, we assessed exceedances relative to three specific CLs, similar to the approach used by Pardo et al. (2011):
 - a. The lower bound of the estimated CL range, as a conservative application of the empirical CLs (3 kg N/ha/yr for dystrophic lakes; 5 kg N/ha/yr for oligotrophic lakes).
 - b. The mid-point of the estimated CL range, as a moderate application of the empirical CLs (4.5 kg N/ha/yr for dystrophic lakes; 7.5 kg N/ha/yr for oligotrophic lakes).



- c. The upper bound of the estimated CL range, which if exceeded indicates a higher level of concern (5 kg N/ha/yr for dystrophic lakes; 10 kg N/ha/yr for oligotrophic lakes).
4. To assess potential exceedances of the CLs under each emissions scenario, we determined N deposition for each of the 35 lakes based on the CALPUFF deposition outputs for each scenario. We compared the effect of using deposition at the lake centroids with using the average deposition in the watershed.
5. As described above, we used lake-specific estimates of N deposition to assess lake-specific exceedances for each emissions scenario, relative to the three CLs applied (i.e., lower bound, mid-point, upper bound), as appropriate for the type of lake (i.e., oligotrophic or dystrophic). An exceedance is predicted when deposition is greater than the assumed CL.
6. To estimate potential exceedances of nutrient-N CLs *for all 859 lakes >1 ha* within the study area (sampled and non-sampled) under each emissions scenario, we did the following:
 - a. We delineated areas with >5 kg N/ha/yr and >3 kg N/ha/yr, representing conservative applications of the empirically-based CLs for permanent, temperate oligotrophic and dystrophic lakes, respectively.
 - b. We determined how many lakes occurred within the area of exceedance of each of these CLs (based on the lake centroid). Both CLs were used for all lakes because, without DOC measurements, we were not able to assess whether non-sampled lakes were oligotrophic or dystrophic (just 4 of the 35 sampled and analyzed lakes (11%) were dystrophic according to the criteria described above). These counts (and the percentage of lakes) provide a regional estimate for the whole study area of the potential for exceedances of eutrophication CLs.
 - c. We compared the results from this extensive approach for all 859 lakes in the PRAS with the intensive approach applied to the 35 sampled lakes (for which lake trophic type is known, and deposition can be more accurately estimated).
7. We displayed the measures of exceedance described above in map form for the alternate empirical CLs under each of the emission scenarios.
8. We summarized the exceedances in both frequency and cumulative frequency distributions and compared the results across all emissions scenarios.
9. We compared the relative performance of different emission scenarios in tabular form, using a consistent set of performance measures.

6.2 Results

6.2.1 Data Quality

6.2.1.1 Final Data Set for Analyses

From among the 37 lakes originally included in the combined DS1 and DS2 data sets, two lakes were excluded from further analyses, reducing the final sample size to 35 lakes:

- AD-SW2: This lake from DS2 was a duplicate sample for Alwyn Lake, which was sampled as part of DS1.



- AD-SW7: This sample from DS2 showed a poor charge balance. The charge balance is the difference between the sum of all the cations (positively charged ions) and all the anions (negatively charged ions), and is a calculation used to assess the cumulative error in the analysis of water quality samples, since natural waters should have a charge balance close to zero (please see Section 6.2.1 for the results of the charge balance analysis of the sampled lakes). Sample AD-SW7 resulted in a charge balance percentage of -46% (i.e., predominance of anions), which might be indicative of sampling and/or analytical errors.

6.2.1.2 Analysis of Charge Balance and Predicted versus Measured Conductivity

Analysis of charge balance and conductivity are tests of data quality that integrate all of the cumulative analytical errors in all measured parameters. The charge balance is the difference between the sum of major cations (positively charged ions) and the sum of major anions (negatively charged ions). The true charge balance for natural waters is neutral (i.e., the sum of charges on total anions balances the sum of charges on total cations). The calculated charge balance should be reasonably close to neutrality (a 1:1 ratio of cations to anions), but is never perfect in natural waters, due to both cumulative measurement errors across many constituents and the complexities of freshwater ionic chemistry (especially organic anions, which have variable charge depending on which organic acids are present and the pH of the solution). If the anions and cations are very close to being balanced, then we have high confidence that the data accurately reflect the true ion composition of the water samples. As shown in Figure 6-6, the two data sets show charge balances close to 1:1, with an average percentage difference of -3.31%. The concentration of anions is higher than the concentration of cations in most of the samples.



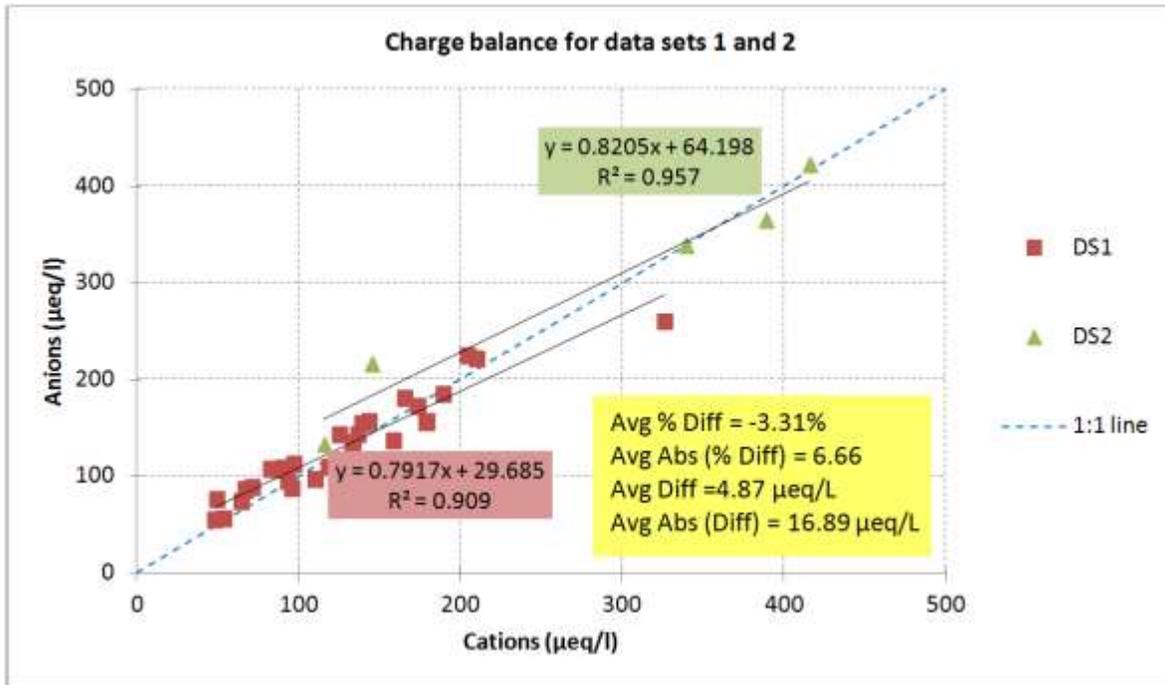


Figure 6-6: Charge balance of the sampled lakes (DS1= EC lakes and DS2=PRLNG lakes). The Y-axis is the sum of all major anions (negatively charged ions); the X-axis the sum of all major cations (positively charged ions). Both 1:1 line (dashed) and the regression lines (solid) for each data set are shown.

We explored how assumed charge density (i.e., density of charge around the ion) of organic anions affected the overall charge balance. Organic anions have variable charge depending on which organic acids are present and the pH of the solution. For lakes in DS2, an assumed charge density of 7.5 μeq per mg of DOC (Oliver et al. 1983) provided the best possible charge balance. For DS1 lakes, charge balance was optimized with an assumed charge density of 5.5 μeq per mg of DOC (Table 6-4).



Table 6-4: Effect of DOC charge density ($\mu\text{eq}/\text{mg}$) on the charge balance of lakes in DS1. *Mean %DIFF* = mean % charge balance (negative values have higher anions; positive values have higher cations). *Mean ABS %* is the mean of the absolute value of deviations from perfect charge balance. *Mean Diff* is the mean deviation from charge balance in $\mu\text{eq}/\text{L}$. *Mean AbsDiff* is the mean of the absolute value of deviations from charge balance in $\mu\text{eq}/\text{L}$. Yellow highlight indicates the selected charge density value ($5.5 \mu\text{eq}/\text{L}$).

Charge Density	Mean %DIFF	Mean ABS %	Mean Diff	Mean AbsDiff	# lakes >10% off charge balance
7.5	-8.47	8.95	-18.72	21.62	11/30
6	-4.49	6.98	-7.22	16.29	8
5.5	-3.07	6.76	-3.38	15.77	6
5.25	-2.34	6.79	-1.47	15.97	6
5	-1.59	6.91	0.45	16.36	6
4	1.51	7.61	8.12	18.37	11

Conductivity was only measured for the 30 lakes in DS1 (Environment Canada). These measured values were compared against estimated conductivity using the US EPA’s CONCAL method for calculated conductance (Baker et al. 1991), as shown in Figure 6-7. Estimated conductivity was generally greater than observed conductivity in the most diluted waters (<15 $\mu\text{S}/\text{cm}$).

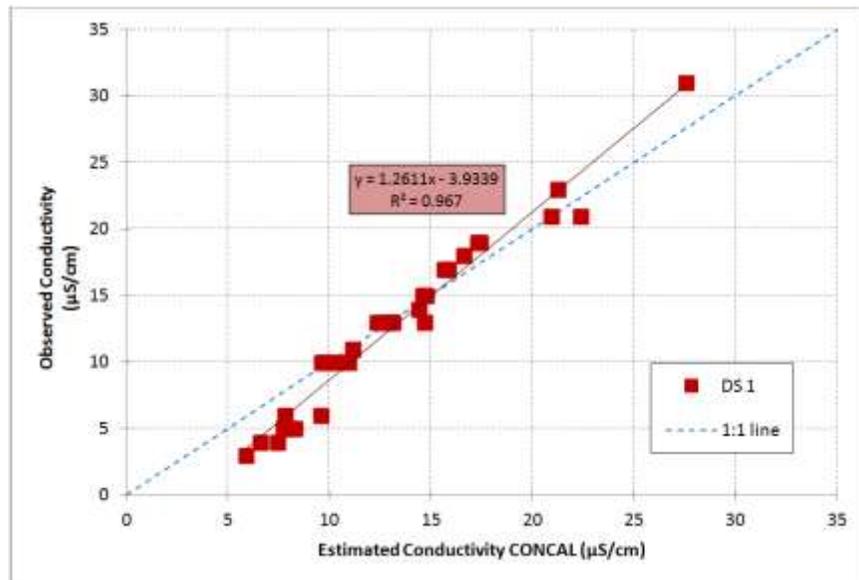


Figure 6-7: Analysis of estimated conductivity versus observed conductivity for the lakes in DS1. Both 1:1 line (dashed) and the regression line (solid) are shown.

Based on the results of these charge balance and conductivity tests, the overall level of data quality in both data sets is acceptable.



6.2.1.3 Determination of Critical ANC

The critical ANC (i.e., $[ANC]_{limit}$) is the ANC level corresponding to a critical pH threshold. As in the STAR and KAA, we assumed that the critical pH threshold of concern was 6.0 (see Section 3.5 in ESSA et al. 2013 for citations of literature supporting this assumption). Using the critical ANC in the SSWC model yields a critical load sufficient to protect lakes from acidifying below a pH level of 6.0, unless lakes were naturally acidic to below pH 6.0 in pre-industrial times due to organic acids and/or chloride derived from sea salt.

For the PRAS, we first assessed whether pH and Gran ANC values for the 35 lakes in DS1 and DS2 were consistent with the pH-Gran ANC titration curve used in the STAR and KAA. DOC was higher in DS1 and DS2 lakes (median value of 9.8 mg/l) than in the KAA lakes (median value of 3.0 mg/l). Since higher DOC can result in a lower pH for a given value of Gran ANC, we completed the following steps to analyze the influence of DOC on the critical ANC value:

1. We divided the DS1 and DS2 data sets into three subsets based on the terciles of DOC (DOC values of 7 mg/l and 12 mg/l divided the data set into three approximately equal subsets).
2. We examined the pattern of pH versus Total Alkalinity for each of these three subsets, and observed different functional relationships between pH and ANC for each subset, consistent with expectations (i.e., lower pH values for the higher DOC lakes; Figure 6-8).

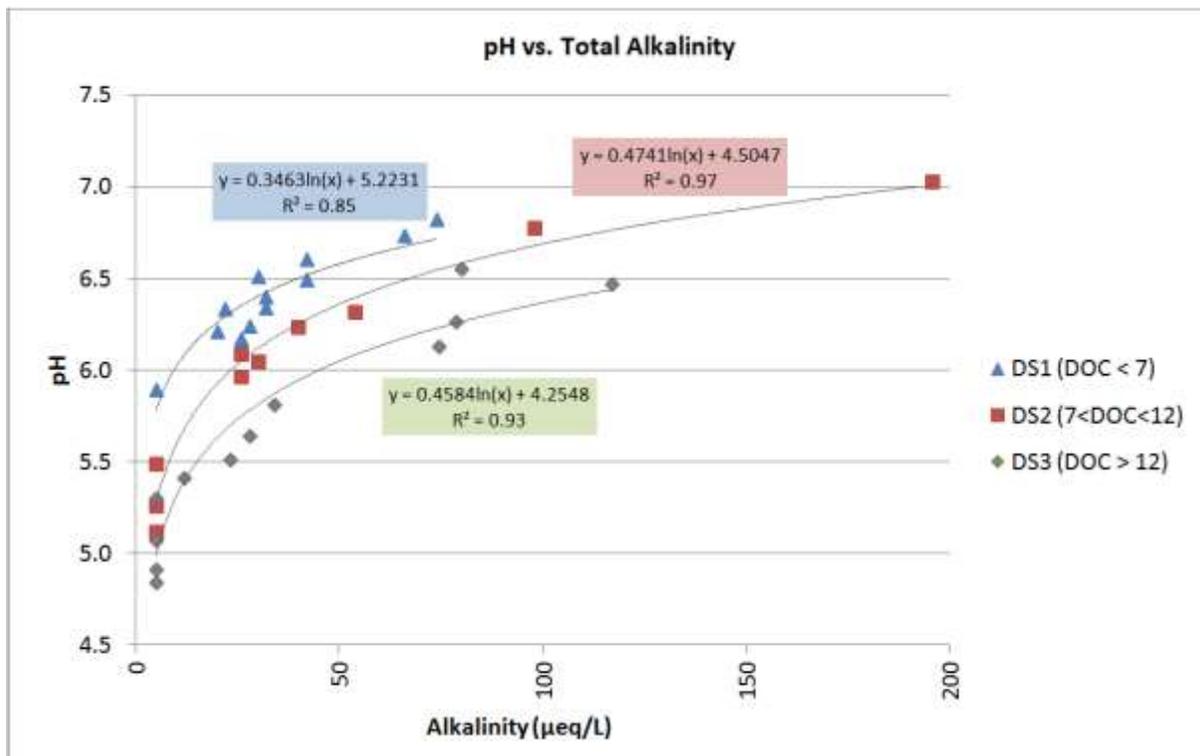


Figure 6-8: Analysis of Total Alkalinity versus pH for the three subsets of the lakes samples according to their DOC level (Group 1/G1 = DOC < 7 mg/l; Group 2/G2 = 7 < DOC < 12 mg/l; Group 3/G3 = DOC > 12 mg/l).



- We used the same methods of non-linear parameter estimation that we applied in the STAR (ESSA et al. 2013, pages 238-239; based on Small and Sutton 1986) to estimate a new titration curve for the combined PRAS and KAA datasets. Using the combined data sets would ensure a wide contrast in Gran ANC and pH values appropriate for fitting the following equation (Small and Sutton 1986):

$$pH = a + \frac{1}{\ln 10} \operatorname{arcsinh} \left[\frac{(Gran\ ANC) - d}{c} \right]$$

Eqn (6.4)

- We graphed the residuals from the new titration curve versus DOC, and found a negative slope (indicating that higher DOC lakes were more likely to fall below the curve);
- We then adjusted Equation 6.4 so that it included an additional term for DOC (Equation 6.5; Figure 6-9):

$$pH = a + \frac{1}{\ln 10} \operatorname{arcsinh} \left[\frac{(Gran\ ANC) - d}{c} \right] - e * DOC$$

Eqn (6.5)

Where a = 5.284, c = 7.753, d = -9.984, and e = 0.022.

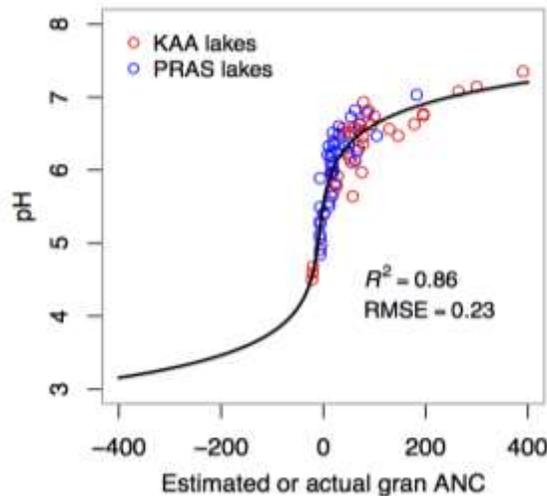


Figure 6-9: Adjusted titration curve including KAA and PRAS data, using Equation 6.5.

- Rearranged Equation 6.5 to determine the Gran ANC associated with a given pH and DOC:

$$GranANC = c * \sinh[\ln(10) * (pH + (e * DOC) - a)] + d$$

Eqn (6.6)



7. Substituted pH = 6 into Equation 6.6, obtaining a Critical ANC associated with pH 6 for any DOC level (Figure 6-10).

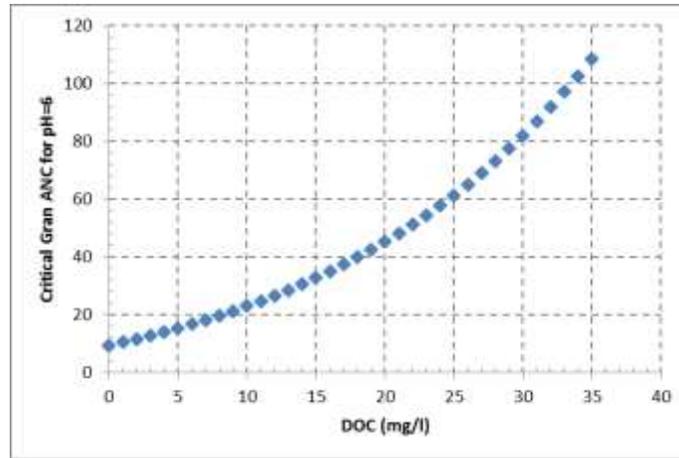


Figure 6-10: Critical ANC corresponding to pH 6, based on dissolved organic concentration (DOC) calculated by substituting pH = 6 into Equation 6.6, together with the parameters estimated by non-linear parameter estimation.

Figure 6-11 graphs pH residuals from Equation 6.4 (the titration curve fit based on the formulation developed by Small and Sutton 1986) versus DOC. Samples with higher DOC levels were generally more likely to fall below the titration curve (i.e., have a lower pH level than predicted), and lakes with lower DOC levels were more likely to fall above the curve (i.e., have a higher pH than predicted), consistent with theoretical expectations (Hemond 1990). This pattern of residuals justified the addition of DOC into the titration curve (Equation 6.5), although this resulted in only a marginal improvement in overall fit (R^2 of 0.86 with Equation 6.5 versus R^2 of 0.88 with Equation 6.6), indicating that much of the remaining variation in pH is unrelated to DOC. Figure 6-11 also shows the higher content of DOC in the lakes of the PRAS area, compared to the lakes from the KAA study. On average, DOC for the lakes in KAA study was 3.04 mg/l, whereas for the lakes in the PRAS this mean DOC value is 10.12 mg/l.



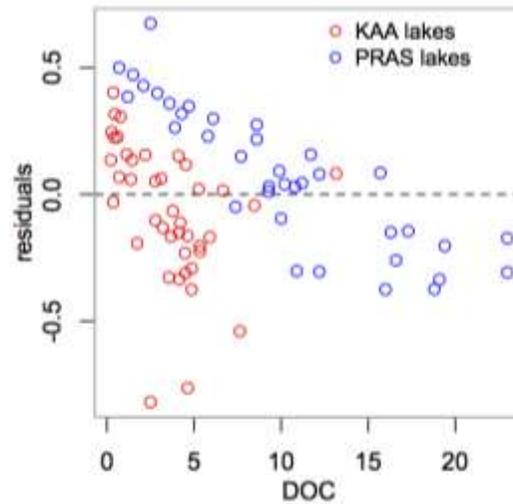


Figure 6-11: Analysis of pH residuals in Equation 6.4 versus DOC (mg/l) for both PRAS and KAA data sets.

6.2.2 Characteristics and Composition of Lakes

In the following three subsections we present the results of our analyses of the data from the 35 sampled lakes in the final data set. Given the mix of criteria applied for selecting the lakes to be sampled, the metrics derived from analyses of these data cannot be considered statistically representative of the whole PRAS study area.

6.2.2.1 Acid Neutralizing Capacity in Sampled Lakes

Total alkalinity was measured for all 35 sampled lakes. The average value of total alkalinity (for both DS1 and DS2 data sets) was 40.05 $\mu\text{eq/L}$. Figure 6-12 shows the frequency distribution of total alkalinity amongst the two data sets separately, and combined. Of the 35 lakes, 12 (34%) had a total alkalinity <25 $\mu\text{eq/L}$, 14 (40%) were in the range of 25-50 $\mu\text{eq/L}$, and the remaining samples (nine lakes or 26%) had total alkalinity values higher than 50 $\mu\text{eq/L}$.



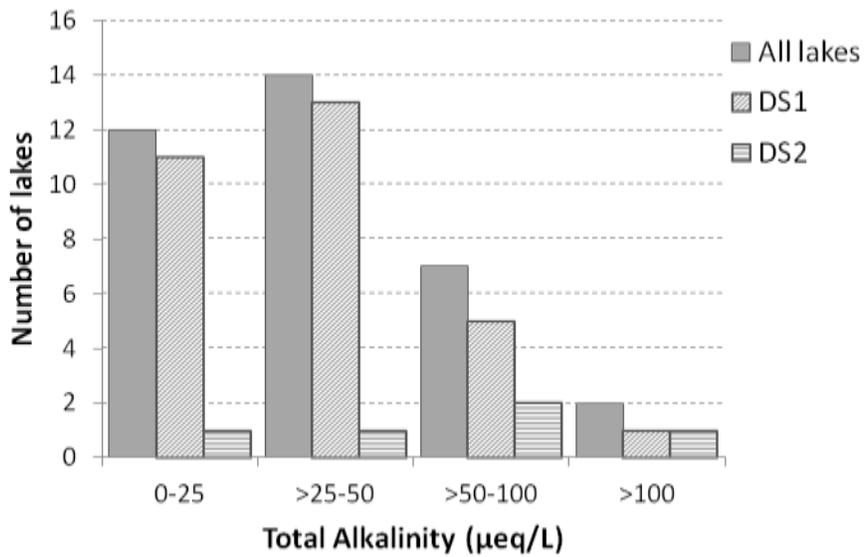


Figure 6-12: Distribution of total alkalinity among sampled lakes, stratified by data set.

The Gran Acid Neutralizing Capacity (Gran ANC) of the lakes was not measured for either of the data sets. As explained in Section 6.1.1, Gran ANC was estimated for the lakes sampled in the PRAS area based on the regression developed in the Kitimat Airshed Assessment (Equation 6.1). The distribution of these estimated GranANC values for sampled lakes is shown in Figure 6-13. On average, Gran ANC values are about 12.26 µeq/L lower than total alkalinity.

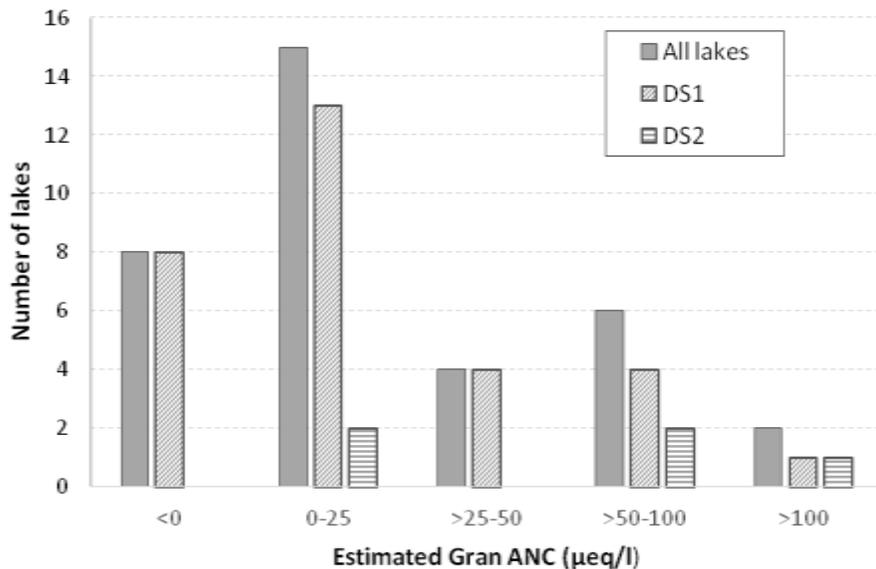


Figure 6-13: Distribution of estimated Gran Acid Neutralizing Capacity (ANC) amongst the sampled lakes.



According to the values shown in Figure 6-13, the PRAS data set included eight acidic lakes (estimated Gran ANC <0), which amounts to 23% of the total sample. About 54% of the sampled and analyzed lakes (19 out of 35) had an estimated GranANC <50 µeq/L and therefore could potentially experience acidic episodes during storm and snowmelt events (Driscoll et al. 2001). The remaining 23% of the lakes had an estimated GranANC >50 µeq/L and therefore are relatively insensitive to acidic deposition.

6.2.2.2 pH Levels in Sampled Lakes

As shown in Figure 6-14, 14 of the 35 sampled lakes (40%) had a lab pH less than 6.0, with eight of these lakes (23%) having a pH value of less than 5.5.

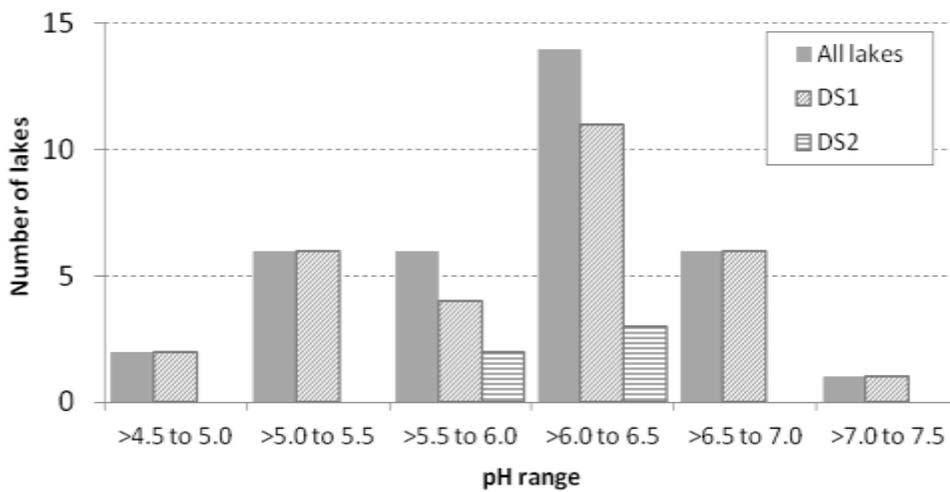


Figure 6-14: Distribution of pH, as measured in the laboratory, among sampled lakes and stratified by data set.

Figure 6-15 illustrates the spatial distribution of pH values of the sampled lakes. There is no clear spatial pattern for pH distribution although it seems that more acidic lakes are predominantly located closer to the sea and in the southern part of the PRAS area. In the following subsection we discuss the likely reasons for the 14 lakes having a pH less than 6.0. Figure 6-16 shows pH distribution across the broader PRAS area, based on the Geoscience BC data. pH values in Figure 6-16 also tend to be lower in the southern streams and lakes, which would be consistent with the observed pH values in the sampled PRAS lakes.



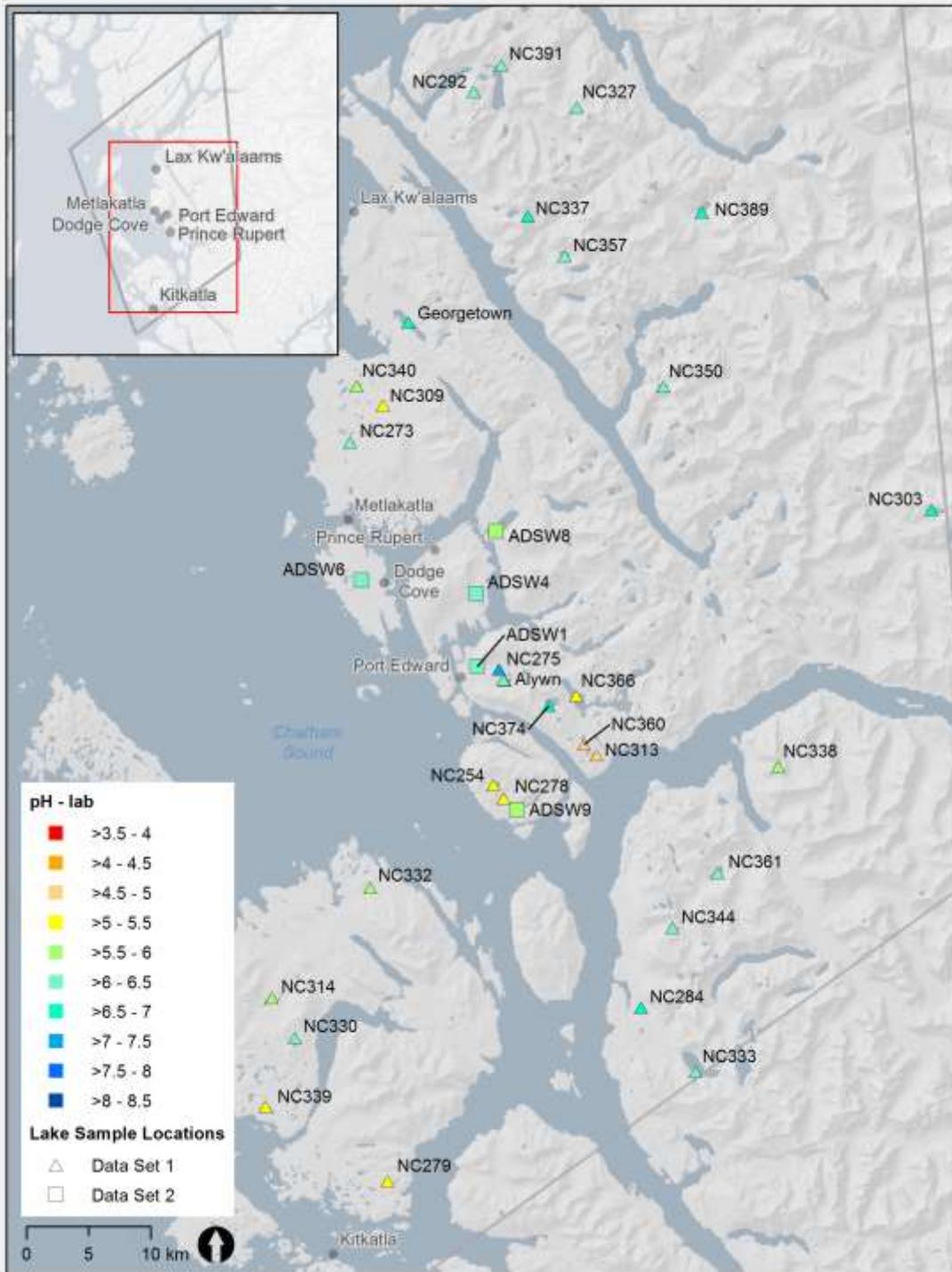


Figure 6-15: Spatial distribution of pH values (laboratory measurements in August-September 2014) of the sampled lakes.

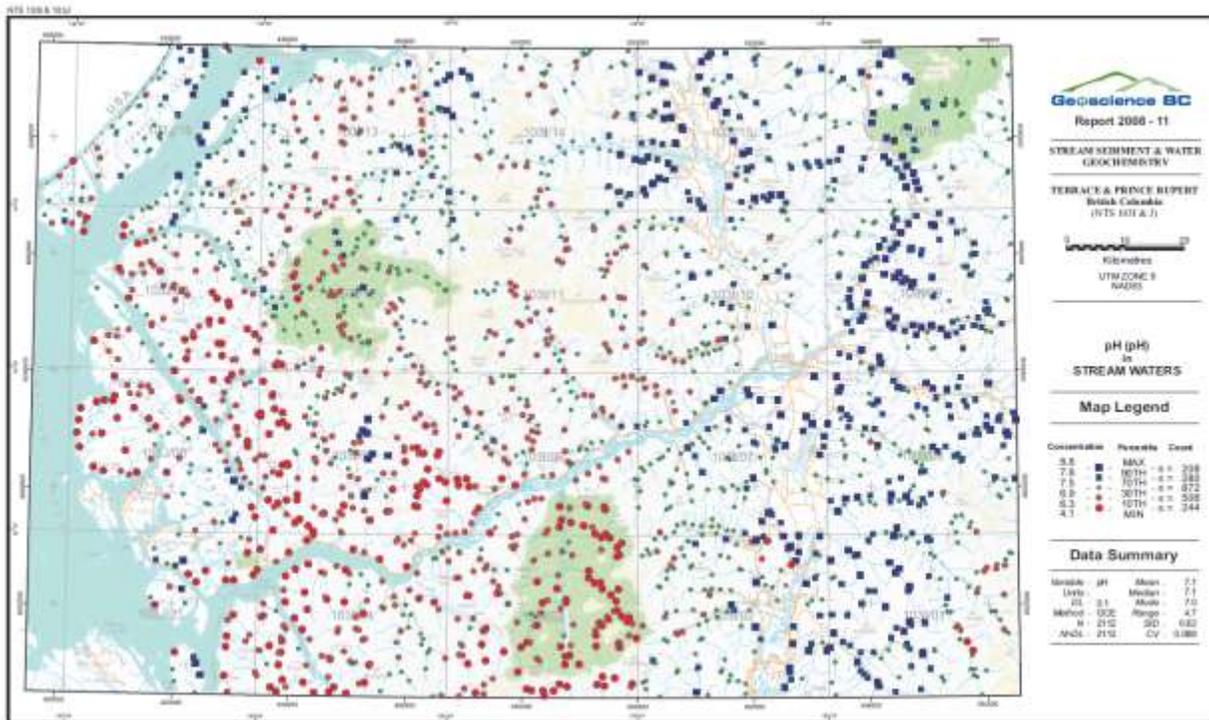


Figure 6-16: Spatial distribution of pH values for stream waters from geochemical surveys in/near the PRAS study area. Streams tend to be more acidic in the southwestern part of the mapped area. Source: BC Government ([Geoscience BC](http://www.geosciencebc.ca)).

6.2.2.3 Anion Composition

The anion composition of lakes provides an indication of the causal factors determining their acid-base status (Marmorek et al. 1989; Baker et al. 1991). We assigned the term ‘dominated’ to an anion which made up more than 50% of the total anions in a sampled lake or stream, and ‘influenced’ when the anion made up more than 25% (but less than 50%). A lake can be dominated by one anion and influenced by another, or have up to three influential anions. Figure 6-17 shows the overall anion composition for the sampled lakes for both data sets.



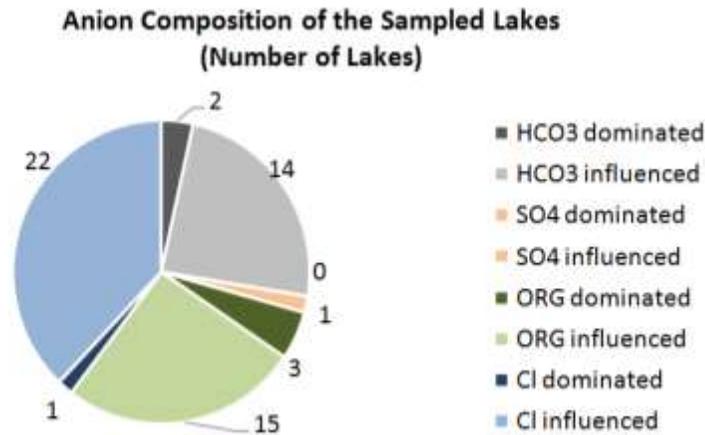


Figure 6-17: Overall anion composition of the 35 sampled lakes. A lake can be in more than one category (e.g., both chloride influenced and organic influenced), so the sum exceeds 35.

The three most common categories were chloride-influenced (22), organic-influenced (15), and bicarbonate-influenced (14). Only one lake showed sulphate influence (Lake NC389).

Out of the total of 35 lakes in the study, 14 have a pH lower than 6.0. The remainder of this section focuses exclusively on the anion composition of those lakes with pH <6.0, to determine why they currently have a low pH. The spatial distribution of lakes with pH <6.0, along with the pie charts of anion composition for 7 of these lakes, are shown in Figure 6-18. Most of these lakes are close to coast, except for Lake NC314 and Lake NC309. As shown in the selected pie charts, chloride and organic are the predominant anions in these acidic lakes.



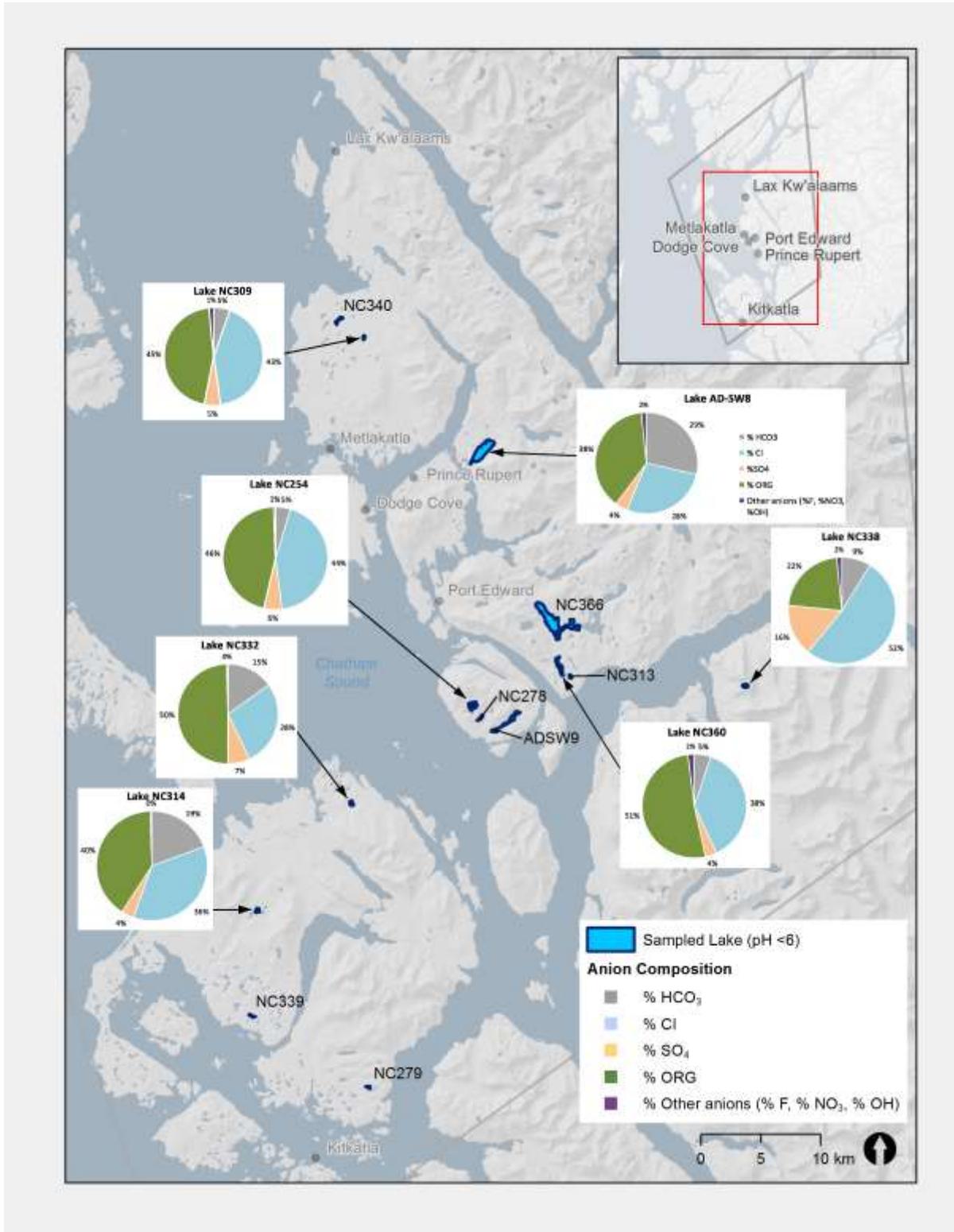


Figure 6-18: Spatial distribution of the 14 lakes with pH < 6.0 and pie charts of anion composition for a sub-set of these lakes.

Table 6-5 shows the anion composition of these 14 lakes, as well as the estimated pre-industrial, original pH (pH_0), based on the modified ESSA-DFO model. All of the 14 lakes with current pH < 6.0 are influenced by chloride and organic anions (> 25% of the anions are chloride and > 25% are organic anions); 4 lakes are dominated by organic anions (> 50% organic anion content). These lakes are of low ionic strength (e.g., mean conductivity of the 12 lakes with current pH < 6.0 in DS1 is 14 $\mu\text{S}/\text{cm}$). The pre-industrial, original pH is calculated to help determine if there are naturally acidic lakes that have always had a pH < 6. As shown in Table 6-5, 12 of the 14 lakes with current pH < 6 (i.e., 86%) are estimated to have also had a pre-industrial, original pH_0 < 6, and are thus considered to be naturally acidic lakes. Natural acidification appears to have been caused primarily by organic acids and sea salt (given their proximity to the coast). Many of the studied lakes contain appreciable levels of dissolved organic carbon (DOC), the average DOC for all lakes is 10.1 mg/l (the maximum DOC value, 23 mg/l, was observed at AD-SW1 and AD-SW4) and organic anions often form a major component of the charge balance. The movement of salt-enriched precipitation by offshore winds can contribute substantial natural acidity to catchments with naturally acidic soils, even in pristine areas (Wright et al. 1988). When precipitation carrying sea salts lands on acidic soils, the basic elements in the precipitation (e.g., sodium) displace the acidic elements in the soil; the free acidic elements then go into solution and acidify the runoff water (Wright et al. 1988).

None of the 14 lakes are inferred to have experienced a pH decrease of more than 0.15 pH units since pre-industrial times (rightmost column of Table 6-5). The lakes which are inferred to have experienced the highest pH change are: NC254 (-0.119), NC338 (-0.118), and NC360 (-0.122). These are small pH changes (within the range of pH measurement error) which could well be a consequence of the combined effect of all of the input data and assumptions in the methods used to infer historical pH. The inferred historical changes in pH primarily reflect removal of the assumed background (anthropogenic) level of acidic deposition of 10 meq/ha/yr of SO_4 deposition and 5 meq/ha/yr of N deposition, and the sensitivity of each lake to acidification (ANC, F-factors for S and N). The low level of historical, anthropogenic pH change is consistent with the low percentage of anion composition from sulphate. Only one (Lake NC338) of the 14 lakes with pH < 6.0 had sulphate forming more than 10% of its total anions (Table 6-5). By contrast, in the KAA study, 23 out of the 30 lakes with pH < 6.0 (about three quarters of these lakes) had sulphate forming more than 10% of their total anions (see Table 6-5 in ESSA et al. 2014a).



Table 6-5: Analysis of the anion composition of 14 lakes with current pH <6. Shaded values indicate anion influence or dominance (≥25%). Bolded numbers indicate anion dominance (≥50%). DOC = dissolved organic carbon (mg/L), HCO₃ = bicarbonate (grey shading), Cl = chloride (blue shading), SO₄ = sulphate, ORG = organic anions (green shading). Last column shows estimated pre-industrial pH_o based on modified ESSA-DFO model (ESSA et al. 2013). Only two (NC314 and NC338) of the 14 lakes with current pH <6 had an original pH_o ≥6 (pH_o in bold). The estimated change in pH from pre-industrial to present is shown in the last column (ΔpH).

LAKE ID (name)	DOC	pH (lab)	% HCO ₃	% Cl	%SO ₄	% ORG	pH _o	ΔpH
NC254	11.20	5.26	5%	44%	6%	46%	5.38	-0.119
NC278	17.30	5.07	4%	38%	4%	54%	5.13	-0.032
NC279	15.70	5.30	3%	45%	5%	46%	5.37	0.000
NC309	10.00	5.12	5%	43%	5%	45%	5.27	-0.065
NC313	16.00	4.84	5%	33%	3%	58%	4.92	-0.084
NC314	10.80	5.97	19%	36%	4%	40%	6.00	-0.032
NC332	19.10	5.64	15%	28%	7%	50%	5.65	-0.008
NC338	2.50	5.89	9%	52%	16%	22%	6.01	-0.118
NC339	16.30	5.41	8%	41%	3%	48%	5.45	-0.044
NC340	16.60	5.81	20%	28%	5%	48%	5.82	-0.010
NC360	12.20	4.91	5%	38%	4%	51%	5.03	-0.122
NC366	8.60	5.49	6%	36%	10%	46%	5.58	-0.095
AD-SW8 (Shawatlan)	7.39	5.98	29%	28%	4%	38%	5.99	-0.010
AD-SW9	18.80	5.51	13%	26%	2%	56%	5.54	-0.032

6.2.3 Analysis of the risk of lakes acidification

6.2.3.1 Critical Loads for Acidification

SSWC Model

The distributions of SO₄ critical loads for the sampled lakes, estimated according to the SSWC model, are shown in Figure 6-19. Dupont et al. (2005) used the following classes to define CL sensitivity: highly sensitive (< 20 meq/m²/yr); sensitive (20-40); moderately sensitive (40-60); low sensitivity (60-100); and very low sensitivity (>100). About 68% (22 out of 35) have a CL higher than 100 meq/m²/yr, and would therefore fall into the very low sensitivity class defined by Dupont et al. 2005 (CL >100 meq/m²/yr). Another 29% of the lakes have low sensitivity (CL = 60 to 100 meq/m²/yr), 3% have moderate sensitivity (CL = 40 to 60 meq/m²/yr), and 6% are sensitive (CL = 20 to 40 meq/m²/yr). By comparison, in the KAA, there were 15 out of 80 analyzed lakes with a CL <0 (19%), and fewer than half of the analyzed lakes (38/80) had a CL >100 meq/m²/yr. The lakes sampled in the PRAS are therefore generally less sensitive to acidification than the lakes sampled in the KAA.



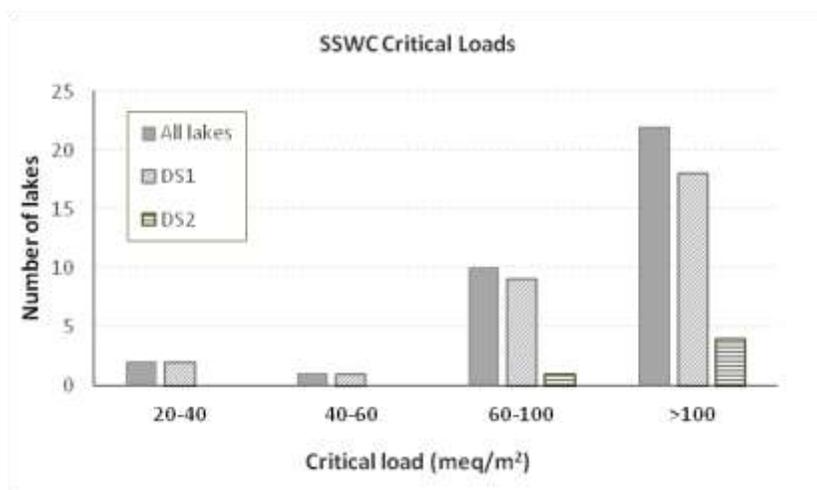


Figure 6-19: Frequency distribution of SSWC critical loads for the 35 sampled lakes.

Higher runoff values can result in higher CLs due to the effect of dilution. Table 6-6 shows the runoff metrics for the two data sets and the overall values; Figure 6-3 shows that the highest runoff occurs in the northeastern part of the study region.

Table 6-6: Annual runoff metrics for the data sets.

Runoff (m/yr)	All lakes	DS1 (n=30)	DS2 (n=5)
mean	2.96	3.05	2.43
min	1.99	2.02	1.99
max	6.37	6.37	3.12

SSWC Critical Loads (CLs) were compared with the Acid Sensitivity Class (ASC), estimated as area-weighted ASC value for each of the lakes' catchments. Figure 6-20 and Table 6-7 summarize these results. Higher classes of ASC have bedrock with a higher potential to neutralize acidity, so we would expect CL values to increase with ASC, and in general this appears to be the case for the maximum, median and mean CL (though sample sizes are very low for ASC 2 and 3). The 14 lakes in ASC 4 showed a large amount of variation in CL values, particularly compared to the 15 lakes in ASC 1 (Figure 6-20).

Table 6-7: Statistics of SSWC Critical Loads according to the lakes Acid Sensitivity Class (ASC).

ASC	SSWC Critical Load Statistics (meq/m ² /yr)					
	# Lakes	Min	Max	Median	Mean	SE
1	15	68.12	137.68	94.97	100.85	6.00
2	3	119.98	176.55	121.00	139.18	18.69
3	3	24.73	448.67	201.86	225.09	122.93
4	14	28.39	802.15	191.16	279.04	60.92



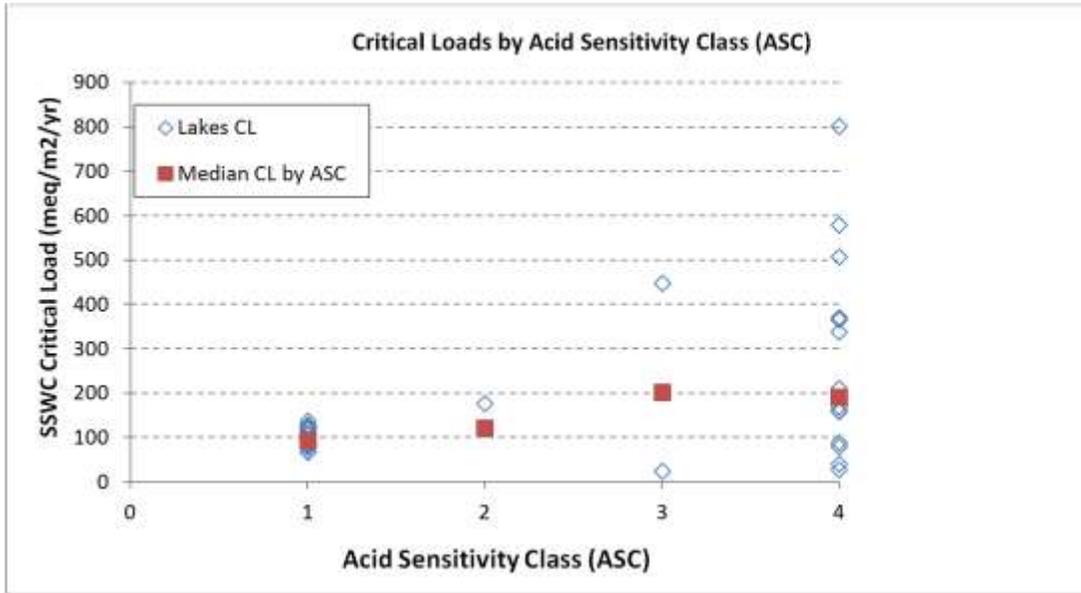


Figure 6-20: Distribution of Critical Loads (CLs) according to the Acid Sensitivity Class (ASC) of the lakes.

Weathering rates calculated from the SSWC model (estimated as original base cation concentrations (BC^*_0) times Runoff) tended to be greater than the weathering rates computed from the Skokloster approach used for the soils analysis in Section 5 (and listed in Appendix 3, Volume 2 of this report). This difference, shown in Figure 6-21, reflects the fact that the Skokloster approach was developed in areas of Scandinavia which have much lower levels of runoff than are observed in the PRAS study area. Runoff in the PRAS, as compared to levels in Scandinavia, will bring greater amounts of base cations into each lake.

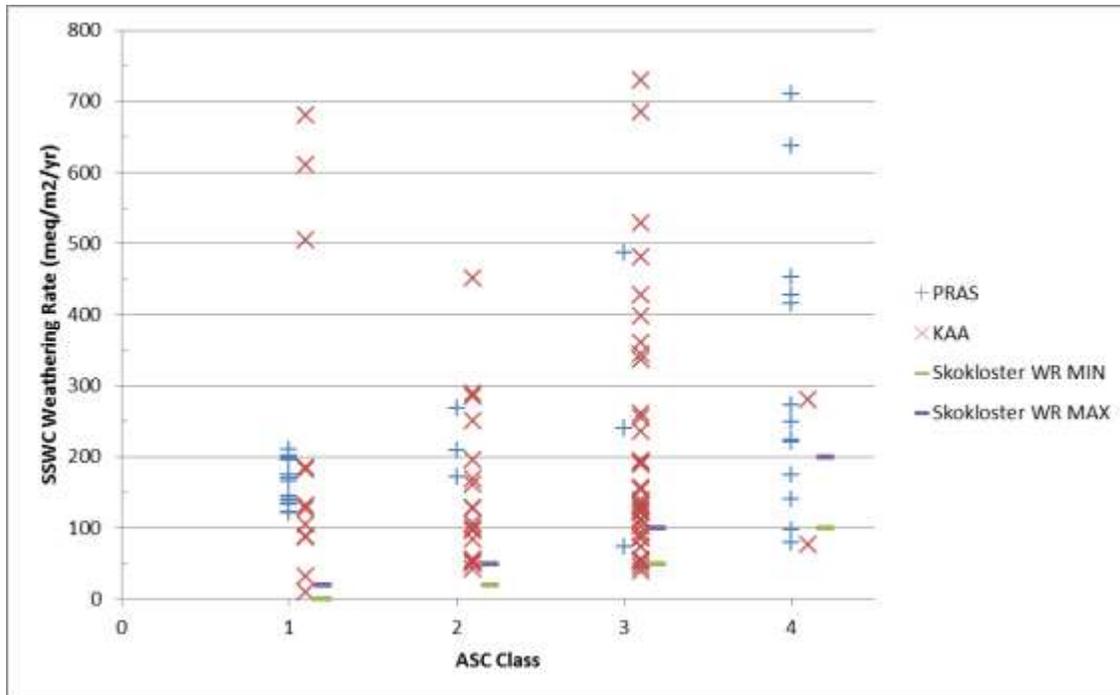


Figure 6-21: Comparison of weathering rates calculated from the SSWC model for both the PRAS and the KAA lake data sets, versus the range of weathering rates in the Skokloster model (as reported in Appendix 3 of Volume 2 of this report).

The spatial distribution of SSWC critical loads is shown in Figure 6-22. As discussed above, most lakes have a CL value greater than 100 meq/m²/yr and would have a very low sensitivity to acidification. No particular spatial pattern can be inferred from Figure 6-22; the lakes with the lowest critical loads (moderately sensitive, green triangles in Figure 6-22) are NC327 and NC338, located in the north and south of the study area, respectively. With the exception of lake NC309 (low sensitivity), most of the sampled lakes in the zone of higher SO₄ deposition have very low sensitivity (Figure 6-23). As discussed in Section 6.4, it is important to sample more lakes in the zone that is predicted to receive higher levels of deposition.

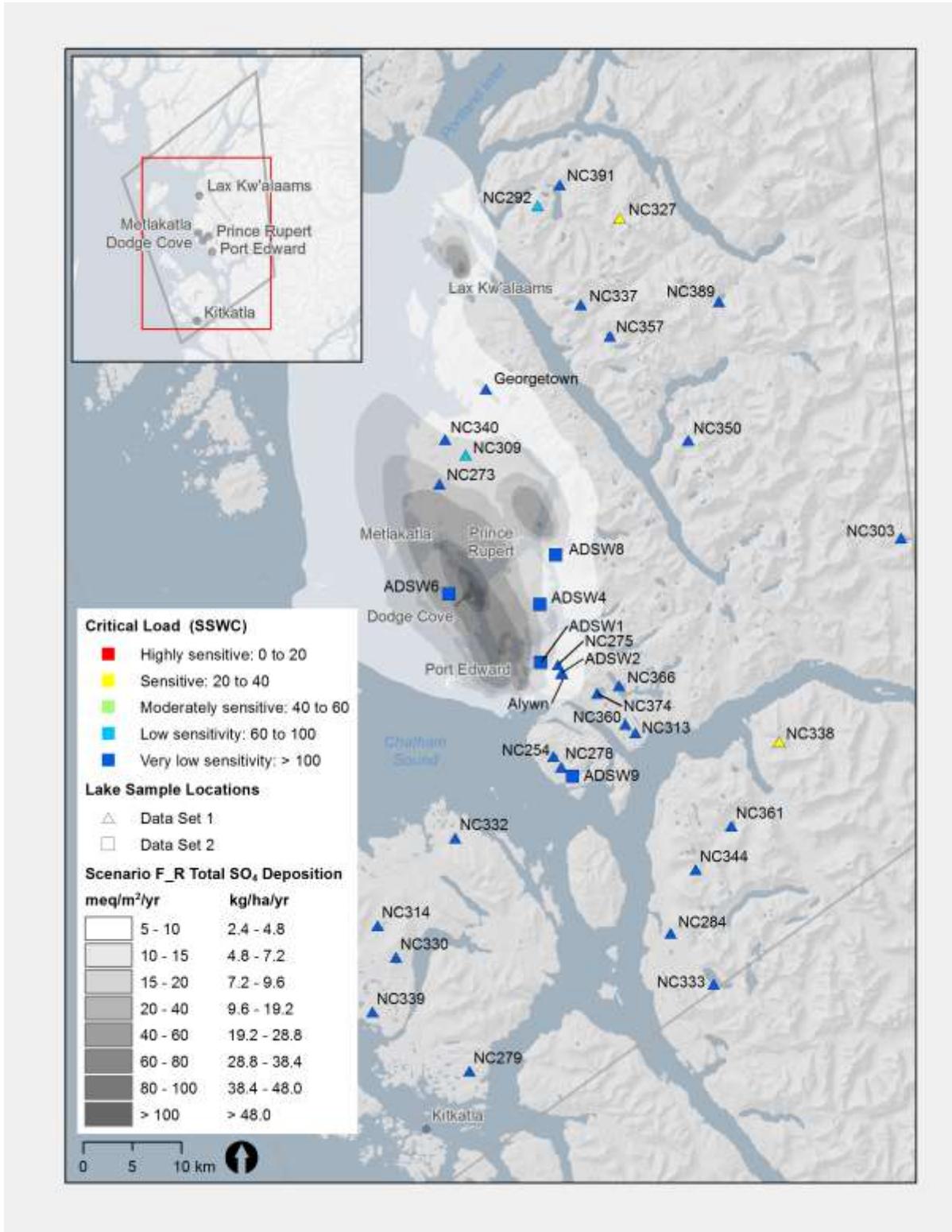


Figure 6-22: Critical loads (meq/m²/yr) acidity for the sampled lakes in the PRAS area as estimated with the SSWC model and overlapped with SO₄ deposition for Scenario F_R.



FAB Model

In the FAB model, the critical load of a sampled lake is not defined by a single value. Instead, critical loads are a function of both S and N deposition. The maximum critical loads for S and N estimated from the FAB model (illustrated in Figure 6-4), are shown in Figure 6-23. As with the SSWC model, none of the studied lakes showed critical load values lower than 0. Overall, the values of CLmax (N) were higher than the values of CLmax (S), as was the case in the KAA (see Figure 6-10 in the KAA, ESSA et al. 2014a). In other words, lakes in both the PRAS and KAA can withstand more N deposition than S deposition, due to the various mechanisms for neutralization of N deposition in watersheds (e.g., uptake of N by vegetation, removal of N by forestry and denitrification).

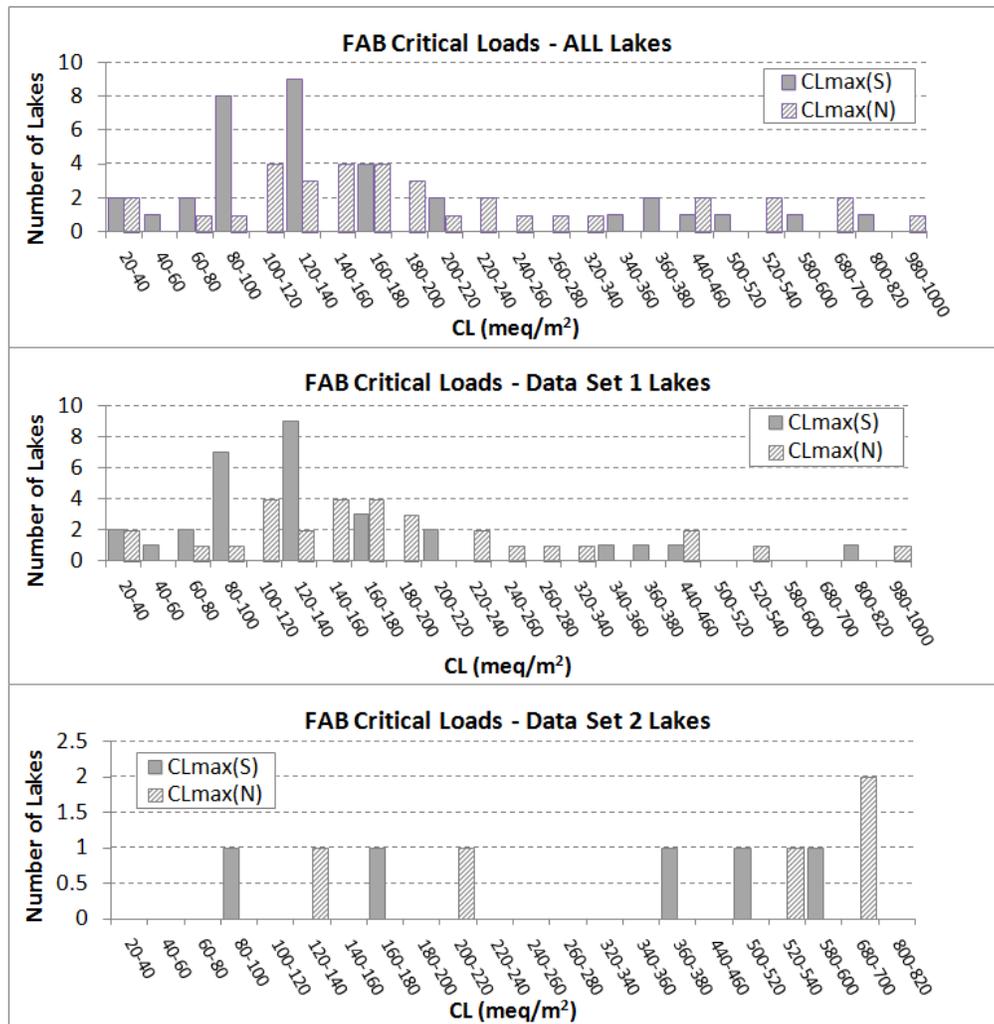


Figure 6-23: Frequency distribution of CLmax (S) and CLmax (N) for the sampled lakes in each of the data sets (upper panel = data set 1, middle panel = data set 2, lower panel = all the 35 sampled lakes), as derived from the FAB model.

Figure 6-24 shows the percentile distributions of the Critical Load Functions (CLFs) of the 35 sampled and analyzed lakes. The ratios of the N and S intercepts of Figure 6-24 illustrate that it



would take roughly 40 to 60% more N deposition to have the same acidification impact as SO₄ deposition.

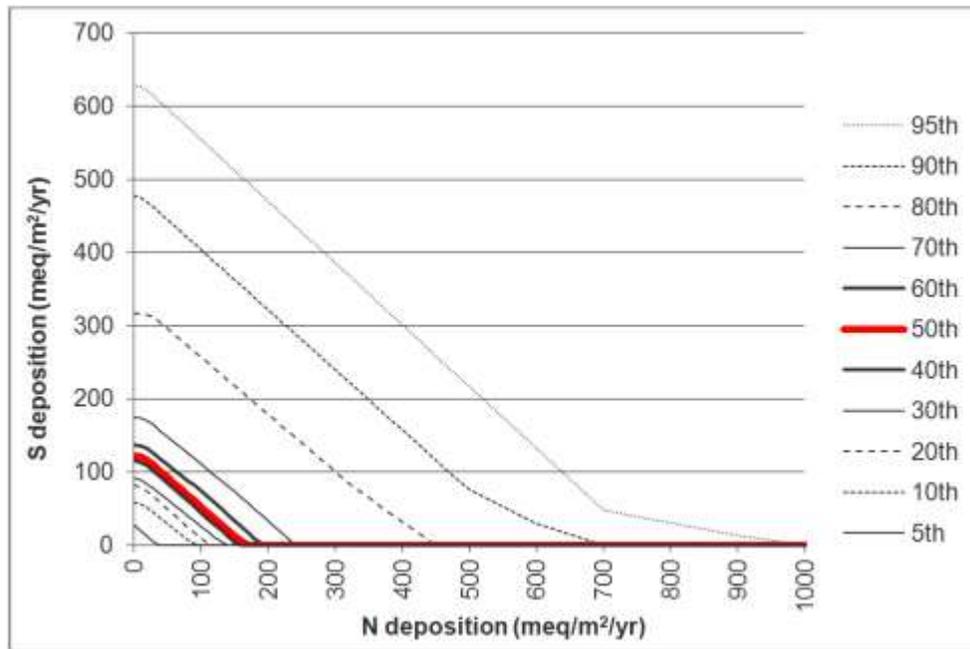


Figure 6-24: Percentile distributions of the Critical Loads Functions (CLFs) for all of the sampled lakes.

Figure 6-25 and Figure 6-26 represent the spatial distribution of $CL_{max}(S)$ and $CL_{max}(N)$, respectively, across the study area. As for the SSWC model discussed above, the distribution of the more sensitive lakes does not seem to follow a particular spatial pattern. The two most sensitive lakes with the lowest $CL_{max}(N)$ are the same two lakes discussed above for $CL_{max}(S)$: lake NC327 in the north, and lake NC338 in the south.



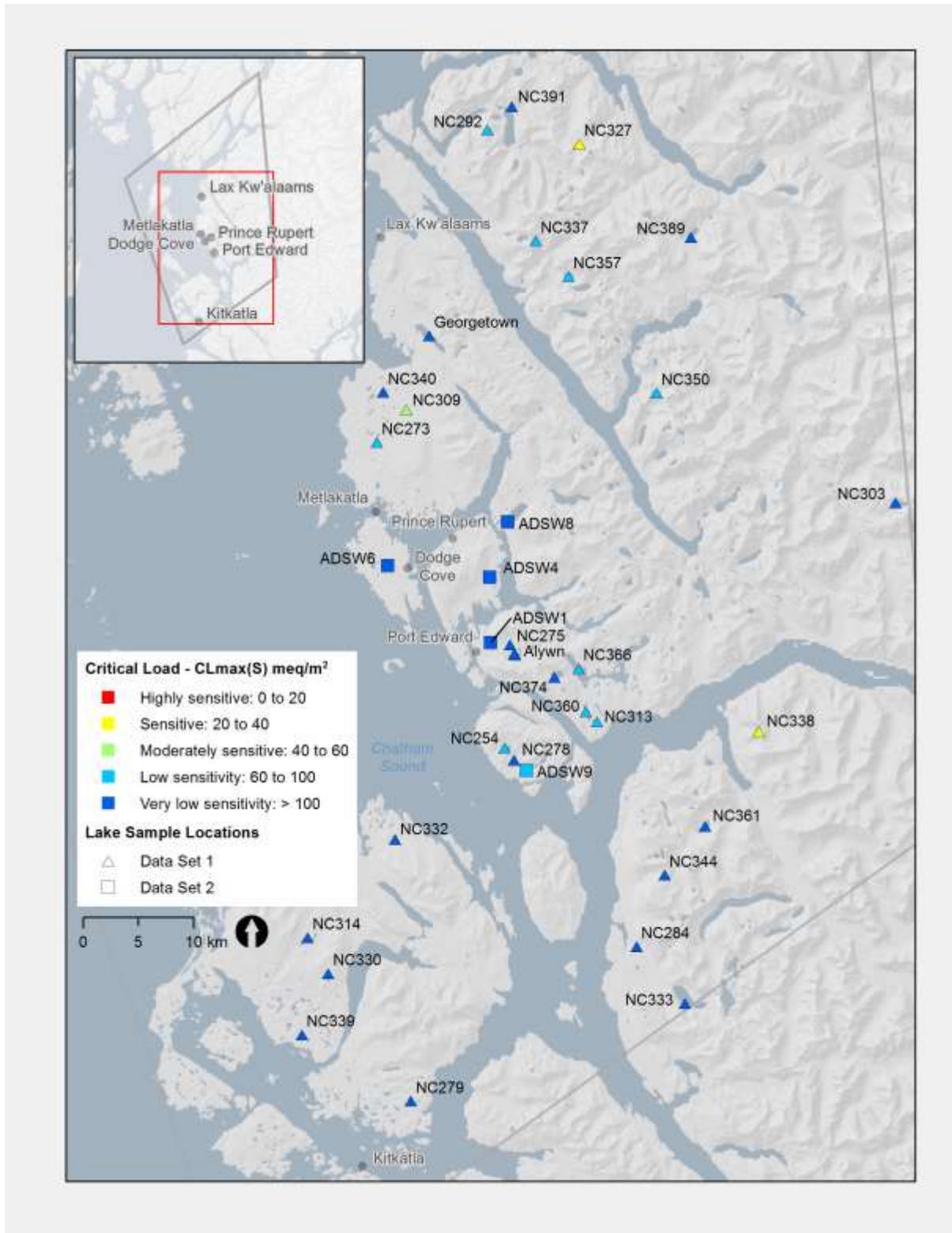


Figure 6-25: Spatial distribution of CL_{max}(S), in meq/m², as calculated by the FAB model, for the sampled lakes in the PRAS area.

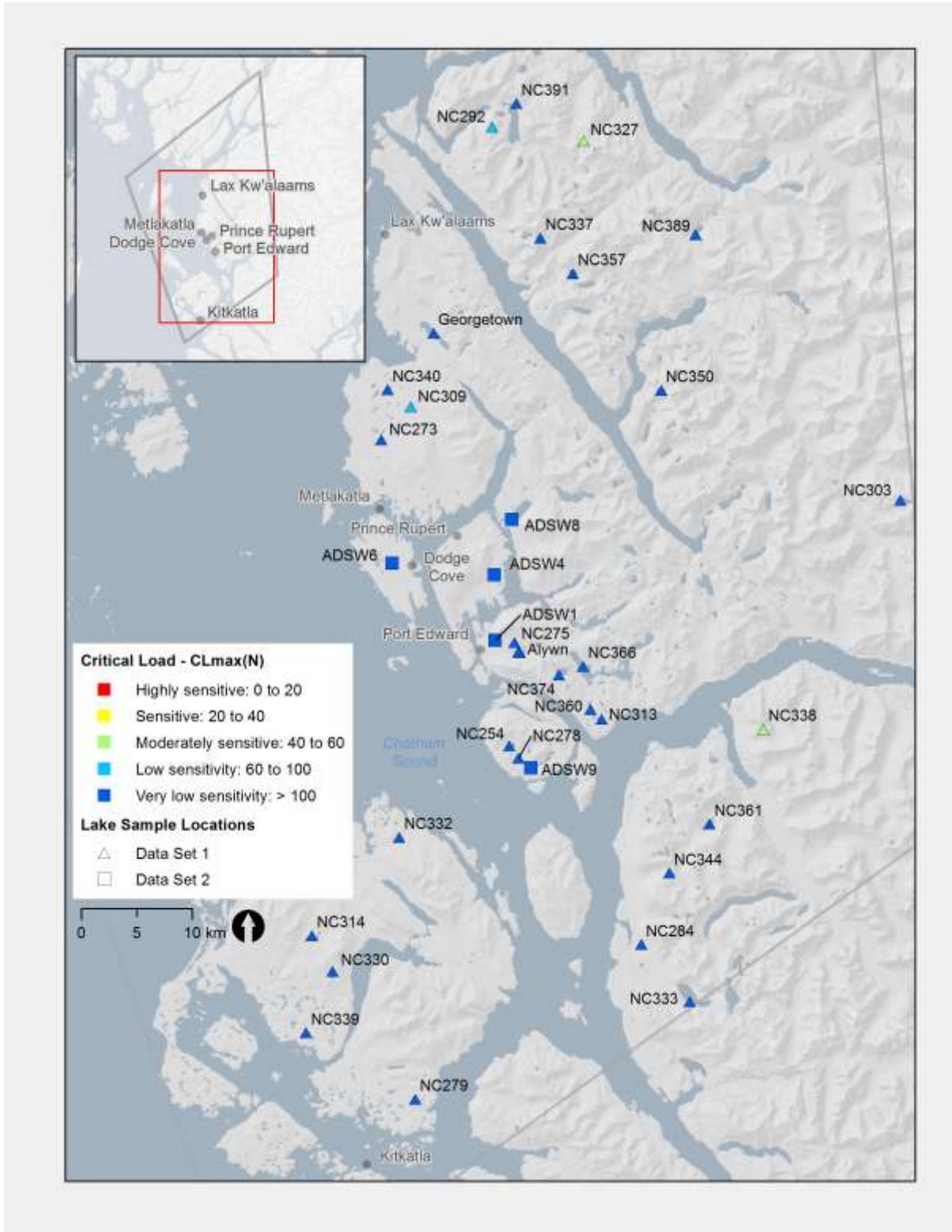


Figure 6-26: Spatial distribution of CL_{max}(N), in meq/m², as calculated by the FAB model, for the sampled lakes in the PRAS area.

6.2.3.2 Exceedances of Critical Loads and Predicted Changes in Lake pH

We calculated the level of exceedance (if any) of the critical loads of each lake under the six emission and deposition scenarios, applying both the SSWC and the FAB models. All the exceedance values were negative (i.e., deposition did not exceed the critical loads) and, therefore, no exceedance event is predicted under any of the scenarios. The following points summarize the main conclusions:

- Due to the way in which the lakes were selected (deliberately biased towards more sensitive bedrock geology, biased towards larger lakes), the 35 lakes used in these analyses cannot be considered statistically representative of the total PRAS area. There are gaps in the coverage of lakes in the northern part of the PRAS region, as well as on various islands, but most importantly in the effects domain where deposition is highest. Ideally these data gaps would be filled to provide a more representative sample from which to draw conclusions.
- No CL exceedance was predicted under any of the emission/deposition scenarios.
- As explained below, the predicted changes in lake pH under the highest emission scenario are all <0.3 pH units (and <0.10 pH units for 34 of the 35 analyzed lakes), and are therefore not considered significant from a biological perspective.
- We conducted a sensitivity analysis considering alternative values for critical ANC (see Appendix 4.4, Volume 2 of this report). SSWC and FAB models were run for $ANC_{limit} = 26 \text{ meq/m}^2/\text{yr}$ (critical ANC determined for the STAR and KAA) and for the lake-specific and DOC-dependent approach proposed in Jeffries et al. (2010). Although the alternative ANC values resulted in 2 to 5 exceedances of critical loads (depending on which model and limit was used), no biologically significant change in pH ($\Delta\text{pH} > 0.3$) was predicted under either of the two alternative assumptions for ANC_{limit} . Since the ANC_{limit} used in the current analysis was based on local data and reflects the wide contrast in DOC values across the region, we believe that it is the most scientifically defensible approach.

SSWC Model

We assessed the potential for sulphur exceedance across all emission and deposition scenarios using the critical loads derived from the SSWC model, and the sulphate deposition levels generated by CALPUFF (Figure 6-27). In all cases, the predicted exceedances were negative values (i.e., Deposition – Critical Load <0), indicating that SO_4 deposition is predicted to be lower than the critical loads in all 35 of the sampled and analyzed lakes (see Table 6-8). The frequency distributions of exceedances for the bookend scenarios, Scenarios A and F_R, were identical, reflecting the fact that there was very little difference in sulphate deposition between the two scenarios (see Figure 2-17 and Figure 2-18).



Table 6-8: Exceedances for the 35 analyzed lakes according to the SSWC model. Results are shaded according to exceedance class: yellow = -10 to 0 meq/L (near to CL), blue = -20 to -10 meq/L (below the CL), and green \leq -20 meq/L (well below the CL).

Lake ID (name)	Exceedances (meq/m ² /yr) across scenarios - SSWC model					
	A	F_R	C	B	D	E
Alywn	-193.66	-193.36	-196.16	-197.11	-196.84	-194.82
Georgetown	-354.41	-354.22	-357.29	-358.28	-357.90	-355.05
NC254	-63.90	-63.80	-64.86	-65.64	-65.61	-64.41
NC273	-60.36	-59.84	-71.39	-66.59	-65.60	-62.84
NC275	-782.17	-781.71	-785.83	-786.57	-786.03	-783.84
NC278	-106.00	-105.90	-106.85	-107.58	-107.52	-106.47
NC279	-116.37	-116.36	-116.45	-116.51	-116.50	-116.42
NC284	-325.51	-325.49	-325.59	-325.83	-325.80	-325.61
NC292	-53.77	-53.70	-54.71	-55.37	-54.73	-54.57
NC303	-141.12	-141.09	-141.42	-141.54	-141.49	-141.24
NC309	-18.31	-17.92	-25.28	-24.65	-23.90	-19.72
NC313	-71.58	-71.51	-71.87	-72.86	-72.71	-71.95
NC314	-107.85	-107.84	-107.94	-108.00	-107.98	-107.91
NC327	-14.32	-14.26	-14.95	-15.26	-15.00	-14.68
NC330	-106.09	-106.08	-106.13	-106.22	-106.20	-106.14
NC332	-163.64	-163.62	-163.88	-163.97	-163.94	-163.76
NC333	-97.46	-97.45	-97.48	-97.67	-97.65	-97.53
NC337	-64.54	-64.46	-65.43	-65.91	-65.66	-64.95
NC338	-9.51	-9.48	-9.75	-10.04	-9.96	-9.68
NC339	-125.71	-125.70	-125.80	-125.83	-125.81	-125.75
NC340	-148.02	-147.64	-154.83	-153.28	-152.56	-149.53
NC344	-110.01	-109.99	-110.07	-110.35	-110.32	-110.11
NC350	-81.26	-81.21	-82.09	-82.27	-82.14	-81.55
NC357	-69.63	-69.56	-70.38	-70.76	-70.57	-69.95
NC360	-55.11	-55.02	-55.58	-56.56	-56.41	-55.53
NC361	-111.28	-111.26	-111.34	-111.61	-111.58	-111.38
NC366 (Diana)	-74.96	-74.87	-75.54	-76.18	-76.11	-75.29
NC374	-186.45	-186.27	-187.68	-188.80	-188.67	-187.12
NC389	-427.28	-427.24	-427.78	-427.93	-427.82	-427.49
NC391	-106.07	-106.01	-106.87	-107.32	-106.95	-106.57
AD-SW1 (Wolfe)	-480.30	-478.86	-488.92	-488.86	-486.94	-484.43
AD-SW4 (Oliver)	-551.17	-550.47	-557.70	-557.78	-555.80	-554.05
AD-SW6	-316.82	-315.78	-340.25	-328.07	-327.23	-329.95
AD-SW8 (Shawatlan)	-135.92	-135.73	-138.28	-139.20	-138.82	-136.61
AD-SW9	-54.60	-54.53	-55.21	-55.77	-55.69	-54.97



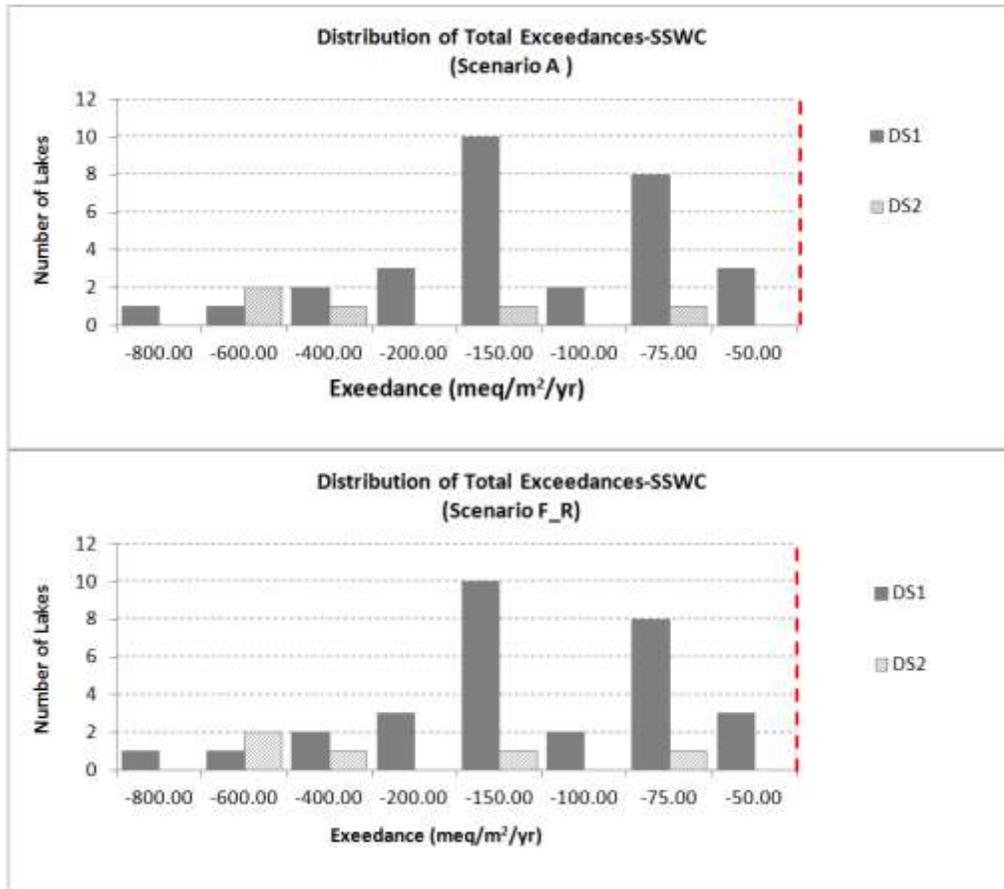


Figure 6-27: Frequency distribution of critical load exceedances (acidic deposition minus critical load) for the 35 sampled lakes, for emission scenarios A (upper panel) and F_R (lower panel). A negative value indicates that acidic deposition is less than the critical load. The label below each interval is the lower bound (i.e., minimum value) for that exceedance category. Y-axis values indicate number of lakes in each category. Red dashed line indicates exceedance value equal to zero.

FAB Model

All exceedance values for the FAB model were negative. Table 6-9 shows the results obtained for the six emission/deposition scenarios. Only three lakes receive deposition within 20 meq/m²/yr of their CL under any of the emission scenarios (i.e., exceedance >-20 meq/m²/yr): lakes NC309, NC327, and NC338.



Table 6-9: Exceedances for the 35 analyzed lakes according to the FAB model. Results are shaded according to exceedance class: yellow = -10 to 0 meq/m²/yr (near to CL), blue = -20 to -10 meq/ m²/yr (below the CL), and green ≤-20 meq/m²/yr (well below the CL).

Lake ID (name)	Exceedances across scenarios (meq/m ² /yr) - FAB model					
	A	F_R	C	B	E	D
Alywn	-211.32	-204.09	-216.94	-216.87	-217.39	-210.19
Georgetown	-387.54	-383.13	-392.21	-396.06	-394.05	-387.45
NC254	-76.11	-70.11	-79.15	-77.74	-79.83	-73.02
NC273	-68.64	-65.20	-81.31	-80.27	-78.74	-72.42
NC275	-853.04	-844.83	-859.71	-860.31	-860.21	-852.71
NC278	-119.83	-114.45	-122.82	-121.58	-123.31	-117.28
NC279	-148.42	-148.11	-148.67	-148.65	-148.62	-148.42
NC284	-381.15	-379.94	-381.91	-381.66	-381.85	-380.76
NC292	-62.16	-57.20	-64.34	-66.00	-60.78	-63.60
NC303	-157.74	-156.99	-158.41	-158.59	-158.42	-157.71
NC309	-19.80	-16.51	-28.04	-31.97	-30.63	-21.37
NC313	-89.89	-87.58	-92.96	-92.09	-92.31	-89.38
NC314	-130.01	-129.63	-130.35	-130.32	-130.28	-130.04
NC327	-11.45	-9.13	-12.82	-13.59	-11.80	-11.80
NC330	-131.33	-130.87	-131.64	-131.55	-131.51	-131.30
NC332	-196.93	-196.26	-197.58	-197.52	-197.53	-197.01
NC333	-118.85	-117.92	-119.36	-119.16	-119.23	-118.55
NC337	-72.29	-69.30	-74.30	-75.40	-73.53	-72.45
NC338	-11.64	-10.34	-12.66	-12.63	-12.53	-11.39
NC339	-147.72	-147.43	-147.96	-147.95	-147.90	-147.73
NC340	-168.04	-165.03	-175.66	-178.26	-177.04	-170.09
NC344	-128.21	-126.66	-129.00	-128.67	-128.84	-127.63
NC350	-85.75	-83.84	-87.44	-87.98	-87.28	-85.72
NC357	-77.08	-74.55	-78.91	-79.70	-78.43	-77.05
NC360	-67.39	-64.38	-70.77	-69.98	-70.34	-66.61
NC361	-122.78	-121.20	-123.60	-123.24	-123.38	-122.20
NC366 (Diana)	-90.62	-87.92	-93.13	-93.01	-93.14	-90.05
NC374	-223.46	-218.08	-227.59	-227.34	-228.02	-221.93
NC389	-470.80	-469.44	-471.85	-472.23	-471.55	-470.88
NC391	-118.30	-114.86	-120.07	-121.22	-118.17	-118.98
AD-SW1 (Wolfe)	-544.45	-534.49	-552.56	-557.91	-555.91	-547.39
AD-SW4 (Oliver)	-595.32	-588.06	-604.14	-607.46	-604.70	-597.67
AD-SW6	-343.96	-337.59	-368.84	-363.90	-363.59	-367.41
AD-SW8 (Shawatlan)	-162.46	-158.18	-167.29	-169.85	-169.02	-161.74
AD-SW9	-82.05	-78.88	-84.34	-83.65	-84.64	-80.81

Figure 6-28 and Figure 6-29 show that the frequency distributions of total exceedance are very similar for the two bookend scenarios, with slightly higher exceedances under Scenario F_R.



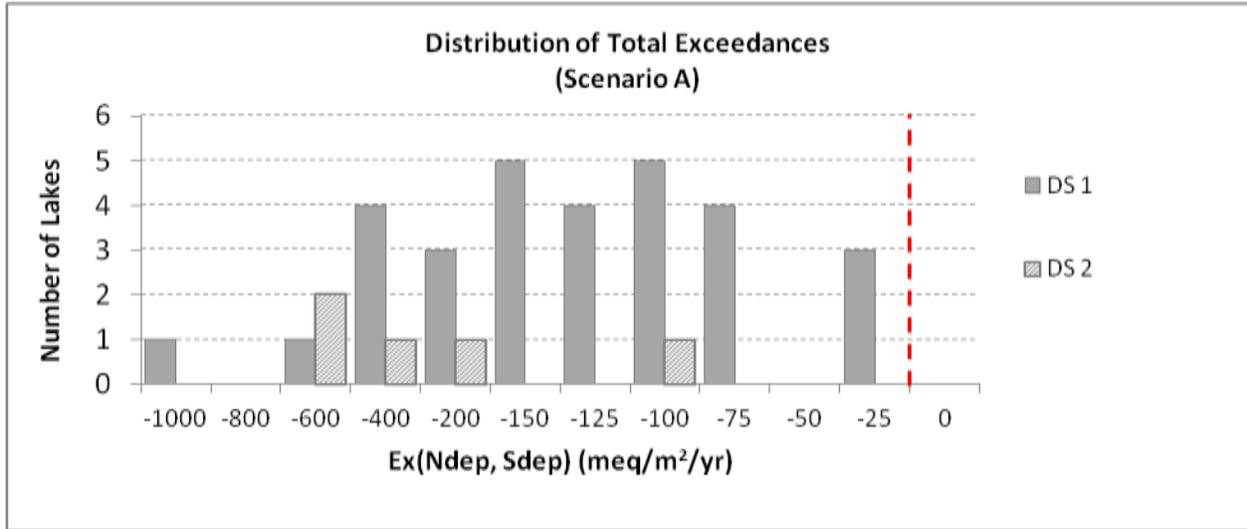


Figure 6-28: Distribution of total exceedances (meq/m²/yr) for Scenario A using the FAB model. The light bars represent the lakes in data set 2 (DS2) and the dark bars represent the lakes in data set 1 (DS1).

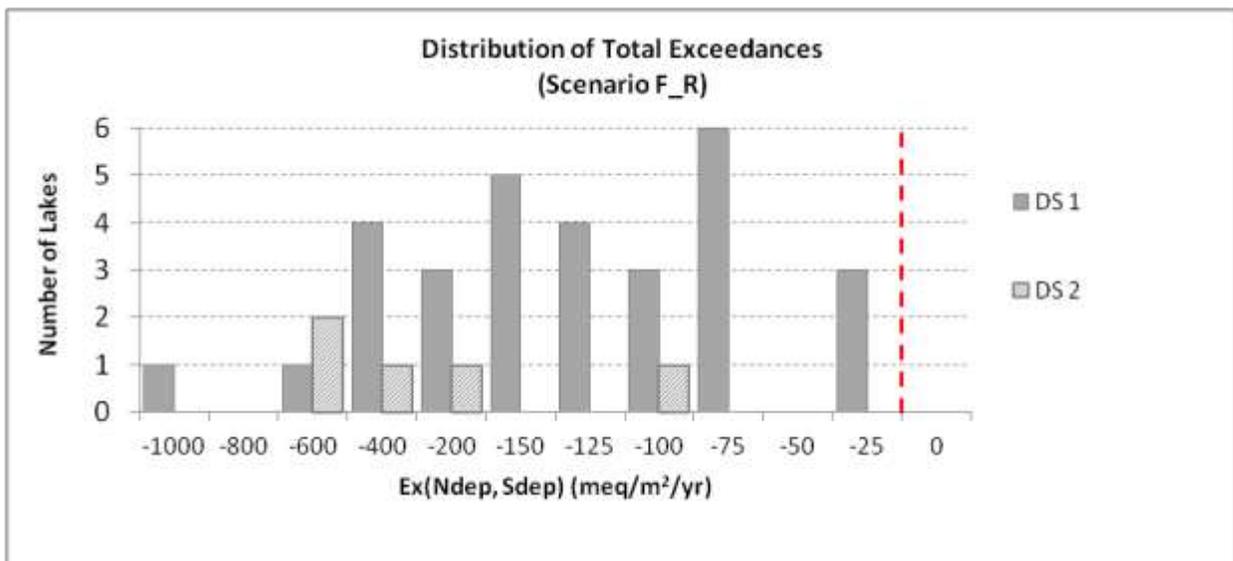


Figure 6-29: Distribution of total exceedances (meq/m²/yr) for Scenario F_R, using the FAB model. The light bars represent the lakes in data set 2 (DS2) and the dark bars represent the lakes in data set 1 (DS1).

The spatial distribution of the exceedance values for Scenario F_R is shown in Figure 6-30 and Figure 6-31, overlapped with S and N deposition values, respectively. Both figures show how most lakes close to the emission sources show deposition values well below the critical load (i.e., exceedance <-20 meq/m²/yr).



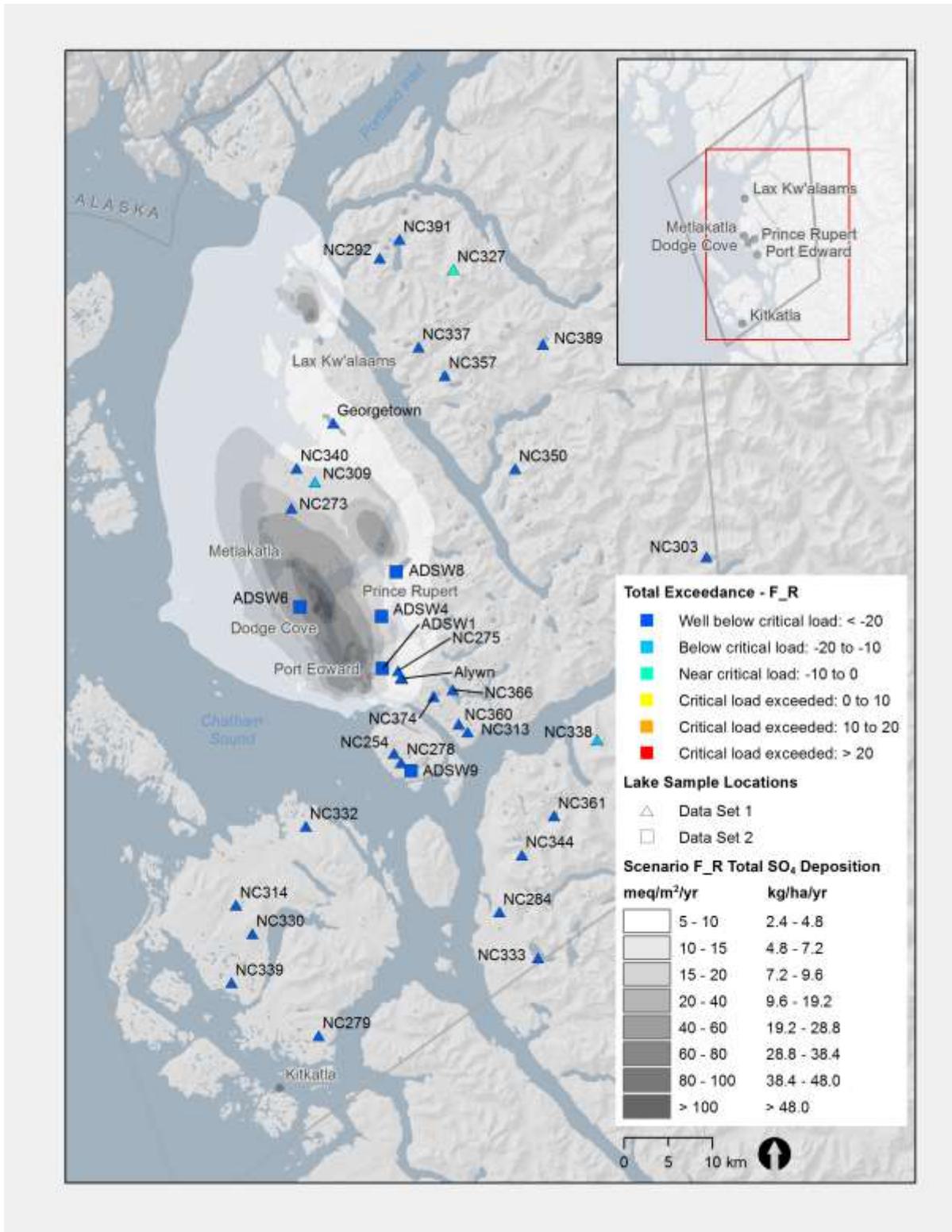


Figure 6-30: Spatial distribution of the total exceedance (meq/m²/yr) for sampled lakes under Scenario F_R, with SO₄ deposition.



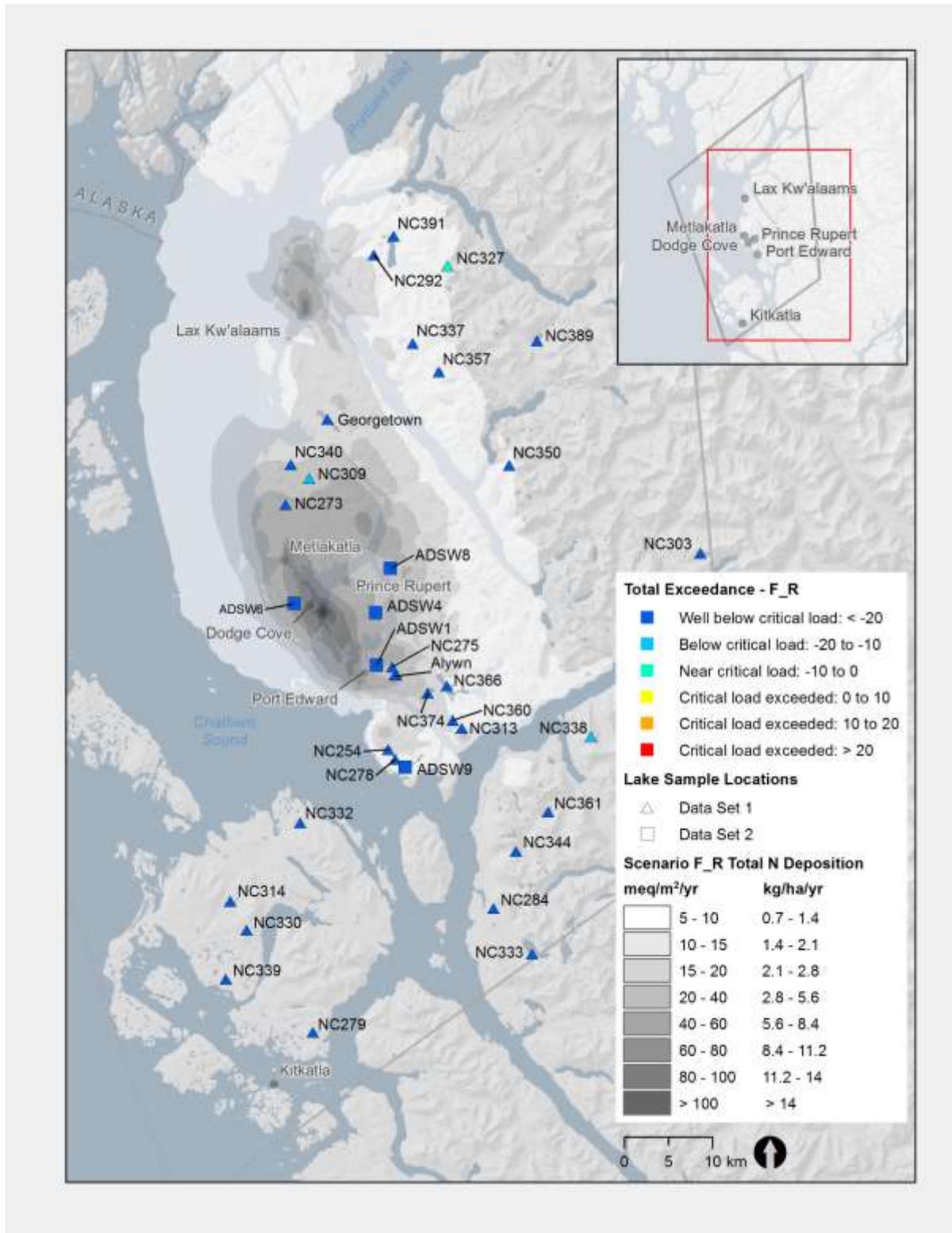


Figure 6-31: Spatial distribution of the total exceedance (meq/m²/yr) for sampled lakes under Scenario F_R, with N deposition.



Changes in pH

Changes in the pH of the lakes under the deposition scenarios were estimated using the modified ESSA-DFO model, which considers the incremental SO₄ and N deposition under each emission scenario (incremental relative to background deposition that contributed to the existing ANC and pH). None of the lakes show more than a 0.3 unit decline in pH under the highest emission scenario, a threshold beyond which significant biological effects are to be expected. Table 6-10 summarizes the results of the modified ESSA-DFO model for all the analyzed scenarios. The largest decrease in pH, ΔpH = -0.29, is expected for Lake EN309 under scenario F_R, and that pH decrease is associated with a predicted decline in ANC of 5.4 µeq/l (Table 6-10). Lake EN309 is about 13 km NW of Prince Rupert (Figure 6-1), and is a naturally acidic lake with a current ANC of -6.4 µeq/L and a current pH of 5.12, due to both chloride (43% of total anions) and organic anions (45% of total anions; Table 6-5). It is a relatively small lake (4.4 ha) compared to the overall set of sampled lakes (Figure 6-2), is located at 111 m of elevation, and its catchment area is 27 ha. Based on the gradients of streams downstream of Lake EN309, it should be accessible to fish, though there is no documented field information confirming the presence of any fish species in this lake in the BC Watershed Atlas. All other lakes are predicted to have less than a 0.1 unit decline in pH; the lack of change between current pH and future steady state pH for most lakes is clear from Figure 6-32.

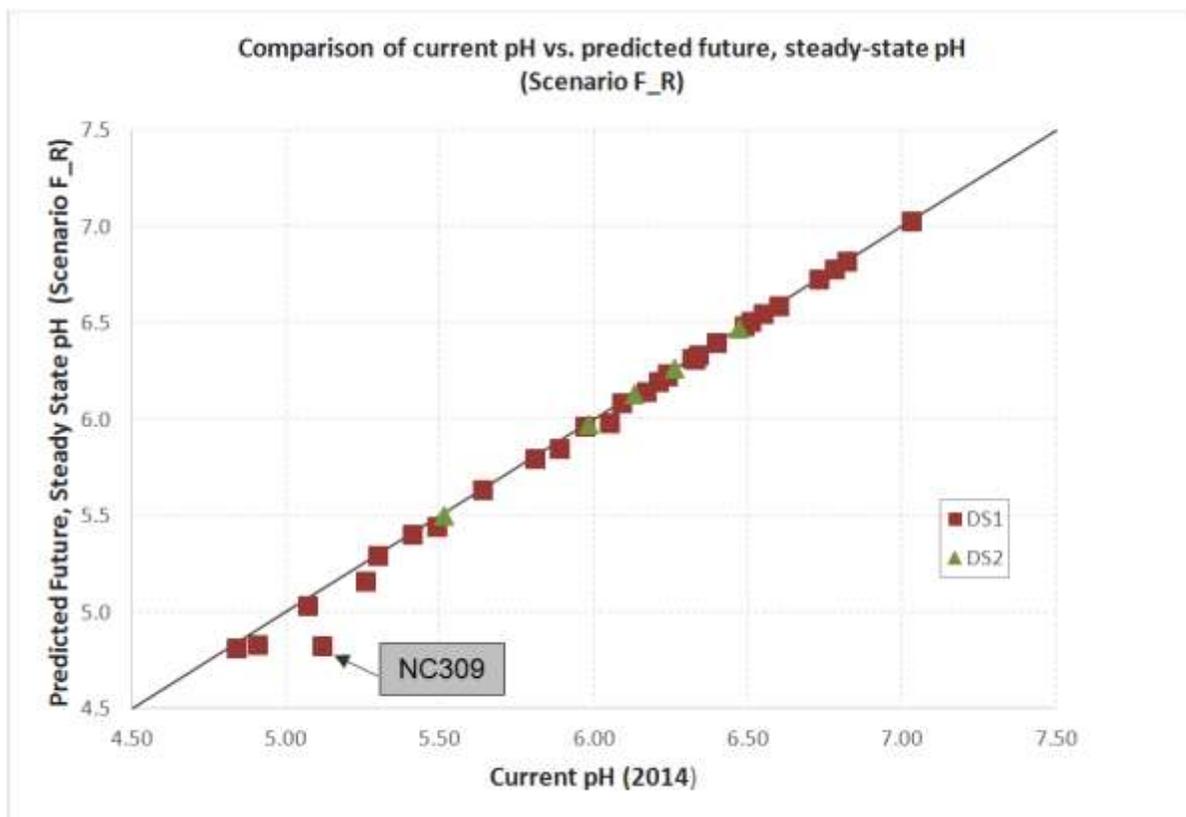


Figure 6-32: Comparison between current pH (as measured in the lab in 2014) and the future, steady state pH for Scenario F_R as calculated by the ESSA-DFO model.



Table 6-10: Changes in pH and ANC across scenarios according to the ESSA-DFO model. Green highlight indicates reductions in pH; yellow highlight indicates $\Delta\text{pH} < -0.1$; and red highlight indicates current pH < 6.0 . Cells with 0.00 indicate that there is no expected change in either pH or ANC due to an F-factor = 1.0.

Lake	Current pH _t	Changes in pH (ΔpH) and ANC (ΔANC) across scenarios – ESSA-DFO model											
		A		F_R		C		B		D		E	
		ΔpH	ΔANC	ΔpH	ΔANC	ΔpH	ΔANC	ΔpH	ΔANC	ΔpH	ΔANC	ΔpH	ΔANC
Alywn	6.32	-0.002	-0.22	-0.002	-0.23	-0.001	-0.13	-0.001	-0.09	-0.001	-0.10	-0.001	-0.18
Georgetown	6.78	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
NC254	5.26	-0.061	-1.16	-0.098	-1.84	-0.039	-0.75	-0.044	-0.85	-0.032	-0.61	-0.077	-1.47
NC273	6.05	-0.064	-3.99	-0.067	-4.18	-0.025	-1.64	-0.040	-2.55	-0.044	-2.77	-0.055	-3.44
NC275	7.03	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
NC278	5.07	-0.024	-0.46	-0.032	-0.62	-0.016	-0.30	-0.014	-0.27	-0.012	-0.23	-0.025	-0.49
NC279	5.30	-0.002	-0.03	-0.002	-0.03	-0.001	-0.02	-0.001	-0.01	-0.001	-0.02	-0.001	-0.03
NC284	6.55	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
NC292	6.17	-0.015	-0.87	-0.027	-1.54	-0.010	-0.56	-0.006	-0.32	-0.018	-1.03	-0.012	-0.66
NC303	6.51	0.000	-0.03	-0.001	-0.04	0.000	-0.02	0.000	-0.02	0.000	-0.02	0.000	-0.03
NC309	5.12	-0.258	-4.73	-0.292	-5.35	-0.155	-2.88	-0.117	-2.20	-0.133	-2.48	-0.239	-4.37
NC313	4.84	-0.020	-0.40	-0.021	-0.41	-0.018	-0.35	-0.009	-0.18	-0.010	-0.20	-0.017	-0.33
NC314	5.97	-0.001	-0.08	-0.002	-0.10	-0.001	-0.05	-0.001	-0.05	-0.001	-0.05	-0.001	-0.07
NC327	6.33	-0.012	-0.56	-0.019	-0.93	-0.007	-0.36	-0.005	-0.25	-0.011	-0.52	-0.011	-0.52
NC330	6.24	-0.001	-0.06	-0.001	-0.07	0.000	-0.04	0.000	-0.03	0.000	-0.04	-0.001	-0.05
NC332	5.64	-0.001	-0.03	-0.001	-0.03	0.000	-0.02	0.000	-0.02	0.000	-0.02	0.000	-0.03
NC333	6.40	-0.001	-0.06	-0.001	-0.09	-0.001	-0.04	-0.001	-0.04	-0.001	-0.04	-0.001	-0.06
NC337	6.60	-0.008	-0.71	-0.012	-1.08	-0.005	-0.45	-0.003	-0.31	-0.006	-0.54	-0.007	-0.68
NC338	5.89	-0.024	-0.47	-0.038	-0.73	-0.015	-0.29	-0.016	-0.31	-0.017	-0.32	-0.028	-0.53
NC339	5.41	-0.001	-0.04	-0.001	-0.04	-0.001	-0.02	-0.001	-0.02	-0.001	-0.02	-0.001	-0.03
NC340	5.81	-0.011	-0.79	-0.011	-0.82	-0.004	-0.29	-0.005	-0.40	-0.006	-0.46	-0.009	-0.68
NC344	6.34	-0.001	-0.06	-0.001	-0.09	-0.001	-0.05	-0.001	-0.04	-0.001	-0.04	-0.001	-0.07
NC350	6.21	-0.010	-0.47	-0.015	-0.65	-0.007	-0.30	-0.005	-0.24	-0.007	-0.31	-0.010	-0.47
NC357	6.24	-0.009	-0.55	-0.013	-0.82	-0.006	-0.35	-0.004	-0.26	-0.006	-0.39	-0.009	-0.55
NC360	4.91	-0.058	-1.11	-0.076	-1.45	-0.036	-0.70	-0.036	-0.70	-0.035	-0.68	-0.061	-1.16
NC361	6.09	-0.002	-0.10	-0.003	-0.17	-0.001	-0.06	-0.001	-0.07	-0.001	-0.07	-0.002	-0.12
NC366 (Diana)	5.49	-0.033	-0.64	-0.044	-0.85	-0.021	-0.41	-0.019	-0.37	-0.019	-0.36	-0.034	-0.66
NC374	6.73	-0.002	-0.27	-0.002	-0.28	-0.001	-0.18	-0.001	-0.11	-0.001	-0.12	-0.002	-0.22



Lake	Current pH _t	Changes in pH (Δ pH) and ANC (Δ ANC) across scenarios – ESSA-DFO model											
		A		F_R		C		B		D		E	
		Δ pH	Δ ANC	Δ pH	Δ ANC	Δ pH	Δ ANC	Δ pH	Δ ANC	Δ pH	Δ ANC	Δ pH	Δ ANC
NC389	6.82	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
NC391	6.49	-0.004	-0.36	-0.006	-0.57	-0.002	-0.23	-0.002	-0.14	-0.004	-0.34	-0.003	-0.30
AD-SW1 (Wolfe)	6.13	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
AD-SW4 (Oliver)	6.47	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
AD-SW6	6.26	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
AD-SW8 (Shawatlan)	5.98	-0.005	-0.37	-0.006	-0.39	-0.003	-0.20	-0.002	-0.13	-0.002	-0.16	-0.005	-0.32
AD-SW9	5.51	-0.008	-0.41	-0.009	-0.49	-0.005	-0.28	-0.004	-0.22	-0.004	-0.21	-0.007	-0.39



6.2.4 Analysis of Lake Eutrophication

As described in Section 6.1.3, we assessed the risk of eutrophication by comparing empirical thresholds for critical loads (CL) for nutrient-N with the expected deposition values for N (kg/ha/yr) under the different scenarios.

The 35 sampled lakes were classified as dystrophic or oligotrophic depending on their pH and the prevalence of their organic anions (i.e., lakes with a pH lower than 6.0 and with organic anions constituting more than 50% of their anion composition were considered dystrophic). Out of the 35 lakes, four lakes (11% of the analyzed lakes) were classified as dystrophic according to these criteria: NC278, NC313, NC360, and AD-SW9.

As described in Section 6.1, we compared N deposition under each of the emission scenarios (using both deposition at the lake’s centroid and average deposition over the watershed) to the following CL thresholds, based on the lower bound of the value ranges developed by de Wit and Lindholm (2010) for oligotrophic and dystrophic lakes:

- Oligotrophic lakes: lower bound = 5 kg N/ha/yr; mid-point = 7.5 N/ha/yr; and upper bound = 10 kg N/ha/yr
- Dystrophic lakes: lower bound = 3 kg N/ha/yr; mid-point = 4 N/ha/yr; and upper bound = 5 kg N/ha/yr

Out of the 35 sampled lakes, only one lake (AD-SW6, located on Digby Island) showed exceedance for Scenarios A, F_R, and C; those exceedances were 0.68 kg N/ha/yr, 1.57 kg N/ha/yr, and 0.90 kg N/ha/yr, respectively, and in all cases for its lower bound CL threshold (i.e., 5 kg N/ha/yr since this lake was classified as oligotrophic). Table 6-11 summarizes the results obtained for the 35 analyzed lakes for their lower bound CL threshold, which represents the worst-case scenario and the only situation for which positive exceedances were predicted. The N deposition values indicated in Table 6-11 are those estimated for the centroid of the lakes. Area-weighted N deposition values were very similar and using them did not significantly change the eutrophication assessment (e.g., the average N deposition value for Scenario A is 0.92 kg N/ha/yr based on the lakes centroids and 0.93 kg N/ha/yr based on the area-weighted deposition; similarly, N deposition is 1.37 kg N/ha/yr and 1.43 kg N/ha/yr, respectively, for Scenario F_R).

Table 6-11: Selected results of the analysis of eutrophication risk for the 35 sampled lakes. Blue highlight indicates lakes that were classified as dystrophic. Occurrence of exceedance has been highlighted in red; negative exceedance values are highlighted in green. Results are provided for the LB = Lower bound nutrient-N critical load (i.e., 3 N kg/ha/yr for dystrophic and 5 N kg/ha/yr for oligotrophic lakes).

Lake	pH	Organic anions (%)	Exceedance of nutrient-N CLs (kg N/ha/yr)					
			A	F_R	C	B	D	E
Alywn	6.32	31%	-3.63	-2.71	-3.47	-3.89	-3.96	-3.42
Georgetown	6.78	20%	-3.78	-3.32	-3.69	-4.50	-4.33	-3.75
NC254	5.26	46%	-4.21	-3.44	-4.09	-4.27	-4.54	-3.77



Lake	pH	Organic anions (%)	Exceedance of nutrient-N CLs (kg N/ha/yr)					
			A	F_R	C	B	D	E
NC273	6.05	36%	-2.28	-1.74	-2.15	-3.13	-3.06	-2.47
NC275	7.03	24%	-3.48	-2.50	-3.29	-3.78	-3.81	-3.33
NC278	5.07	54%	-2.36	-1.87	-2.28	-2.44	-2.63	-2.12
NC279	5.30	46%	-4.93	-4.88	-4.92	-4.95	-4.94	-4.92
NC284	6.55	29%	-4.81	-4.66	-4.79	-4.84	-4.87	-4.75
NC292	6.17	33%	-4.44	-3.67	-4.34	-4.76	-4.06	-4.53
NC303	6.51	7%	-4.83	-4.72	-4.81	-4.89	-4.87	-4.80
NC309	5.12	45%	-3.12	-2.59	-3.01	-4.02	-3.93	-3.11
NC313	4.84	58%	-2.15	-1.72	-2.08	-2.28	-2.35	-1.97
NC314	5.97	40%	-4.92	-4.86	-4.91	-4.94	-4.93	-4.91
NC327	6.33	10%	-4.66	-4.31	-4.61	-4.83	-4.59	-4.65
NC330	6.24	33%	-4.92	-4.85	-4.91	-4.93	-4.93	-4.90
NC332	5.64	50%	-4.85	-4.77	-4.84	-4.89	-4.89	-4.85
NC333	6.40	17%	-4.86	-4.73	-4.84	-4.88	-4.90	-4.81
NC337	6.60	13%	-4.48	-4.01	-4.41	-4.74	-4.48	-4.43
NC338	5.89	22%	-4.70	-4.46	-4.66	-4.77	-4.77	-4.61
NC339	5.41	48%	-4.94	-4.90	-4.93	-4.95	-4.95	-4.93
NC340	5.81	48%	-3.33	-2.89	-3.23	-4.03	-3.97	-3.36
NC344	6.34	30%	-4.79	-4.55	-4.75	-4.81	-4.84	-4.68
NC350	6.21	20%	-4.56	-4.26	-4.51	-4.75	-4.66	-4.50
NC357	6.24	23%	-4.52	-4.16	-4.47	-4.76	-4.58	-4.48
NC360	4.91	51%	-2.20	-1.75	-2.13	-2.35	-2.43	-2.02
NC361	6.09	35%	-4.77	-4.56	-4.73	-4.81	-4.83	-4.68
NC366 (Diana)	5.49	46%	-4.24	-3.76	-4.17	-4.41	-4.48	-4.06
NC374	6.73	18%	-3.93	-3.09	-3.80	-4.15	-4.28	-3.57
NC389	6.82	4%	-4.73	-4.55	-4.70	-4.85	-4.77	-4.72
NC391	6.49	21%	-4.54	-4.06	-4.49	-4.81	-4.36	-4.62
AD-SW1 (Wolfe)	6.13	44%	-2.86	-1.46	-2.53	-3.46	-3.47	-2.58
AD-SW4 (Oliver)	6.47	39%	-2.95	-2.09	-2.75	-3.70	-3.59	-2.87
AD-SW6	6.26	40%	0.68	1.57	0.90	-0.55	-0.68	-0.87
AD-SW8 (Shawatlan)	5.98	38%	-3.24	-2.58	-3.13	-4.17	-4.16	-3.01
AD-SW9	5.51	56%	-2.48	-2.08	-2.42	-2.52	-2.68	-2.27

The analysis of the risk of eutrophication was extended to all the lakes in the PRAS area with a surface of more than 1 ha (i.e., 859 lakes in total). Since water chemistry data are not available for all these lakes, and their trophic status is therefore unknown, the N deposition values for these lakes (based on their centroids) were compared with two CL conservative thresholds: 3 kg N/ha/yr to assess potential damage to dystrophic lakes; and 5 kg N/ha/yr for oligotrophic lakes. As oligotrophic lakes are expected to be the predominant lake type in the study area, the



threshold of 5 kg N/ha/yr is likely to be more generally applicable. Figure 6-33 shows the frequency distribution of total N exceedances under all scenarios and Table 6-12 summarizes the results. Given that the percentage of dystrophic lakes in the sampled PRAS lakes was only 11% (i.e., 4 out of 35), we can infer that the true proportion of lakes in the PRAS study area with exceedance of eutrophication thresholds is likely less than 1.5%. The percentage of lakes in the effects domain (Figure 5-4) would obviously be much higher, but to be consistent with the risk categories developed in the KAA (which were based on all sampled lakes within the study area) we have provided percentages based on the complete sample of lakes.

The most likely consequence of exceeding nutrient-N Critical Loads will be a change in the composition of the algal and macrophyte communities, shifting towards species which thrive when phosphorus is the limiting nutrient, as the added nitrogen will make phosphorus more limiting (de Wit and Lindholm 2010; Bobbink et al. 2010; Bobbink and Hettelingh 2010). The responses that these changes in algal and macrophyte species composition may elicit from higher trophic levels such as zooplankton, benthos or fish, are not well understood and have not been quantified (de Wit and Lindholm 2010). Potential effects could include shifts in species abundance as habitat conditions change (e.g., as discussed in de Wit and Lindholm (2010), the growth of filamentous algae related to increased N deposition in oligotrophic streams could possibly imply a more extensive habitat for specific taxa, while at the same time reduce periphyton growth). The following evidence supports the contention that biological changes may occur in nutrient-poor, temperate, boreal and arctic lakes as N deposition increases (from the abstract of de Wit and Lindholm 2010):

- “Lake sediment studies show shifts in algal communities and increases in algal growth related to higher N concentrations.
- Regional surveys in boreal lakes show higher chlorophyll concentrations per unit P in areas with higher N deposition, indicative of higher primary production.
- Experimental nutrient additions in lakes (mesocosm studies and bioassays) support the finding of the regional surveys by showing that N limitation of algal growth is common, especially under conditions of low N availability.
- Increased N availability can stimulate productivity of sediment- and rock-dwelling algae (benthic algae) but here data are scarce.
- Water plant dynamics from oligotrophic lakes relate significant plant community shifts (loss of key species, dominance of new species) to increased ammonium deposition and increased availability of N species, but other factors (CO₂, liming) may also explain some of the observed changes.
- To what extent N enrichment in oligotrophic waters eventually may cascade up the food chain and affect biodiversity is hard to predict. This will depend on possible changing dominance of pelagic versus littoral productivity and whether habitats will be affected by changing growth of macrophytes and benthic algae.”



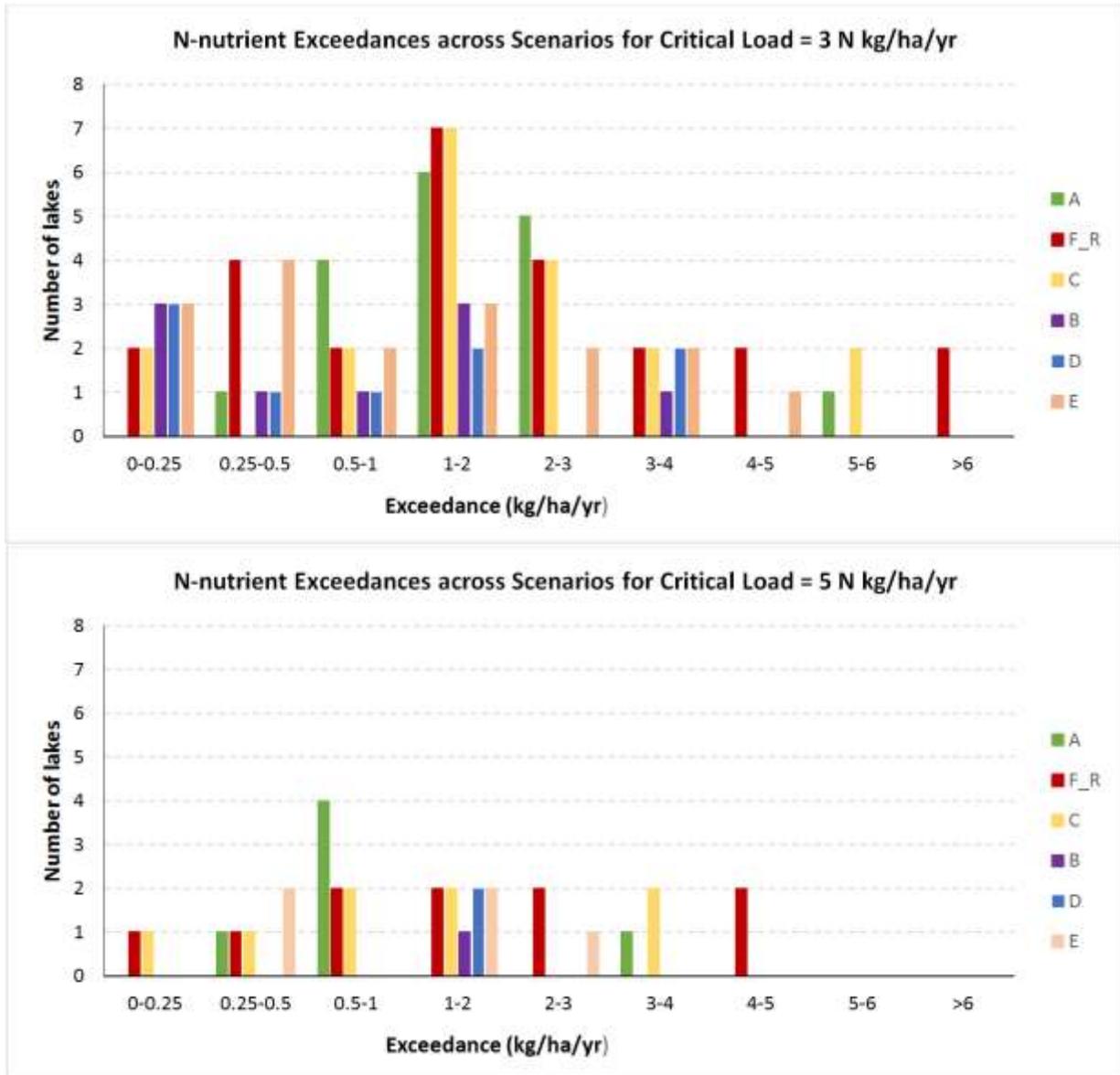


Figure 6-33: Frequency distribution of total exceedances of nutrient-N Critical Loads across scenarios for all of the 859 lakes in the PRAS area. Upper panel represents exceedances for a CL threshold of 3 N kg/ha/yr (applicable to dystrophic lakes) and lower panel shows exceedances for a CL threshold of 5 N kg/ha/yr (applicable to oligotrophic lakes)



Table 6-12: Exceedance results for nutrient-N Critical Loads for all lakes (with a surface area greater than 1 ha) in the PRAS area. Yellow highlight indicates a moderate level of risk (i.e., 0.1-2.5% of the total lakes show exceedance) and orange highlight indicates a high level of risk (i.e., 2.5 to 5% of lakes result in exceedance), according to the risk framework introduced in Section 6.1.3.

N-nutrient CL thresholds	Exceedance across scenarios					
	A	F_R	C	B	D	E
CL = 3 N kg/ha/yr						
# lakes with exceedance	17	25	19	9	9	17
%lakes	2%	3%	2%	1%	1%	2%
Median exc. (kg/ha/yr)	1.54	1.69	1.58	0.66	0.73	0.83
CL = 5 N kg/ha/yr						
# lakes with exceedance	6	10	8	1	2	5
%lakes	1%	1%	1%	0%	0%	1%
Median exc. (kg/ha/yr)	0.77	1.67	1.02	1.90	1.67	1.53

Figure 6-34 and Figure 6-35 show the spatial distribution of the lakes which potentially could exceed the critical load threshold, under Scenario F_R, for oligotrophic (CL = 5 kg N/ha/yr) and dystrophic (CL = 3 kg N/ha/yr) lakes, respectively, and be at risk of the eutrophication effects described above. Figure 6-35, which shows 25 lakes at risk, represents a worst-case estimate of the risk of eutrophication because dystrophic lakes have a lower threshold. Dystrophic lakes, however, are not expected to be the dominant type of lake in the study area.

This risk assessment is at a screening level and does not recognize the particular uses of each lake (e.g., whether any of the lakes predicted to exceed the nutrient nitrogen critical load are drinking water reservoirs, or are otherwise valued by people). Furthermore, the percentages shown in Table 6-13 have been calculated for the entire study area, of which only a small part is subject to N deposition; constraining the lakes only to the effects domain (as completed for soils) would yield higher percentages of lakes with exceedance of N critical loads. Our understanding of the trophic distribution of lakes in the Prince Rupert area is limited. Uncertainties regarding the sensitivity of surface waters to eutrophication will diminish as lake and stream sampling increases over time.



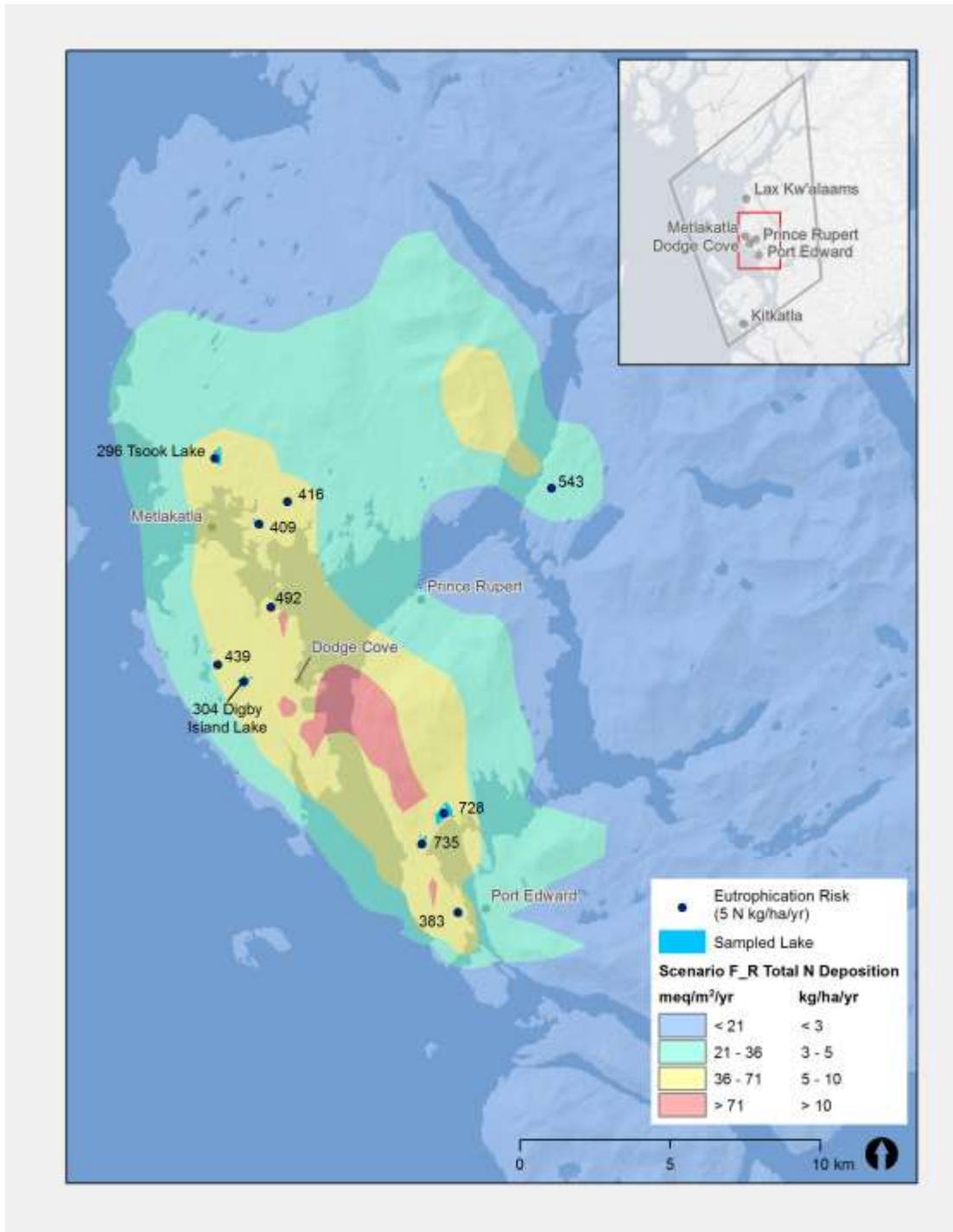


Figure 6-34: Spatial distribution of lakes potentially susceptible to eutrophication under Scenario F_R for a nutrient-N critical load of 5 N kg/ha/yr (i.e., threshold for oligotrophic lakes). Mapped deposition contours may not exactly match the predicted deposition at the centroid of a lake (i.e., one lake appears to be in the deposition zone of 3-5 kg/ha/yr, but actually has a deposition >5 kg/ha/yr). Numbers are labels for individual lakes.

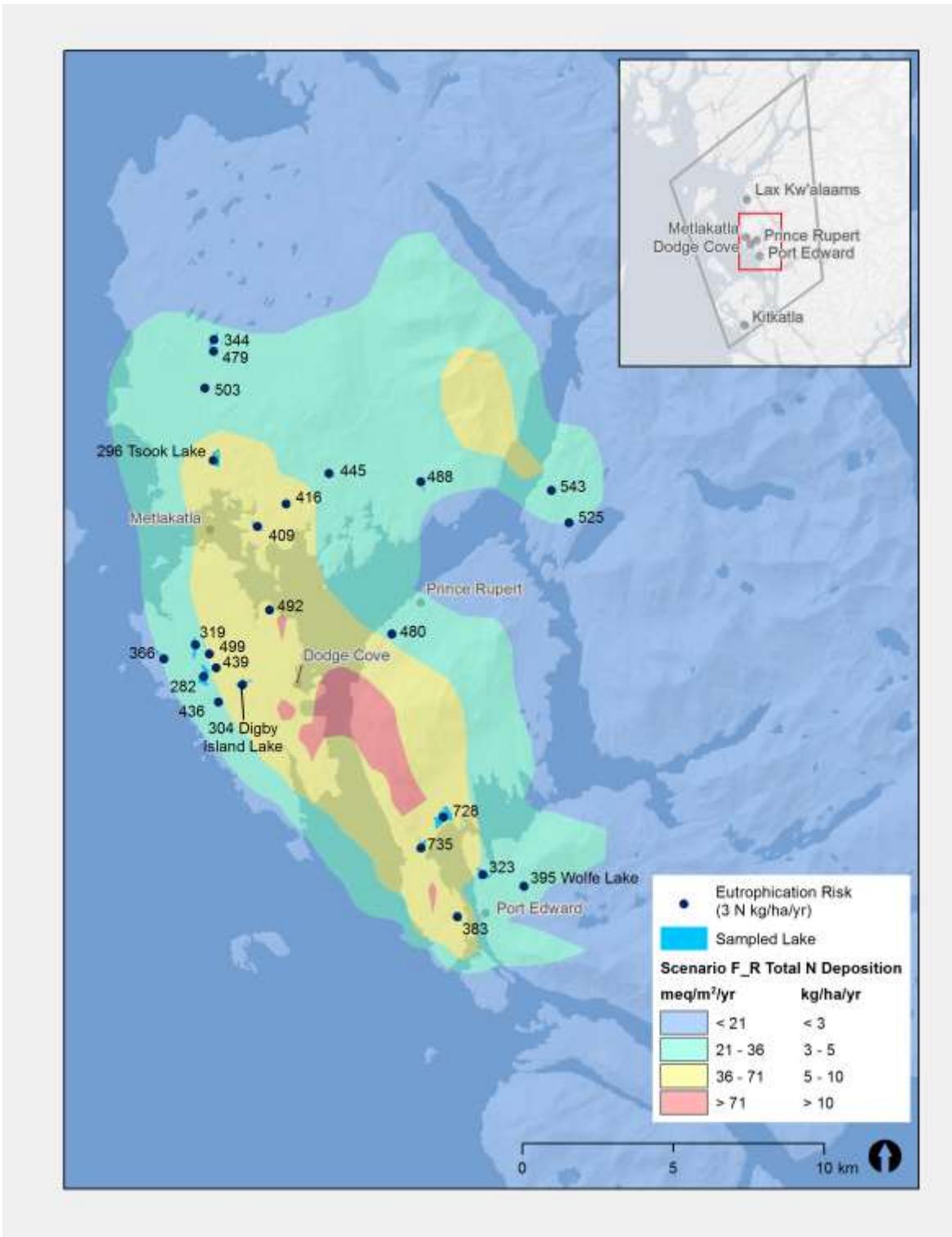


Figure 6-35: Spatial distribution of lakes potentially susceptible to eutrophication under Scenario F_R and for a nutrient-N critical load of 3 N kg/ha/yr (i.e., lower threshold, for dystrophic lakes). Numbers are labels for individual lakes.

6.2.5 Overall risk assessment

Considering that no CL exceedances have been predicted under SSWC or FAB, and the fact that estimated pH changes are all under the biologically significant threshold of $\Delta\text{pH} = -0.3$, the risk of acidification for the 35 sampled lakes is considered Low (i.e., none of the analyzed lakes shows a $\Delta\text{pH} \geq 0.3$). Table 6-13 summarizes the different factors of risk (i.e., exceedances of critical loads, changes in pH and risk of eutrophication) across scenarios.

To assess the risk of eutrophication for the lakes in the broader PRAS area, we applied an approach similar to the one used in the KAA for acidification risk. Under this framework, a CL exceedance within 1.3% to 3.6% of the studied lakes was considered a moderate risk. Using an overly precautionary assumption that all lakes were dystrophic within the zone receiving more than 3 kg/ha/yr of N, one would conclude that the risk of eutrophication was High for Scenario F_R and Moderate for all other scenarios (Table 6-12). If the proportion of dystrophic lakes in the overall PRAS study region was similar to that in the sampled lakes (11%), then that proportion would drop to about 1.3% to 1.5%, which still falls into the Moderate impact category. A more reasonable assumption is to apply the standard of 5 kg/ha/yr of N, applicable to oligotrophic lakes, which formed 89% of the sampled lakes. This assumption also leads to a conclusion of Moderate impacts.



Table 6-13: Exceedances, pH changes, eutrophication risk and overall risk category for the 35 sampled lakes across scenarios. See footnotes below for details.

LAKES	SITE ATTRIBUTES					ANION COMPOSITION					SSWC MODEL			FAB MODEL (EXCEEDANCES)					CHANGES IN pH				EUTROPHICATION RISK		RISK CATEGORY	
	Lake ID/name	Elevation m	Lake Area ha	Watershed Area ha	Acid Sensitivity Class (ASC)	Runoff m	HCO ₃ ⁻ %	Cl ⁻ %	SO ₄ ⁻² %	ORG %	F %	Critical Load meq/m ² /yr	BC ₅ weathering rate µeq/L	Exceedance (F_R) meq/m ² /yr	A meq/m ² /yr	F_R meq/m ² /yr	C meq/m ² /yr	B meq/m ² /yr	D meq/m ² /yr	E meq/m ² /yr	Estimated original pH pH ₀	Measured current pH pH _t	Predicted future steady-state pH (F_R) pH _e	ΔpH		A
Alywn	139	27.9	847	4	2.8	34%	24%	10%	31%	1%	211.8	97.2	-193.36	-211.32	-204.09	-216.94	-216.87	-217.39	-210.19	6.32	6.32	6.32	0.00	-3.64	-2.72	No/No
Georgetown	40	152.9	5591	4	2.7	43%	17%	18%	20%	1%	371.9	157.9	-354.22	-387.54	-383.13	-392.21	-396.06	-394.05	-387.45	6.78	6.78	6.78	0.00	-3.78	-3.33	No/No
NC254	294	26.7	270	1	2.3	5%	44%	6%	46%	0%	78.9	58.8	-63.80	-76.11	-70.11	-79.15	-77.74	-79.83	-73.02	5.38	5.26	5.16	-0.10	-4.21	-3.45	No/No
NC273	78	4.8	22	4	2.2	21%	38%	5%	36%	0%	88.8	63.6	-59.84	-68.64	-65.20	-81.31	-80.27	-78.74	-72.42	6.08	6.05	5.98	-0.07	-2.29	-1.75	No/No
NC275	153	5.4	161	4	2.7	75%	0%	0%	24%	0%	802.1	325.4	-781.71	-853.04	-844.83	-859.71	-860.31	-860.21	-852.71	7.03	7.03	7.03	0.00	-3.49	-2.51	No/No
NC278	174	7.2	517	2	2.3	4%	38%	4%	54%	0%	121.0	91.2	-105.90	-119.83	-114.45	-122.82	-121.58	-123.31	-117.28	5.13	5.07	5.04	-0.03	-2.37	-1.87	No/No
NC279	110	4.9	28	1	2.1	3%	45%	5%	46%	1%	128.3	94.5	-116.36	-148.42	-148.11	-148.67	-148.65	-148.62	-148.42	5.37	5.30	5.30	0.00	-4.93	-4.88	No/No
NC284	55	13.0	233	4	2.8	36%	24%	11%	29%	0%	339.5	146.8	-325.49	-381.15	-379.94	-381.91	-381.66	-381.85	-380.76	6.55	6.55	6.55	0.00	-4.82	-4.66	No/No
NC292	579	4.5	49	1	3.2	29%	32%	4%	33%	1%	68.1	38.1	-53.70	-62.16	-57.20	-64.34	-66.00	-60.78	-63.60	6.21	6.17	6.14	-0.03	-4.44	-3.67	No/No
NC303	997	55.3	249	4	6.4	54%	17%	20%	7%	0%	158.6	35.1	-141.09	-157.74	-156.99	-158.41	-158.59	-158.42	-157.71	6.52	6.51	6.51	0.00	-4.83	-4.72	No/No
NC309	114	4.4	27	4	2.4	5%	43%	5%	45%	1%	41.1	40.2	-17.92	-19.80	-16.51	-28.04	-31.97	-30.63	-21.37	5.27	5.12	4.83	-0.29	-3.13	-2.60	No/No
NC313	123	4.8	47	1	2.3	5%	33%	3%	58%	0%	86.0	72.6	-71.51	-89.89	-87.58	-92.96	-92.09	-92.31	-89.38	4.92	4.84	4.82	-0.02	-2.15	-1.73	No/No
NC314	151	6.6	160	1	2.2	19%	36%	4%	40%	0%	120.1	78.1	-107.84	-130.01	-129.63	-130.35	-130.32	-130.28	-130.04	6.00	5.97	5.97	0.00	-4.92	-4.86	No/No
NC327	728	8.8	235	4	4.6	29%	42%	17%	10%	1%	28.4	17.3	-14.26	-11.45	-9.13	-12.82	-13.59	-11.80	-11.80	6.37	6.33	6.31	-0.02	-4.66	-4.31	No/No
NC330	314	18.1	174	1	2.2	26%	36%	5%	33%	0%	117.9	75.4	-106.08	-131.33	-130.87	-131.64	-131.55	-131.51	-131.30	6.26	6.24	6.24	0.00	-4.92	-4.85	No/No
NC332	64	10.2	320	2	2.1	15%	28%	7%	50%	0%	176.6	125.0	-163.62	-196.93	-196.26	-197.58	-197.52	-197.53	-197.01	5.65	5.64	5.64	0.00	-4.85	-4.77	No/No
NC333	174	234.3	1584	1	4.1	29%	39%	13%	17%	1%	109.9	40.4	-97.45	-118.85	-117.92	-119.36	-119.16	-119.23	-118.55	6.41	6.40	6.40	0.00	-4.86	-4.73	No/No
NC337	717	9.8	67	1	3.5	48%	31%	7%	13%	0%	80.4	34.6	-64.46	-72.29	-69.30	-74.30	-75.40	-73.53	-72.45	6.62	6.60	6.59	-0.01	-4.48	-4.01	No/No
NC338	752	11.9	59	3	4.0	9%	52%	16%	22%	1%	24.7	18.4	-9.48	-11.64	-10.34	-12.66	-12.63	-12.53	-11.39	6.01	5.89	5.85	-0.04	-4.70	-4.46	No/No
NC339	47	4.4	118	1	2.0	8%	41%	3%	48%	0%	137.7	103.8	-125.70	-147.72	-147.43	-147.96	-147.95	-147.90	-147.73	5.45	5.41	5.41	0.00	-4.94	-4.90	No/No
NC340	33	10.5	150	4	2.1	20%	28%	5%	48%	0%	170.6	116.1	-147.64	-168.04	-165.03	-175.66	-178.26	-177.04	-170.09	5.82	5.81	5.80	-0.01	-3.33	-2.90	No/No
NC344	489	15.9	148	1	4.3	30%	34%	5%	30%	1%	123.0	45.7	-109.99	-128.21	-126.66	-129.00	-128.67	-128.84	-127.63	6.35	6.34	6.34	0.00	-4.79	-4.55	No/No
NC350	532	21.0	245	1	3.8	27%	30%	22%	20%	0%	95.0	37.5	-81.21	-85.75	-83.84	-87.44	-87.98	-87.28	-85.72	6.24	6.21	6.20	-0.01	-4.56	-4.27	No/No
NC357	139	27.5	1145	1	3.6	32%	28%	14%	23%	1%	83.5	37.1	-69.56	-77.08	-74.55	-78.91	-79.70	-78.43	-77.05	6.27	6.24	6.23	-0.01	-4.52	-4.16	No/No
NC360	121	32.1	334	1	2.4	5%	38%	4%	51%	2%	69.5	56.4	-55.02	-67.39	-64.38	-70.77	-69.98	-70.34	-66.61	5.03	4.91	4.83	-0.08	-2.21	-1.75	No/No
NC361	529	37.2	3428	1	3.8	23%	33%	7%	35%	1%	125.1	52.6	-111.26	-122.78	-121.20	-123.60	-123.24	-123.38	-122.20	6.11	6.09	6.09	0.00	-4.77	-4.56	No/No
Diana	79	262.6	5152	1	2.7	6%	36%	10%	46%	1%	89.4	54.2	-74.87	-90.62	-87.92	-93.13	-93.01	-93.14	-90.05	5.58	5.49	5.45	-0.04	-4.24	-3.76	No/No
NC374	392	61.6	356	3	2.5	46%	24%	11%	18%	1%	201.9	94.3	-186.27	-223.46	-218.08	-227.59	-227.34	-228.02	-221.93	6.73	6.73	6.73	0.00	-3.93	-3.10	No/No
NC389	257	56.8	1213	3	3.6	41%	13%	41%	4%	0%	448.7	135.5	-427.24	-470.80	-469.44	-471.85	-472.23	-471.55	-470.88	6.82	6.82	6.82	0.00	-4.73	-4.55	No/No
NC391	151	252.3	6020	2	3.6	39%	27%	12%	21%	0%	120.0	48.2	-106.01	-118.30	-114.86	-120.07	-121.22	-118.17	-118.98	6.50	6.49	6.48	-0.01	-4.54	-4.06	No/No
Wolfe		2.6	31	4	2.4	25%	29%	1%	44%	0%	507.4	267.0	-478.86	-544.45	-534.49	-552.56	-557.91	-555.91	-547.39	6.13	6.13	6.13	0.00	-2.87	-1.46	No/No
Oliver		2.3	74	4	2.4	34%	25%	1%	39%	0%	579.2	294.1	-550.47	-595.32	-588.06	-604.14	-607.46	-604.70	-597.67	6.47	6.47	6.47	0.00	-2.96	-2.10	No/No
AD-SW6		8.0	105	4	2.0	28%	29%	2%	40%	0%	365.6	227.6	-315.78	-343.96	-337.59	-368.84	-363.90	-363.59	-367.41	6.26	6.26	6.26	0.00	0.66	1.56	No/No
Shawatian		155.7	4732	4	3.1	29%	28%	4%	38%	0%	161.7	70.6	-135.73	-162.46	-158.18	-167.29	-169.85	-169.02	-161.74	5.99	5.98	5.97	-0.01	-3.24	-2.59	No/No
AD-SW9		47.4	580	4	2.2	13%	26%	2%	56%	0%	79.9	77.5	-54.53	-82.05	-78.88	-84.34	-83.65	-84.64	-80.81	5.54	5.51	5.50	-0.01	-2.48	-2.09	No/No



Footnotes:

1. Acid Sensitivity Class (ASC) is based on the bedrock geology. A lower ASC number means higher bedrock sensitivity to acidification. Refer to Section 6.2.3.1 for discussion on the relationship between ASC and critical loads.
2. Anion composition analyses – refer to Section 6.2.2.3 for results and discussion. The colored shading indicates if a lake/stream is “influenced” ($\geq 25\%$, lighter shading) or “dominated” ($\geq 50\%$, darker shading with bold font) by a particular anion. The color coding used for the different anion species is the following:
 - a. Grey: Bicarbonate (HCO_3^-)
 - b. Blue: Chloride (Cl^-)
 - c. Orange: Sulphate (SO_4^{2-})
 - d. Green: Organic anions
3. Critical load and exceedance analyses – refer to Section 6.1.3 for methods and Section 6.2.3 for results. The colored shading indicates the critical load class or exceedance class, using the following classification schemes.
For critical loads, the classes are:
 - Highly sensitive (0 to 20 meq/m²/yr; red)
 - Sensitive (20 to 40 meq/m²/yr; yellow)
 - Moderately sensitive (40 to 60 meq/m²/yr; green)
 - Low sensitivity 60 to 100 meq/m²/yr; blue)
 - Very low sensitivity (>100 meq/m²/yr; darker blue)For exceedances, the classes are:
 - Critical load exceeded (>20 meq/m²/yr; red)
 - Critical load exceeded (10 to 20 meq/m²/yr; purple)
 - Critical load exceeded (0 to 10 meq/m²/yr; orange)
 - Near critical load (-10 to 0 meq/m²/yr; yellow)
 - Below critical load (-20 to -10 meq/m²/yr; blue)
 - Well below critical load (<-20 meq/m²/yr; green)
4. Estimated original pH and predicted future pH are based on the modified ESSA-DFO model – refer to 6.1.2 for methods and Section 6.2.3 for results. Predicted changes in pH ($|\Delta\text{pH}|$) equal or higher than 0.1 are shaded in yellow.
5. Eutrophication risk – refer to Section 6.1.4 for methods and 6.2.4 for results- shows N-nutrient exceedance results for Scenarios A and F_R. Results are provided for the LB = Lower bound nutrient-N critical load (i.e., 3 N kg/ha/yr for dystrophic and 5 N kg/ha/yr for oligotrophic lakes)
6. Risk categories (column at farthest right) are based on the risk framework developed by MOE for KAA (Table 6-3).



6.3 Main Sources and Implications of Quantitative Scientific Uncertainty

Table 6-14 outlines some of the key assumptions in this assessment and whether they imply overestimating or underestimating the risk of lake acidification or eutrophication, or if they could bias the assessment in either direction (e.g., runoff, annual allowable cut assumptions).

Table 6-14: Key assumption in the PRAS assessment and their implications.

Model Assumptions Causing Overestimate of Risk to Lakes	Model Assumptions Causing Underestimate of Risks to Lakes
<p>The sample of PRAS lakes in DS1 (Environment Canada lakes) was deliberately biased towards lakes in more acid-sensitive geologies. Figure 6-20 shows that critical loads are indeed lowest in ASC 1 (acid sensitivity class 1).</p>	<p>The sample is biased towards larger lakes, as discussed in Section 6.1.1.1, and by missing smaller lakes will tend to exclude both the most acid-sensitive and least acid-sensitive lakes.</p> <p>Only about a third of the sampled lakes occurred within the part of the study area that is predicted to experience the highest levels of acidic deposition (Figure 6-30 and Figure 6-31).</p>
<p>The ESSA-DFO model assumes that there is no reduction in DOC with acidification. With the DOC-dependent titration curve used in the model (Equation 6.5), this may cause an underestimate of the future steady state pH (i.e., an overestimate of the amount of future acidification). Various lines of evidence suggest that DOC may decline with acidification (Marmorek et al. 1988; Sullivan et al. 2000).</p>	
<p>The F-factors used in the SSWC and ESSA-DFO model are likely to underestimate the level of watershed neutralization of acidic deposition (based on comparisons between the F-factors assumed or implied in simulation models and the F-factors inferred from paleolimnological studies (Sullivan et al. 1992; Turner et al. 1992; Sullivan 2000)).</p>	
<p>The method used to derive F-factors from base cation concentrations (Henriksen et al. 1997, cited in Henriksen et al. 2002) was based on lakes in northern Europe which have lower levels of runoff than lakes in the PRAS area, and therefore less dilution of acidic deposition. F-factors may therefore be underestimated for the PRAS lakes. However, a larger proportion of runoff may be surface rather than subsurface flow in the PRAS region (compared to Europe), which would act in the opposite direction (reducing the F-factor).</p>	
<p>Assumed levels of background S and N deposition, 10 and 5 meq/m²/yr respectively, from industrial sources outside the study area are applied to all lakes equally; these might be higher or lower in some areas.</p>	
<p>Assuming the entire AAC is logged overestimates base cations removed in harvest, underestimates CL, and overestimates exceedance.</p>	<p>Assuming the entire AAC is logged overestimates N removed in harvested trees, underestimates N acidification, but assumed N uptake rates are low (minor effect).</p>
<p>Runoff may be underestimated for some catchments, leading to an overestimate of acidification risks.</p>	<p>Runoff may be overestimated for some catchments, leading to an underestimate of acidification risks.</p>
<p>Gran ANC was not measured in any of the 35 analyzed lakes. Gran ANC values were estimated based on a regression of Gran ANC versus Total Alkalinity. This is unlikely to cause any biases in the assessment but does add uncertainty.</p>	
<p>A threshold for pH change of 0.3 units was adopted to assess the results of the ESSA-DFO model. This criterion does not account for the different sensitivities to changes in pH values that different species of aquatic biota may present.</p>	



Model Assumptions Causing Overestimate of Risk to Lakes	Model Assumptions Causing Underestimate of Risks to Lakes
<p>The predominant type of lake expected in the PRAS area is oligotrophic, which has a lower bound CL threshold of 5 kg N/ha/yr. The broader assessment of eutrophication risk estimated the potential risk for the lower bound CL threshold of 3 kg N/ha/yr for all lakes with surface area >1 ha. Since this is the CL threshold for dystrophic lakes, the risk of eutrophication is likely overestimated. Furthermore, the analysis used only the lower bound of the ranges of critical loads for eutrophication; application of the midpoint of these ranges resulted in no sampled lakes with exceedances.</p>	

6.4 Recommendations on Impact Assessment Guidance

There are gaps in coverage of lakes in the northern part of the PRAS region, as well as on various islands, and most importantly in the effects domain (Figure 5-4), the area predicted to receive levels of SO₄ and N deposition that could potentially acidify soils and surface waters. Ideally these data gaps would be filled to provide a more representative sample of lakes from which to draw conclusions.

The deposition models for S and N indicate that the affected area (i.e., predicted plume of acidic deposition) will be located mainly to the north of Port Edward. It would be effective to focus further monitoring and sampling efforts on the lakes within this area, particularly lakes within the effects domain (≥15 meq/m²/yr of SO₄ deposition), as well as other lakes within the zone receiving ≥10 meq/m²/yr of SO₄ deposition (see Figure 2-18). Although no exceedances of critical loads are predicted for any of the emission scenarios using the SSWC and FAB models, the ESSA-DFO predicted a pH decrease close to the biologically significant threshold of 0.3 pH units in Lake NC309 (a pH decrease of 0.29). A sensitivity analysis (Appendix 4.4, Volume 2 of this report) identifies exceedances of critical loads under alternative critical ANC values for five lakes (NC309, NC327, NC338, NC360, and AD-SW9) but only Lake NC309 is predicted to have a pH decrease of more than 0.1 pH units. These potentially more vulnerable lakes, which are located close to Port Edward, could be monitored/followed-up more closely. Another lake that could merit more attention as part of impact evaluation is AD-SW 8, Shawatlan Lake. This lake is used as a backup drinking water supply for the community of Port Edward. Woodworth Lake, the primary drinking water supply for Port Edward, was not sampled, but should be.

For specific projects that are moving forward, it will be important to have a set of sensitive lakes and streams within the predicted plume of acidic deposition, that are systematically monitored over time, similar to the Environmental Effects Monitoring program that has been implemented by Rio Tinto Alcan for their new smelter in Kitimat (ESSA et al. 2014b). A representative sample of lakes should be drawn from the effects domain shown in Figure 5-4. Some of the lakes and streams should be monitored more intensively to assess the risk of acidic episodes.

The broader analysis of eutrophication risk in the PRAS area was applied to all lakes in the area with surface area greater than one hectare. The water chemistry and (therefore) the trophic



status of these lakes are unknown. The eutrophication analysis is based solely on N deposition values and empirical nutrient-N critical loads for oligotrophic and dystrophic lakes. It would be informative to extend the monitoring coverage to some of these lakes for which N exceedance and potential eutrophication risk have been predicted, obtaining baseline estimates of algal biomass and community structure as well as nutrient concentrations.



7 Synthesis of Results

7.1 Overview

Figure 7-1 presents a high-level synthesis of the study results according to the four-colour categories described in Table 7-1. Findings by receptor are summarized on the following pages.

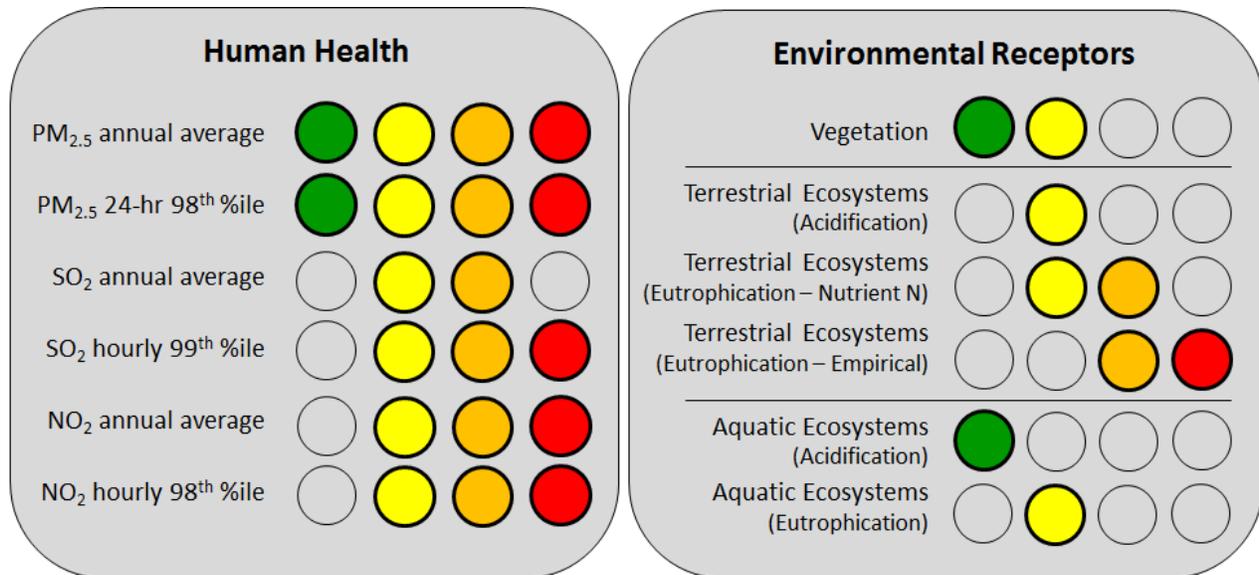


Figure 7-1: Overview of assessment results. Circles are filled in if at least one scenario was in that colour category.

Table 7-1: Description of the meaning of the colour-coded categories. Quantitative thresholds between categories are provided in Sections 3, 4, 5 and 6.

For Human Health, which follows an adapted version of the CCME air quality categorization scheme:	
	Ambient concentrations associated with “clean” environments
	Modelled concentrations are less than half way between green and red
	Modelled concentrations are more than half way between green and red
	Modelled concentrations are above the air quality objectives
For Environmental Receptors (vegetation, terrestrial ecosystems, aquatic ecosystems):	
Low	Scenario expected to have no, or negligible, impact
Moderate	Scenario expected to have an impact, but of a magnitude, frequency, and spatial distribution considered to be acceptable ^a
High	Scenario expected to have an impact of a magnitude, frequency or spatial distribution, considered to be unacceptable ^a
Critical	Scenario expected to have an impact of a magnitude, frequency or spatial distribution, considered to be extremely unacceptable ^a

^a Acceptability of impacts depends on one’s values, and is ultimately a policy decision.

The scenarios modelled fall into two groups, which are useful to keep in mind when interpreting the results:

- Scenarios A, C and F_R compare different treatment levels across the same full set of facilities. These are referred to in the text as ‘full build’ scenarios.
- Scenarios B, D and E compare three hypothetical situations in which different combinations of only some LNG facilities are built (i.e., fewer facilities than in scenarios A, C and F_R). These are referred to in the text as ‘partial build’ scenarios.

7.2 Human Health

The human health effects assessment was conducted for 34 locations in the study area, including 17 community locations, nine recreational and cultural areas, and eight industrial locations.

This health effect categorization for human health used the CCME air quality categorization scheme, adapting it to employ the BC Air Quality Objectives for PM_{2.5}, and Interim Air Quality Objectives for SO₂ and NO₂. The colours have the following meanings (which are different from the meanings for the risk colours for the environmental receptors):

- Green: the lowest category associated with very low exposures. A threshold value separates the Green and Yellow category, and is associated with the range of ambient concentrations associated with “clean” environments.
- Yellow: above the “background” level but below the mid-way threshold between background and the CAAQS. Concentration values below this mid-way threshold, but higher than Green, are assigned to the Yellow category.
- Orange: above the midway threshold, but below the Red category, the concentration values are assigned to the Orange category.
- Red: the highest category and is associated with concentrations above the air quality objectives.

Figure 7-2 presents the characterization by scenario across all locations. More locations fall into the yellow category than any other category – for all scenarios, air quality criteria and pollutants. There is little difference among the scenarios in the pattern of results (for any air quality criterion or pollutant). The biggest differences are between pollutants (there is more variation in results among locations for PM_{2.5} than for SO₂), and between air quality criteria (e.g., more locations have green or yellow results for the annual averaging period than for the 98th or 99th percentile values of concentrations).



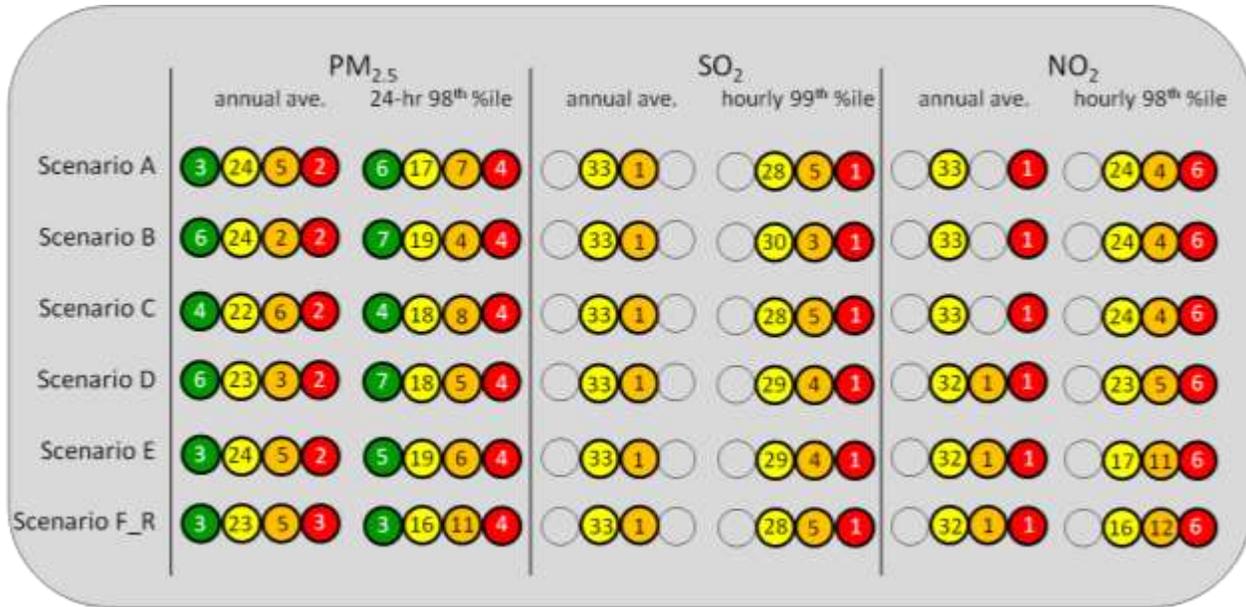


Figure 7-2: Summary of results categories for human health, by scenario. A circle is shaded if the study found that result for any of the 34 locations. Numbers in the circles convey how many of the 34 locations were in each colour for each scenario.

Table 7-2 presents the human health risk characterization for each of the residential locations across all scenarios. Table 7-3 and Table 7-4 present the same summaries for recreational and cultural areas and industrial locations, respectively. In addition to the dominance of results in the yellow category noted above, it is also clear which of the 17 residential locations have any results in the red category. Three residential locations – Prince Rupert Residential, Dodge Cove and Crippen Cove – were in the red category for the NO₂ hourly 98th percentile threshold under one or more scenarios.



Table 7-2: Summary of colour categories for human health in each of the 17 residential locations across all six emission scenarios. Each cell contains four circles for each of the four categories. A circle is shaded if the study found that result for any of the scenarios.

Community Locations:	PM _{2.5}		SO ₂		NO ₂	
	annual ave.	24-hr 98%ile	annual ave.	hourly 99%ile	annual ave.	hourly 98%ile
Port Edward Residential	○●○○	○○●○	○●○○	○●○○	○●○○	○●○○
P.E. Future Residential Expansion	○●○○	○○●○	○●○○	○●○○	○●○○	○●○○
P.E. Proposed Hotel	○●○○	○○●○	○●○○	○●○○	○●○○	○●○○
Lax Kw'alaams	●●○○	●●○○	○●○○	○●○○	○●○○	○●○○
Prince Rupert Residential	○●○○	○○●○	○●○○	○●○○	○●○○	○○○●
Metlakatla	○●○○	○○●○	○●○○	○●○○	○●○○	○○●○
Kitkatla	●○○○	●○○○	○●○○	○●○○	○●○○	○●○○
Dodge Cove	○●○○	○○●○	○●○○	○○●○	○●○○	○○○●
Rainbow Lake	●●○○	○○●○	○●○○	○●○○	○●○○	○●○○
Prudhomme Lake	○●○○	○○●○	○●○○	○●○○	○●○○	○●○○
Kloiya Bay	○●○○	○○●○	○●○○	○●○○	○●○○	○●○○
North Pacific Cannery	○●○○	○○●○	○●○○	○●○○	○●○○	○●○○
Cassiar Cannery	○●○○	○○●○	○●○○	○●○○	○●○○	○●○○
Osland	●●○○	●●○○	○●○○	○●○○	○●○○	○●○○
Hunts Inlet	●○○○	●○○○	○●○○	○●○○	○●○○	○●○○
Oona River	●○○○	●○○○	○●○○	○●○○	○●○○	○●○○
Crippen Cove	○●○○	○○●○	○●○○	○●○○	○●○○	○○○●

Table 7-3: Summary of colour categories for human health in each of the nine recreational and cultural areas across all six emission scenarios. Each cell contains four circles for each of the four categories. A circle is shaded if the study found that result for any of the scenarios.

Recreational and Cultural Areas:	PM _{2.5}		SO ₂		NO ₂	
	annual ave.	24-hr 98%ile	annual ave.	hourly 99%ile	annual ave.	hourly 98%ile
Prince Rupert Golf Course	○●○○	○○●○	○●○○	○●○○	○●○○	○○●○
Mount Oldfield Trail	○●○○	○○●○	○●○○	○●○○	○●○○	○○●○
Mount Hayes Trail	○○○●	○○○●	○●○○	○○●○	○●○○	○○○●
Butze Rapids Trail	○●○○	○○●○	○●○○	○●○○	○●○○	○●○○
Metlakatla Sandbar	○●○○	●●○○	○●○○	○●○○	○●○○	○○●○
Pike Island	○●○○	●●○○	○●○○	○●○○	○●○○	○●○○
Sandbar N. of Casey Point	○○●○	○○○●	○●○○	○○●○	○●○○	○○○●
Oliver Lake	○●○○	○○●○	○●○○	○●○○	○●○○	○●○○
Kitson Island	○●○○	○○●○	○●○○	○●○○	○●○○	○○●○



Table 7-4: Summary of colour categories for human health in each of the eight industrial locations across all six emission scenarios. Each cell contains four circles for each of the four categories. A circle is shaded if the study found that result for any of the scenarios.

Industrial Locations:	PM _{2.5}		SO ₂		NO ₂	
	annual ave.	24-hr 98%ile	annual ave.	hourly 99%ile	annual ave.	hourly 98%ile
Canoxy North Industrial	○●○○	○●●○	○●○○	○●○○	○●○○	○●○○
Inverness Passage Commercial	○●○○	○●●○	○●○○	○●○○	○●○○	○●○○
Outer Harbour Industrial	○○○●	○○○●	○●○○	○●○○	○●○○	○●○○
Prince Rupert NE Industrial	○●○○	○●○○	○●○○	○●○○	○●○○	○●○○
South. Prince Rupert Industrial	○○○●	○○○●	○●○○	○○○●	○○○●	○○○●
Stapleton Island Industrial	○●○○	○●○○	○●○○	○●○○	○●○○	○●○○
Watson Island Industrial	○●●○	○○●○	○●○○	○●●○	○●○○	○●●○
Prince Rupert Airport	○●○○	●○○○	○●○○	○●○○	○●○○	○●○○

7.3 Environmental Receptors

Table 7-5 presents the risk characterization results for the environmental receptors for each scenario. The quantitative metrics and thresholds for each of these risk categories are specific to each of the environmental receptors (vegetation, terrestrial ecosystems, and aquatic ecosystems), and are presented in Sections 4, 5 and 6. A brief description of the results is provided in the following subsections.

Table 7-5: Summary of risk categories for environmental receptors across all six emission scenarios.

Receptor	Scenario					
	A	B	C	D	E	F_R
VEGETATION						
SO ₂	■	■	■	■	■	■
NO ₂	■	■	■	■	■	■
TERRESTRIAL ECOSYSTEMS						
Acidification	■	■	■	■	■	■
Eutrophication, using CL _{nut} (N)	■	■	■	■	■	■
Eutrophication, using CL _{emp} (N)	■	■	■	■	■	■
AQUATIC ECOSYSTEMS						
Acidification	■	■	■	■	■	■
Eutrophication	■	■	■	■	■	■

7.3.1 Vegetation

The methods used for the vegetation assessment for this study are the same as those used for the KAA, with the exception that exposure statistics have been updated to match the BC Interim Air Quality Objectives adopted in 2014.



Effects of SO₂

All scenarios resulted in similar profiles with regard to thresholds of concern. Modelled concentrations of SO₂ in all scenarios have predicted daily peak concentrations for 1 or 3 hours well below those reported in the literature to cause visible injury to sensitive vegetation. The highest concentrations are predicted to occur during night time hours. The exceedances are clustered, and the daily peak 1-hour concentrations fall off rapidly with distance from the location with the greatest predicted concentration.

Based on the results of dispersion modelling for 2012, little or no effect on sensitive higher vegetation would be expected under any scenario – and if there were any effect it would likely be confined to the immediate area of the industrial development. From the results and interpretation of modeled air concentrations of SO₂ in this study, the risk to vegetation is categorized as Low.

Potential effects on lichen flora are likely to occur in an area bounded by an annual mean concentration of 10-20 µg/m³. The quantitative effect on that flora is unknown, and would depend on the sensitivity of the species present. If effects occur, the diversity, abundance, and distribution of lichens could be affected.

Effects of NO₂

Modelled maximum concentrations of NO₂ are within the range that could cause visible injury to sensitive vegetation, if present, and if exposed during a sensitive period (e.g., during the growing season and during the day). The highest concentrations occurred during nighttime hours.

The European standard of 30 µg/m³ annual average concentration of NO₂ is exceeded no more than once at any single receptor for all scenarios over all hours, including during the growing season. Multiple receptors show a single exceedance of the 30 µg/m³ threshold level. The spatial extent of daily peak concentrations that exceed thresholds is confined to an area of about 10 km x 10 km. The annual average NO₂ concentration exceeds the 30 µg/m³ standard at one location under all scenarios. Under the worst case, the area where the annual average is exceeded is relatively small and restricted to the current industrial area.

Based on the results of dispersion modelling for 2012, injury to sensitive higher vegetation is possible in the immediate vicinity of the maximum receptor location. The spatial extent and severity of visible injury would likely be small based on the pattern of modelled concentrations for Scenario F_R. Results indicate a larger area of concern for potential effects on lichens, including near Lax Kw'alaams if results from studies in Europe are applicable to the Prince Rupert area. From the results and interpretation of modeled air concentrations of NO₂ in this study, the risk to vegetation is classified as Moderate.

Potential effects on lichen flora are likely to occur in an area bounded by an annual mean concentration of 30 µg/m³. As for SO₂, the quantitative the quantitative effects on lichen flora are



unknown and would depend on the sensitivity of the species present. If effects occur, the diversity, abundance, and distribution of lichens could be affected. It is also possible that there would be a shift in the composition of the lichen community, favouring lichen species that respond positively to high nitrogen inputs versus those that do not.

7.3.2 Soils and Terrestrial Ecosystems

The assessment of critical loads of acidification and eutrophication (nutrient nitrogen) for terrestrial ecosystems in the Prince Rupert Airshed Study area focused on natural habitats covering up to 82% of the terrestrial study area (forest, shrubland and wetland ecosystems).

The potential impact of acidic (sulphur and nitrogen) deposition depends on the sensitivity of the receptor ecosystem (e.g., forest soils) and the magnitude of atmospheric deposition. The BC Ministry of the Environment delineates 7.5 kg SO₄²⁻/ha/yr (15.6 meq/m²/yr) and 5 kg N/ha/yr (35.7 meq/m²/yr) as deposition thresholds of concern leading to potential impacts on terrestrial ecosystem receptors. Under the highest sulphur and nitrogen oxide emissions scenario (F_R), the threshold SO₄²⁻ and N deposition isopleths were centred around Kaien Island and Digby Island encompassing an area of approximately 250 km² and 100 km², respectively.

Acidification

The area of the receptor ecosystems (forest, shrub and wetland) exceeded under the six emissions scenarios ranged from 4.04 km² (Scenario B) to 10.27 km² (Scenarios C and F_R). The greatest areal exceedance (Scenarios C and F_R) represented <2% of the mapped receptor ecosystem within the acidification effects domain (586 km²).

Average predicted exceedance was <25 meq/m²/yr under all emissions scenarios (the highest magnitude was estimated under Scenario F_R), indicating that a small area of receptor ecosystems will receive acidic deposition somewhat in excess of their critical load. The exceeded area was located at the north end of Digby Island and Metlakatla. Under all emissions scenarios, sulphur exceedance was greater than nitrogen exceedance. Nonetheless, all exceeded receptor grids (1 km × 1 km) require S or N reductions to achieve non-exceedance.

The predicted areal exceedance of critical loads of acidity ranged from 0.69% to 1.75% of the 'effects domain' (the area enclosed by a 15 meq/m²/yr modelled sulphur and nitrogen deposition isopleth under Scenario F_R), and therefore falls within the Moderate risk category.

Eutrophication

Under all scenarios, the exceeded area was much greater (>4 times) for empirical critical loads (CL_{emp}(N)) compared with the nutrient mass balance (CL_{nut}(N)). The area in which CL_{nut}(N) was exceeded ranged from 4.97 km² to 23.54 km² compared to 19.57 km² to 93.82 km² for CL_{emp}(N), from Scenario B (minimum area exceeded) to scenario F_R (maximum area exceeded). Under Scenario F_R, exceedance of CL_{nut}(N) was primarily predicted along the south east of Digby Island and the west of Kaien Island. Notably only two 1 km × 1 km grids exceeded both acidity and mass balance nutrient nitrogen. In contrast, large areas of Kaien and Digby Islands and



further north were predicted to exceed $CL_{emp}(N)$ under Scenario F_R. The greatest proportional areal exceedance was 4.0% for $CL_{nut}(N)$ and 16.1% for $CL_{emp}(N)$ (Scenario F_R) of the mapped receptor ecosystem within the effects domain.

Based on the areal exceedances in proportion to the effects domain, the risk categories for the scenarios range from Moderate to High, or from High to Critical, depending on whether the risk rating is based on nutrient mass balance or on empirical critical loads.

Implications for Vegetation

The likely effects of N deposition on vegetation will be through nutrient nitrogen and not through acidification. The primary concern will be a potential change in epiphytic macro-lichen species composition, with the possibility of an increased risk for composition shifts in N-sensitive vascular plants as well. Coupled with the potential direct effects of SO_2 and NO_2 on lichens, impacts on communities may occur within the critical concentration isopleths and where critical loads are exceeded. It appears that those areas are restricted in spatial extent.

7.3.3 Aquatic Ecosystems

Acidification

Results for exceedance and expected changes in pH were combined in an integrative risk assessment for the freshwater ecosystems in the study area. The risk assessment framework was based on the approach developed by the BC Ministry of Environment for the KAA. The Prince Rupert study area only had data for half as many lakes as were available for the KAA (35 versus 80). The risk categories in this study are therefore coarser, and represent slightly different percentages of the sampled and analyzed lakes in each risk category. While 30 of the 35 lakes were deliberately selected from acid-sensitive bedrock geologies, the lake data set in the Prince Rupert study area was biased towards larger lakes. This area bias means that the sample may have missed both the most acid-sensitive and the least acid-sensitive lakes.

No exceedances of critical loads for acidification have been predicted, and the estimated pH changes are all under the biologically significant threshold of $\Delta pH = -0.3$. The risk of acidification for the 35 sampled lakes is therefore considered Low.

Given the mix of criteria used to choose lakes that were sampled, the combined data set available for this study (35 of the 859 lakes in the study area that are greater than 1 ha in size) cannot be considered to be statistically representative of the region as a whole, or statistically representative of the effects domain where deposition levels are highest. Assessing the chemistry of a statistically representative sample of lakes in the effects domain should be a high priority for future work.

Eutrophication

Sample size is not an issue for the assessment of eutrophication risk, because in addition to an intensive analysis for the 35 sampled lakes, we applied an empirical approach to an extensive



analysis of all 859 lakes greater than 1 ha in size within the PRAS area (using estimated deposition at the centroids of these lakes). We also applied a risk assessment categorization similar to that used for lakes in the KAA. Under this framework, and using an overly precautionary assumption that all lakes are dystrophic within the zone receiving more than 3 kg/ha/yr of N, the risk of eutrophication would be Moderate. If the proportion of dystrophic lakes in the overall PRAS study region was similar to that in the sampled lakes (11%), then that proportion would drop to about 1.3% to 1.5%, which is still in the Moderate impact category.

7.4 Observations across Scenarios

Table 7-6 shows the results by risk colour for all of the receptors across all six scenarios, to reveal potential patterns and to facilitate comparisons that might be informative for decision-makers. For the human health, vegetation and aquatic ecosystem receptors, impact ratings are remarkably consistent across scenarios, suggesting that the variation in emissions across scenarios (2.4-fold for SO₂, 2.6-fold for NO_x, 3.9-fold for PM_{2.5}; Table 1-2) is generally not sufficient to trigger different impact categories. Only terrestrial ecosystem eutrophication risk varies among scenarios, and is lower for partial build scenarios (B, D and E) compared to full build scenarios (A, C and F_R).

Table 7-6: Colour category results across all scenarios and receptors – bearing in mind that the meaning of the colours differs between the human health and the environmental receptors. For the human health rows, the cell is shaded the colour category that occurs in more locations than any other category. The smaller inset boxes show what other colours occurred at any locations. Each inset box represents no more than 12 (and in most instances much fewer) of the 34 locations included in the health assessment.

Receptors	Scenario					
	A	B	C	D	E	F_R
HUMAN HEALTH – colour categories						
PM _{2.5} , annual average & 24-hr 98 th %ile, all locations						
SO ₂ , annual average, all locations						
SO ₂ , hourly 99 th %ile, all locations						
NO ₂ , annual average, all locations						
NO ₂ , hourly 98 th %ile, all locations						
ENVIRONMENTAL RECEPTORS – impact risk categories						
Vegetation – SO ₂						
Vegetation – NO ₂						
Terrestrial Ecosystem Acidification						
Terrestrial Ecosystem Eutrophication, using CL _{nut} (N)						
Terrestrial Ecosystem Eutrophication, using CL _{emp} (N)						
Aquatic Ecosystem Acidification						
Aquatic Ecosystem Eutrophication						



The lack of contrast in cumulative emissions of SO₂ and NO_x across scenarios is an important factor in explaining the consistency in risk ratings across scenarios for most receptors. SO₂ emissions show less variation than expected due to consistent emissions of 2.2 t/d from the container port across all scenarios, the single largest source of SO₂ (Figure 1-7). Emission controls do not cause as much variation in NO_x emissions among scenarios due to the counteracting effect of emissions from LNG terminals and ships. For example, Scenario A, which specifies e-drive industrial processes, has the lowest cumulative emissions of NO_x from the six LNG facilities in that scenario (2.0 t/d cumulatively), but because of high LNG production still has 24.7 t/d of NO_x emissions from LNG terminals and ships, as shown in Figure 1-6. Relative to Scenario A, Scenario B has greater cumulative NO_x emissions from the three LNG facilities with dry low NO_x emission combustion systems (18.8 t/d), but due to lower total LNG production has lower emissions from LNG terminals and ships (9.6 t/d). As a result, Scenarios A and B have almost exactly the same cumulative emissions of NO_x (34.0 and 34.7 t/d respectively; Table 1-2).

Relative to SO₂ and NO_x, PM_{2.5} shows a higher level of contrast across scenarios (Figure 1-8). While emissions of PM_{2.5} from LNG terminals and ships do increase with full versus partial build scenarios, this counteracting effect is less evident for PM_{2.5} than for NO_x (i.e., comparing Figure 1-6 and Figure 1-8, noting the 10-fold difference in scale on the y-axis).

During review of the draft study report by MOE and the Prince Rupert Port Authority, SO₂ emission rates for the container ships and bulk carriers were found to be overly conservative, because they did not account for the recent decrease in bunker fuel sulphur content from 2.6% to 0.1% by mass. Additionally, sulphur content in sales gas may have been underestimated in SO₂ emission rates for Pacific NorthWest LNG, and for facilities for which emission rates for Pacific NorthWest were used as a proxy (Aurora LNG, Grassy Point LNG, and WCC LNG).

If updates were made for these two emission unit types, the decrease in marine SO₂ emission and the increase in LNG SO₂ emissions may result in only a small overall increase in total SO₂ emission rates. In other words, the updated total study-wide SO₂ emission rates may be similar to what was modelled. However, because the emissions are from different locations of units with different stack parameters, the modelled results would not be as similar, and the change would be non-uniform. Maximum modelled results at the maximum locations near the southern Prince Rupert industrial area would likely be substantially lower, and results would likely be moderately higher in the mid-range and low-range modelled concentration and deposition levels near the LNG facilities.

NO₂ model results are far greater in magnitude than SO₂ or PM_{2.5} results, for all scenarios, and also show higher risk categories among all environmental receptors. Therefore, differences between nitrogen deposition and NO₂ concentration results are summarized below, and not described for SO₂ and PM_{2.5}.

Overall, the nitrogen deposition levels are very similar across all scenarios, particularly at the higher levels of deposition in areas closest to the emissions sources. This lack of variation in



deposition reflects the lack of variation in NO_x emissions, as already discussed, and the concentration of both stationary and mobile emission sources in the area of Digby and Kaien islands (Figure 1-2 and Figure 1-3).

All NO₂ concentration isopleth plots (presented in Section 2 and Appendix 2.6 (Concentration and Deposition Maps for Scenarios B to F_M) in Volume 2 of this report) show highest concentrations near Fairview. These high concentrations are likely over-predicted by CALPUFF due to the use of area sources to represent mobile diesel activities. NO_x emissions from Fairview's marine vessels may also be overestimated due to conservative assumptions applied in the Fairview air dispersion modelling analysis for engine loads during various activities. Additionally, results were not excluded for locations within each facility's property, which resulted in particularly high concentrations at locations very near the emission sources themselves.

Comparison among treatment alternatives for the full build Scenarios (A, C, and F_R)

Scenarios A, C, and F_R each represent all LNG facilities, Port facilities, and power generating facilities being built at full capacity, but with different levels of NO_x control.

Looking across scenarios A, C, and F_R one can see patterns of increasing maximum concentrations of NO₂, increasing levels of nitrogen deposition, and a larger spatial extent of the lowest concentration contour. These patterns are expected, because each scenario has higher modelled NO_x emission rates than the previous one. However, the variation across scenarios is less than might be expected for the reasons discussed above. The risk categories for human health and vegetation from NO_x are largely based on maximum NO₂ concentrations at the site(s) with the highest concentrations. Therefore, even though the spatial extent of concentrations expands from Scenario A to C to F_R, the risk categories do not change because there is little change in maximum concentration of NO₂ at the sites with the highest concentrations. The risk of acidification to lakes is low across Scenarios A, C and F_R due to three factors: 1) the 35 sampled lakes are generally not sensitive to acidification; 2) many of the 35 sampled lakes are outside of the zone of highest N deposition; and 3) there isn't enough S and N deposition in any of these three scenarios to cause exceedance of critical loads or thresholds of pH change (Figure 2-15 and Figure 2-16). The risk of lake eutrophication is moderate across Scenarios A, C, and F_R, because for these scenarios there is little variation in the percent of the 859 lakes found within the 3 and 5 kg/ha/yr isopleths of N deposition (Table 6-12). The risk of acidification to terrestrial ecosystems does not change among these three scenarios, because while there are differences in the area and percent of soils with exceedance (highest under scenario F_R), these differences are not large enough to shift the risk category.

The PM_{2.5} 24-hour plots show only a very slight increase in highest concentrations between each of these three scenarios. A more noticeable increase is seen in the area encompassed within the lowest concentration contour (12.5 µg/m³). While the modelled PM_{2.5} concentration differences between Scenario A and Scenario C might be expected to be larger based on the large difference in PM_{2.5} emission rates between the two scenarios (1.4 t/d versus 5.4 t/d), the sources with the highest PM_{2.5} emission rates from a single location (Prince Rupert Grain and



LNG terminal operations) were unchanged among these three scenarios. Risk categories for PM_{2.5} air quality criteria are largely based on the maximum PM_{2.5} concentrations, which do not change among scenarios. Therefore, even though the levels and extents vary at the lower concentrations, the risk categorizations do not change among these three scenarios.

SO₂ emission rates are identical between Scenarios A, and F_R, and nearly identical between Scenarios A and C. Therefore, sulphur deposition levels, SO₂ concentrations, and the resulting risk colour ratings don't change across these scenarios.

Comparison among alternative partial build Scenarios (B, D, E)

Scenarios B, D, and E each represent a different subset of the modelled LNG and power generating facilities:

- Scenario B represents building the Pacific NorthWest LNG, Aurora LNG, and BC Hydroelectric generating facilities.
- Scenario D represents building the Grassy Point LNG, Aurora LNG, and Watson Island LNG facilities.
- Scenario E represents building the Pacific NorthWest LNG, WCC LNG, Prince Rupert LNG, and BC Hydroelectric generating facilities.

Scenario B has the lowest modelled emission rates for each pollutant among the three scenarios, and Scenario E has the highest. All scenarios include the existing port facilities, new port facilities (Canpotex), and port expansion projects (Fairview Phase II).

While there are some differences among Scenarios B and D in the NO₂ 1-hour and annual concentration contour plots, the human health and vegetation risk categories are largely based on the maximum NO₂ concentrations, which do not change among scenarios.

The SO₂ emission rates vary somewhat among Scenario B, D, and E, however the SO₂ 1-hour and annual concentration plots for Scenarios B, D, and E all have very similar concentration contour levels with the same maximum contour level. This lack of variation indicates the dominance of SO₂ emissions from the non-LNG terminal marine vessels on modelled SO₂ results. Risk categories for human health and vegetation receptors are largely based on the maximum hourly or maximum annual average SO₂ concentrations, which do not change much among these three scenarios. Therefore, even though the levels and extents vary at the lower concentrations, the risk categories do not change between these three scenarios.

The PM_{2.5} 24-hour concentration plots for Scenarios B and D have nearly identical contours. Scenario E has the same maximum contour levels as Scenarios B and D, but the lowest contour level (12.5 µg/m³) is more expansive over land than Scenarios B and D. The PM_{2.5} annual concentration plots for Scenario B, D, and E all have nearly identical contours. Therefore, the PM_{2.5} risk categorization for human health does not vary among these scenarios.



Nitrogen and sulphur deposition varies between Scenarios B, D, and E because of localized effects of the different sources being modelled in each scenario. Overall, the maximum extent of deposition occurs in the Prince Rupert and Port Edward areas under Scenario E, and the highest deposition levels occur in the Lax Kw'alaams area under Scenario D. As shown in Table 7-6, the risk of acidification does not change across Scenarios B, D, and E: low for aquatic ecosystems, and moderate for terrestrial ecosystems. The risk of eutrophication is moderate for Scenarios B, D, E for both aquatic ecosystems and for terrestrial ecosystems using the threshold of $CL_{nut}(N)$. Using the more stringent threshold of $CL_{emp}(N)$, the risk of eutrophication to terrestrial ecosystems is high under Scenarios B and D, and critical under Scenario E.



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Final Report



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Aquatic Species at Risk &
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Appendices



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YEARS

Prince Rupert Airshed Study

Volume 2: Appendices

Note: A Supplementary Report of the Prince Rupert Airshed Study has been completed and should be referred to when reviewing study results. The Supplementary Report to the study represents a refined data set based on facility design improvements, an updated emissions inventory, additional receiving environment information, and the addition of a base scenario.



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Prince Rupert Airshed Study

Volume 2: Appendices

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Venn Pass, from Mount Hays looking to Metlakatla village (credit: Gary Robinson, used by permission).

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1 Appendices for Scenario F_M and F_R Results

This appendix contains the results for Scenarios F_M and F_R for each of the receptors. Scenario F_M assumes the same facility characteristics as Scenario F_R, but uses a different chemical transformation scheme for the dispersion modelling. The Kitimat Airshed Emissions Effects Assessment (KAA) used the MESOPUFF chemical transformation scheme. For the Prince Rupert Airshed Study, all scenarios except Scenario F_M applied the RIVAD with ISORROPIA chemical transformation scheme. These two chemical transformation schemes are discussed further in Section 2.1.3 of Volume 1 of this report. The purpose of including Scenario F_M was to better understand the effects of the change to RIVAD for this study, in order to facilitate comparisons of study results for the other scenarios with the results from the KAA.

1.1 Scenario F_M and F_R Results for Human Health Assessment

1.1.1 Categorization of Annual Average Concentrations of PM_{2.5}

The table below provides the value for the maximum annual average concentration of PM_{2.5} among the grid points assigned to each location, for Scenario F_M and Scenario F_R. The colours are assigned based on the thresholds described in Table 3-1 (Volume 1 of this report).

Table A1.1-1: Annual average concentration of PM_{2.5} for Scenario F_M and Scenario F_R.

Concentrations in µg/m ³ Background = 3.5 µg/m ³	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Residential		
Dodge Cove	5.9	6.8
Future Residential Expansion	5.0	5.2
Kitkatla	3.7	3.6
Lax Kw'alaams	4.1	4.2
Metlakatla	4.6	5.3
Port Edward Proposed Hotel	4.8	5.2
Port Edward Residential	5.4	5.7
Prince Rupert Residential	5.5	6.5
Rainbow Lake	4.2	4.4
Prudhomme Lake	4.4	4.7
Kloiya Bay	4.5	5.0
North Pacific Cannery	4.6	4.8
Cassiar Cannery	4.5	4.7
Osland	4.3	4.4
Hunts Inlet	3.8	3.8



Concentrations in $\mu\text{g}/\text{m}^3$ Background = $3.5 \mu\text{g}/\text{m}^3$	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Oona River	3.8	3.8
Crippen Cove	5.3	6.5
Cultural & Recreational		
Prince Rupert Golf Course	4.8	5.4
Mount Oldfield Trail	5.2	5.8
Mount Hayes Trail	7.2	8.7
Butze Rapids Trail	4.6	5.0
Metlakatla Sandbar	4.3	4.7
Pike Island	4.4	4.7
Sandbar N. of Casey Point	6.7	7.9
Oliver Lake	4.7	5.2
Kitson Island	4.4	4.4
Industrial		
Canoxy North Industrial	5.2	5.6
Outer Harbour Industrial	26.2	27.0
Inverness Pass. Commercial	5.3	5.6
Prince Rupert NE Industrial	4.5	5.0
South. Prince Rupert Indus.	19.4	21.9
Stapleton Island Industrial	4.7	4.7
Watson Island Industrial	5.9	6.5
Prince Rupert Airport	4.5	4.7

1.1.2 Categorization of 98th Percentile of 24-Hour Averaged Concentrations of $\text{PM}_{2.5}$

The table below provides the value for the maximum of the 98th percentile of the 24-hour averaged concentrations of $\text{PM}_{2.5}$ among the grid points assigned to each location, for Scenario F_M and Scenario F_R. The colours are assigned based on the thresholds described in Table 3-1 (Volume 1 of this report).



Table A1.1-2: 98th percentile of 24-hour averaged concentration of PM_{2.5} for Scenario F_M and Scenario F_R.

Concentrations in µg/m ³ Background = 7.00 µg/m ³	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Residential		
Dodge Cove	16.1	21.2
Future Residential Expansion	14.5	15.6
Kitkatla	8.6	8.7
Lax Kw'alaams	9.8	10.6
Metlakatla	10.7	13.4
Port Edward Proposed Hotel	13.8	17.0
Port Edward Residential	16.7	20.2
Prince Rupert Residential	15.4	21.4
Rainbow Lake	11.3	13.3
Prudhomme Lake	12.4	15.1
Kloiya Bay	13.2	16.8
North Pacific Cannery	12.7	14.4
Cassiar Cannery	12.2	14.4
Osland	11.9	13.3
Hunts Inlet	9.7	9.6
Oona River	9.6	9.7
Crippen Cove	13.5	19.4
Cultural & Recreational		
Prince Rupert Golf Course	13.0	18.7
Mount Oldfield Trail	16.0	20.7
Mount Hayes Trail	23.9	31.3
Butze Rapids Trail	12.8	16.9
Metlakatla Sandbar	9.9	10.6
Pike Island	10.0	10.7
Sandbar N. of Casey Point	21.3	28.2
Oliver Lake	13.8	17.8
Kitson Island	13.4	13.5
Industrial		
Canoxy North Industrial	17.2	20.6
Outer Harbour Industrial	119.3	117.5
Inverness Pass. Commercial	16.4	19.5
Prince Rupert NE Industrial	12.6	16.2
South. Prince Rupert Indus.	59.1	67.2
Stapleton Island Industrial	13.3	14.7



Concentrations in $\mu\text{g}/\text{m}^3$ Background = $7.00 \mu\text{g}/\text{m}^3$	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Watson Island Industrial	18.9	20.5
Prince Rupert Airport	10.5	11.2

1.1.3 Categorization of Annual Average Concentrations of SO_2

The table below provides the value for the maximum of the annual average concentrations of SO_2 among the grid points assigned to each location, for Scenario F_M and F_R. The colours are assigned based on the thresholds described in Table 3-1 (Volume 1 of this report).

Table A1.1-3: Annual average concentration of SO_2 for Scenario F_M and F_R.

Concentrations in $\mu\text{g}/\text{m}^3$ Background = $4 \mu\text{g}/\text{m}^3$	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Residential		
Dodge Cove	8.5	7.9
Future Residential Expansion	5.2	5.0
Kitkatla	4.0	4.0
Lax Kw'alaams	4.4	4.2
Metlakatla	5.4	4.9
Port Edward Proposed Hotel	5.1	4.7
Port Edward Residential	5.6	5.3
Prince Rupert Residential	6.6	6.0
Rainbow Lake	4.3	4.1
Prudhomme Lake	4.4	4.2
Kloiya Bay	4.6	4.3
North Pacific Cannery	4.8	4.6
Cassiar Cannery	4.6	4.4
Osland	4.4	4.2
Hunts Inlet	4.1	4.1
Oona River	4.1	4.1
Crippen Cove	7.5	6.8
Cultural & Recreational		
Prince Rupert Golf Course	5.3	4.8
Mount Oldfield Trail	5.3	4.9
Mount Hayes Trail	13.2	12.4
Butze Rapids Trail	4.7	4.4



Concentrations in $\mu\text{g}/\text{m}^3$ Background = 4 $\mu\text{g}/\text{m}^3$	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Metlakatla Sandbar	4.8	4.5
Pike Island	4.9	4.6
Sandbar N. of Casey Point	7.8	7.2
Oliver Lake	4.9	4.5
Kitson Island	4.7	4.6
Industrial		
Canoxy North Industrial	5.9	5.6
Outer Harbour Industrial	8.0	7.5
Inverness Pass. Commercial	5.7	5.4
Prince Rupert NE Industrial	4.8	4.5
South. Prince Rupert Indus.	27.9	26.7
Stapleton Island Industrial	5.1	4.9
Watson Island Industrial	8.2	7.7
Prince Rupert Airport	5.3	5.0

1.1.4 Categorization of 99th Percentile of Hourly Average Concentrations of SO₂

The table below provides the value for the maximum of the 99th percentile of the daily maximum hourly concentrations of SO₂ among the grid points assigned to each location, for Scenario F_M and Scenario F_R. The colours are assigned based on the thresholds described in Table 3-1 (Volume 1 of this report).

Table A1.1-4: 99th percentile of hourly average concentration of SO₂ for Scenario F_M and Scenario F_R.

Concentrations in $\mu\text{g}/\text{m}^3$ Background = 10.67 $\mu\text{g}/\text{m}^3$	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Residential		
Dodge Cove	103.6	103.6
Future Residential Expansion	112.8	112.7
Kitkatla	12.5	12.3
Lax Kw'alaams	20.9	20.9
Metlakatla	47.8	44.3
Port Edward Proposed Hotel	46.3	39.5
Port Edward Residential	81.9	80.0
Prince Rupert Residential	96.3	92.8



Concentrations in $\mu\text{g}/\text{m}^3$ Background = $10.67 \mu\text{g}/\text{m}^3$	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Rainbow Lake	18.3	17.1
Prudhomme Lake	21.3	18.5
Kloiya Bay	27.8	23.4
North Pacific Cannery	31.6	27.9
Cassiar Cannery	25.0	21.9
Osland	19.8	19.3
Hunts Inlet	17.0	16.0
Oona River	15.5	14.6
Crippen Cove	69.9	69.9
Cultural & Recreational		
Prince Rupert Golf Course	48.7	45.5
Mount Oldfield Trail	55.4	49.8
Mount Hayes Trail	182.0	181.9
Butze Rapids Trail	34.0	33.6
Metlakatla Sandbar	29.6	29.4
Pike Island	31.9	29.2
Sandbar N. of Casey Point	142.9	136.9
Oliver Lake	34.9	30.0
Kitson Island	60.6	60.6
Industrial		
Canoxy North Industrial	72.0	68.5
Outer Harbour Industrial	67.2	67.0
Inverness Pass. Commercial	87.3	86.9
Prince Rupert NE Industrial	33.0	32.9
South. Prince Rupert Indus.	505.8	505.3
Stapleton Island Industrial	95.9	93.6
Watson Island Industrial	123.9	124.1
Prince Rupert Airport	45.4	43.4

1.1.5 Categorization of Annual Average Concentrations of NO_2

The table below provides the value for the maximum of the annual average concentrations of NO_2 among the grid points assigned to each location, for Scenario F_M and Scenario F_R. The colours are assigned based on the thresholds described in Table 3-1 (Volume 1 of this report).



Table A1.1-5: Annual average concentration of NO₂ for Scenario F_M and Scenario F_R.

Concentrations in µg/m ³ Background = 5.64 µg/m ³	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Residential		
Dodge Cove	22.0	27.5
Future Residential Expansion	16.9	12.7
Kitkatla	5.8	6.0
Lax Kw'alaams	7.2	8.3
Metlakatla	10.3	12.5
Port Edward Proposed Hotel	7.9	9.4
Port Edward Residential	15.7	12.8
Prince Rupert Residential	15.6	19.5
Rainbow Lake	6.3	7.2
Prudhomme Lake	6.5	7.6
Kloiya Bay	6.9	8.2
North Pacific Cannery	12.7	11.4
Cassiar Cannery	10.5	11.0
Osland	7.0	8.2
Hunts Inlet	6.0	6.4
Oona River	6.0	6.4
Crippen Cove	15.8	19.9
Cultural & Recreational		
Prince Rupert Golf Course	9.1	11.1
Mount Oldfield Trail	10.0	12.4
Mount Hayes Trail	33.2	36.2
Butze Rapids Trail	7.4	8.8
Metlakatla Sandbar	8.7	10.3
Pike Island	9.1	10.8
Sandbar N. of Casey Point	29.9	31.6
Oliver Lake	7.6	9.1
Kitson Island	7.9	9.1
Industrial		
Canoxy North Industrial	8.7	10.4
Outer Harbour Industrial	16.2	19.1
Inverness Pass. Commercial	27.7	15.0
Prince Rupert NE Industrial	8.1	9.7
South. Prince Rupert Indus.	221.7	107.0
Stapleton Island Industrial	9.3	10.4
Watson Island Industrial	17.9	14.2



Concentrations in $\mu\text{g}/\text{m}^3$ Background = $5.64 \mu\text{g}/\text{m}^3$	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Prince Rupert Airport	9.7	11.6

1.1.6 Categorization of 98th Percentile of Hourly Average Concentrations of NO₂

The table below provides the value for the maximum of the 98th percentile of the daily maximum hourly concentrations of NO₂ among the grid points assigned to each location, for Scenario F_M and Scenario F_R. The colours are assigned based on the thresholds described in Table 3-1 (Volume 1 of this report).

Table A1.1-6: 98th percentile of hourly average concentration of NO₂ for Scenario F_M and Scenario F_R.

Concentrations in $\mu\text{g}/\text{m}^3$ Background = $24.44 \mu\text{g}/\text{m}^3$	Scenario	Scenario
Human Health Receptor Location	F_M	F_R
Residential		
Dodge Cove	540.9	620.4
Future Residential Expansion	186.1	151.3
Kitkatla	34.3	38.0
Lax Kw'alaams	111.8	133.8
Metlakatla	94.6	109.7
Port Edward Proposed Hotel	73.4	88.5
Port Edward Residential	122.2	123.7
Prince Rupert Residential	421.4	485.5
Rainbow Lake	43.0	50.0
Prudhomme Lake	48.6	61.5
Kloiya Bay	51.9	75.5
North Pacific Cannery	80.2	90.5
Cassiar Cannery	68.3	74.3
Osland	48.5	67.5
Hunts Inlet	47.9	56.3
Oona River	44.1	50.6
Crippen Cove	322.8	374.6
Cultural & Recreational		
Prince Rupert Golf Course	101.7	127.2
Mount Oldfield Trail	104.5	127.2
Mount Hayes Trail	879.3	712.6



Concentrations in $\mu\text{g}/\text{m}^3$ Background = 24.44 $\mu\text{g}/\text{m}^3$	Scenario	Scenario
Human Health Receptor	F_M	F_R
Location		
Butze Rapids Trail	56.6	76.0
Metlakatla Sandbar	62.6	72.7
Pike Island	72.2	82.1
Sandbar N. of Casey Point	948.7	802.9
Oliver Lake	59.9	83.5
Kitson Island	127.4	150.3
Industrial		
Canoxy North Industrial	87.7	100.4
Outer Harbour Industrial	115.7	144.3
Inverness Pass. Commercial	338.2	157.0
Prince Rupert NE Industrial	114.7	133.7
South. Prince Rupert Indus.	4008.8	1795.0
Stapleton Island Industrial	113.5	129.8
Watson Island Industrial	149.8	114.3
Prince Rupert Airport	71.8	86.4



1.2 Scenario F_M and F_R Results for Vegetation Assessment

Table A1.2-1: Averaging periods and modelled concentrations for SO₂ under Scenario F_M.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	US EPA Secondary Standards ^b (µg/m ³)	Maximum Date and Start Time All Receptors	
					Julian Day	Time
1-hour	1st	548	548		232	0100
	2nd		547		103	2300
	4th		506		200	2100
3-hour	1st	462		1300	232	0000
	2nd	323			233	0000
Annual	Mean	28				
Annual Growing Season ^c		33				
Annual Growing Season Daylight ^c		25				

a Modelled concentrations of 3-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include background concentrations corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations are provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 4.0 ppb = 10.7 µg/m³ for 1-hour and 3-hour averaging period; 1.5 ppb = 4.0 µg/m³ for the annual averaging period.

b Secondary National Ambient Air Quality Standard (NAAQS) define the levels that protect the public welfare from any known or anticipated adverse effects of a pollutant. The secondary standard for the 3-hour averaging period is not to be exceeded more than once per calendar year. Therefore, results are compared to the second high.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.



Table A1.2-2: Averaging periods and modelled concentrations for SO₂ under Scenario F_R.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	US EPA Secondary Standards ^b (µg/m ³)	Maximum Date and Start Time All Receptors	
					Julian Day	Time
1-hour	1st	547	547		103	2300
	2nd		547		232	0100
	4th		505		231	2000
3-hour	1st	413			232	0100
	2nd	315		1300	197	2200
Annual	Mean	27				
Annual Growing Season ^c		32				
Annual Growing Season Daylight ^c		23				

a Modelled concentrations of 3-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include background concentrations corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations are provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 4.0 ppb = 10.7 µg/m³ for 1-hour and 3-hour averaging period; 1.5 ppb = 4.0 µg/m³ for the annual averaging period.

b Secondary National Ambient Air Quality Standard (NAAQS) define the levels that protect the public welfare from any known or anticipated adverse effects of a pollutant. The secondary standard for the 3-hour averaging period is not to be exceeded more than once per calendar year. Therefore, results are compared to the second high.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.



Table A1.2-3: Averaging periods and modelled concentrations for NO₂ under Scenario F_M.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	European Critical Level ^b (µg/m ³)	Maximum Date and Start Time All Receptors	
					Julian Day	Time
1-hour	1st	5241	5241		140	2300
	2nd		4645		232	0100
	8th		4009		198	0000
Annual	Mean	222		30		
Annual Growing Season ^c		252		30		
Annual Growing Season Daylight ^c		140				

a Modelled concentrations of 1-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include a background concentration corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. NO₂ concentrations are determined based on modelled NO_x concentrations and ambient ratios according to U.S. EPA Guidance (28-June- 2010 and 01-March-2011). Maximum modelled concentrations exclude receptors located on water. Background concentrations were provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 13.0 ppb = 24.44 µg/m³ for the 1-hour averaging period; 3.0 ppb = 5.64 µg/m³ for the annual averaging period.

b Comparison to the WHO Guideline is not intended to provide conclusions related to impacts on the environment. The European Critical Level is intended for protection of vegetation.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.



Table A1.2-4: Averaging periods and modelled concentrations for **NO₂** under Scenario F_R.

Averaging Period	Rank	Maximum Concentration ^a (µg/m ³)	Daily Maximum Concentration ^a (µg/m ³)	European Critical Level ^b (µg/m ³)	Maximum Date and Start Time All Receptors	
					Julian Day	Time
1-hour	1st	2482	2482		140	2300
	2nd		2311		200	2100
	8th		1795		173	2300
Annual	Mean	107		30		
Annual Growing Season ^c		130		30		
Annual Growing Season Daylight ^c		95				

a Modelled concentrations of 1-hour and annual averaging periods represent the maximum of the 2012 meteorological year modelled, and include a background concentration corresponding to the appropriate averaging period. Daily maximum concentrations of 1-hour averaging period represent the daily maximum modelled (i.e., the 2nd daily maximum will not be on the same day as the 1st daily maximum) plus the 1-hour background concentration. Maximum modelled concentrations exclude receptors located on water. Background concentrations were provided by MOE on 06-Mar-2015, and converted from ppb to µg/m³ based on the values in BC AQOs table: 13.0 ppb = 24.44 µg/m³ for the 1-hour averaging period; 3.0 ppb = 5.64 µg/m³ for the annual averaging period.

b Comparison to the WHO Guideline is not intended to provide conclusions related to impacts on the environment. The European Critical Level is intended for protection of vegetation.

c Growing Season is from 15-April through 15-September; Growing Season Daylight is from 7 AM to 7 PM (Pacific Time) in Growing Season. The annual background concentration is applied to these concentrations.



1.3 Scenario F_M and Scenario F_R Results for Soils and Terrestrial Ecosystems Assessment

Table A1.3-1: Exceedance of the: Critical Load Function (CLF: see Figure 5-3 in Volume 1 of this report) for acidification (defined by $CL_{max}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$) of forest (coniferous, deciduous and mixed), herb, shrub and wetland ecosystems (see Figure 5-1, Volume 1), critical load of nutrient nitrogen ($CL_{nut}(N)$) for forest (coniferous, deciduous and mixed), herb, shrub and wetland ecosystems on mineral soil (see Figure 5-1, Volume 1), and empirical nutrient nitrogen ($CL_{emp}(N)$) for terrestrial habitats (see Table 5-4, Volume 1), under Scenario F_M and Scenario F_R.

Scenario	F_M	F_R
Acidity (sulphur and nitrogen)		
Risk category ^a		
Average exceedance (meq/m ² /yr)	0	24.44
Average exceedance S (meq/m ² /yr)	0	8.78
Average exceedance N (meq/m ² /yr)	0	15.66
Exceeded area (%) ^b	0	1.75
Exceeded area (km ²)	0	10.27
Exceeded area >10 meq/m ² /yr (km ²)	0	7.26
Exceeded area >20 meq/m ² /yr (km ²)	0	6.34

Scenario	F_M	F_R
Nutrient Nitrogen		
Risk category ^a		
$CL_{nut}(N)$ exceedance (meq/m ² /yr)	5.16	19.03
$CL_{nut}(N)$ exceeded area (%) ^b	0.01	4.02
$CL_{nut}(N)$ exceeded area (km ²)	0.07	23.54
Risk category ^a		
$CL_{emp}(N)$ exceedance (meq/m ² /yr)	8.07	16.07
$CL_{emp}(N)$ exceeded area (%) ^b	1.56	15.44
$CL_{emp}(N)$ exceeded area (km ²)	9.50	93.82

^a Risk category based on exceedance area (%); note two risk categories were assigned to nutrient nitrogen based on $CL_{nut}(N)$ and $CL_{emp}(N)$ exceeded area (%). The risk category colours are assigned based on the scheme outlined in Table 5-6, Volume 1 of this report.

^b Exceeded area presented as a proportion (%) of the effects domain, which is defined as the receptor ecosystem area enclosed by a 15 meq/m²/yr modelled sulphur and nitrogen deposition isopleth under Scenario F_M ($CL_{acidity}(S+N)$: 586 km²; $CL_{nut}(N)$: 513 km²; $CL_{emp}(N)$: 608 km²).



1.4 Scenario F_M and Scenario F_R Results for Aquatic Ecosystems Assessment

Table A1.4-1: Results for lakes analysis under Scenario F_M, including: exceedances according to the SSWC and FAB models (results are shaded according to exceedance class: yellow = -10 to 0 meq/L, blue = -20 to -10 meq/L, and green \leq -20 meq/L); changes in pH according to the ESSA-DFO model; and exceedance of N-nutrient (column at far right) estimated for the eutrophication analysis (see Section 6.2.4 in Volume 1 of this report). The second right-most column presents the risk category as defined in Table 6-3 (Volume 1). Current pH values <6 are shaded in pink.

Lake	Current pH	Exceedance (meq/m ² /yr)		ESSA-DFO model	CL exceedance?/ Δ pH >0.3?	N exceedance (N kg/ha/yr)
		SSWC	FAB	Δ pH		
Alywn	6.32	-195.45	-212.76	-0.001	No/No	-3.72
Georgetown	6.78	-358.20	-393.07	0.000	No/No	-4.26
NC254	5.26	-64.26	-72.51	-0.081	No/No	-3.72
NC273	6.05	-73.49	-91.98	-0.015	No/No	-3.89
NC275	7.03	-785.16	-856.91	0.000	No/No	-3.60
NC278	5.07	-106.44	-117.42	-0.025	No/No	-2.13
NC279	5.30	-116.46	-148.47	-0.001	No/No	-4.92
NC284	6.55	-325.56	-381.00	0.000	No/No	-4.80
NC292	6.17	-55.16	-62.41	-0.014	No/No	-4.23
NC303	6.51	-141.53	-158.26	0.000	No/No	-4.84
NC309	5.12	-26.72	-34.77	-0.084	No/No	-4.09
NC313	4.84	-72.18	-90.91	-0.015	No/No	-2.21
NC314	5.97	-107.94	-130.07	-0.001	No/No	-4.91
NC327	6.33	-15.17	-11.80	-0.011	No/No	-4.57
NC330	6.24	-106.15	-131.26	-0.001	No/No	-4.90
NC332	5.64	-163.87	-197.14	0.000	No/No	-4.86
NC333	6.40	-97.49	-118.73	-0.001	No/No	-4.85
NC337	6.60	-65.81	-73.52	-0.006	No/No	-4.45
NC338	5.89	-9.84	-12.22	-0.019	No/No	-4.74
NC339	5.41	-125.80	-147.77	-0.001	No/No	-4.93
NC340	5.81	-156.14	-182.82	-0.003	No/No	-4.22
NC344	6.34	-110.10	-128.02	-0.001	No/No	-4.74
NC350	6.21	-82.45	-87.47	-0.006	No/No	-4.63
NC357	6.24	-70.70	-78.24	-0.007	No/No	-4.56
NC360	4.91	-55.65	-68.10	-0.052	No/No	-2.26
NC361	6.09	-111.37	-122.67	-0.002	No/No	-4.78
Diana	5.49	-75.59	-91.86	-0.026	No/No	-4.41
NC374	6.73	-187.43	-223.84	-0.001	No/No	-3.85
NC389	6.82	-427.94	-471.31	0.000	No/No	-4.72
NC391	6.49	-107.21	-119.00	-0.003	No/No	-4.51
Wolfe	6.13	-486.65	-554.51	0.000	No/No	-3.28
Oliver	6.47	-557.91	-608.09	0.000	No/No	-3.91
AD-SW6	6.26	-344.57	-393.79	0.000	No/No	-2.48
Shawatlan	5.98	-139.07	-167.64	-0.002	No/No	-3.96
AD-SW9	5.51	-54.97	-81.24	-0.007	No/No	-2.38
Overall risk					Low	Low



Table A1.4-2: Results for lakes analysis under Scenario F_R, including: exceedances according to the SSWC and FAB models (results are shaded according to exceedance class: yellow = -10 to 0 meq/L, blue = -20 to -10 meq/L, and green \leq -20 meq/L); changes in pH according to the ESSA-DFO model; and exceedance of N-nutrient (column at far right) estimated for the eutrophication analysis (see Section 6.2.4 in Volume 1 of this report). The second right-most column presents the risk category as defined in Table 6-3 (Volume 1). Current pH values <6 are shaded in pink.

Lake	Current pH	Exceedance (meq/m ² /yr)		ESSA-DFO model	CL exceedance?/ Δ pH > 0.3?	N exceedance (N kg/ha/yr)
		SSWC	FAB	Δ pH		
Alywn	6.32	-193.36	-204.09	-0.002	No/No	-2.71
Georgetown	6.78	-354.22	-383.13	0.000	No/No	-3.32
NC254	5.26	-63.80	-70.11	-0.098	No/No	-3.44
NC273	6.05	-59.84	-65.20	-0.067	No/No	-1.74
NC275	7.03	-781.71	-844.83	0.000	No/No	-2.50
NC278	5.07	-105.90	-114.45	-0.032	No/No	-1.87
NC279	5.30	-116.36	-148.11	-0.002	No/No	-4.88
NC284	6.55	-325.49	-379.94	0.000	No/No	-4.66
NC292	6.17	-53.70	-57.20	-0.027	No/No	-3.67
NC303	6.51	-141.09	-156.99	-0.001	No/No	-4.72
NC309	5.12	-17.92	-16.51	-0.292	No/No	-2.59
NC313	4.84	-71.51	-87.58	-0.021	No/No	-1.72
NC314	5.97	-107.84	-129.63	-0.002	No/No	-4.86
NC327	6.33	-14.26	-9.13	-0.019	No/No	-4.31
NC330	6.24	-106.08	-130.87	-0.001	No/No	-4.85
NC332	5.64	-163.62	-196.26	-0.001	No/No	-4.77
NC333	6.40	-97.45	-117.92	-0.001	No/No	-4.73
NC337	6.60	-64.46	-69.30	-0.012	No/No	-4.01
NC338	5.89	-9.48	-10.34	-0.038	No/No	-4.46
NC339	5.41	-125.70	-147.43	-0.001	No/No	-4.90
NC340	5.81	-147.64	-165.03	-0.011	No/No	-2.89
NC344	6.34	-109.99	-126.66	-0.001	No/No	-4.55
NC350	6.21	-81.21	-83.84	-0.015	No/No	-4.26
NC357	6.24	-69.56	-74.55	-0.013	No/No	-4.16
NC360	4.91	-55.02	-64.38	-0.076	No/No	-1.75
NC361	6.09	-111.26	-121.20	-0.003	No/No	-4.56
Diana	5.49	-74.87	-87.92	-0.044	No/No	-3.76
NC374	6.73	-186.27	-218.08	-0.002	No/No	-3.09
NC389	6.82	-427.24	-469.44	0.000	No/No	-4.55
NC391	6.49	-106.01	-114.86	-0.006	No/No	-4.06
Wolfe	6.13	-478.86	-534.49	0.000	No/No	-1.46
Oliver	6.47	-550.47	-588.06	0.000	No/No	-2.09
AD-SW6	6.26	-315.78	-337.59	0.000	No/No	1.57
Shawatlan	5.98	-135.73	-158.18	-0.006	No/No	-2.58
AD-SW9	5.51	-54.53	-78.88	-0.009	No/No	-2.08
Overall risk					Low	Low



Table A1.4-3: Summary of the eutrophication risk analysis for the 859 lakes in the PRAS area with a surface greater than 1 ha. Exceedances results are provided for two Critical Load (CL) thresholds: 3 N kg/ha/yr (dystrophic lakes) and 5 N kg/ha/yr (oligotrophic lakes). According to the risk categorization framework defined in Section 6.1.3 (Volume 1 of this report), green shading indicates low risk and yellow shading indicates moderate risk of eutrophication.

Eutrophication Risk for All Lakes	Average N deposition (N kg/ha/yr)	N-nutrient Exceedances			
		CL = 3 N kg/ha/yr		CL = 5 N kg/ha/yr	
		#lakes	%lakes	#lakes	%lakes
Scenario F_M	0.35	0	0%	0	0%
Scenario F_R	0.51	25	3%	10	1%



2 Appendices for Air Dispersion and Deposition Modelling

2.1 Modelling Protocol

Approved CALMET Protocol:

Model selection: CALMET version 6. 40, Level 121203

Domain (approved):

South: 53.217045° North: 55.771456° West: -132.013106° East: -128.882566°

The domain includes 50 km buffer beyond the study area and extends to include the WRF grid (see the plot at the end of the email).

Coordinate system: UTM, zone 9, datum WGS-84. The low left corner of the domain is located at point X= 30.5.6 km and Y= 5897.6 km it encompasses a 203 x 283 km area. Grid resolution is 1km hence NX=203 and NY=283.

In vertical dimension the domain will extend to 4km including 10 layers defined by the following vertical levels:

ZFACE = 0.,20.,40.,80.,160.,300.,600.,1000.,1500.,2200.,3000., 4000

Meteorological data included:

- Output of WRF
- Hourly surface observation from the stations provided by the BC Ministry of Environment (MOE)
- Buy data for SEA.dat if available provided by MOE
- Twice-daily upper air observations – one station with good amount of observations was found within the CALMET domain - ANNETTE ISLAND AIRPORT with WBAN=25308 LAT=55.03N, LON=131.57W, elevation = 33.22m
 - o We originally discussed not including any upper air stations. However Annette Island is well within the modelling domain and is expected to be representative of the nearby area.
- Precipitation would include records from the WRF model outputs and/or data provided by MOE

Terrain:

- Elevation data will be obtained from Canadian Digital Elevation Model (CDEM) at 1.5 arc second (~45 meter) resolution
 - o We discussed elevation data coming from Canadian Digital Elevation Data (CDED). However, the Geobase portal transitioned to GeoGratis (Natural Resources of Canada), at: <http://geogratias.gc.ca>. On the Geogratias server, the Canadian Digital Elevation Model (CDEM) provides elevation data that can be extracted easily for the coordinates and resolution defined by the user: <http://geogratias.gc.ca/site/eng/extraction?layers=cdem>
 - o The Canadian Digital Elevation Model (CDEM) is part of Natural Resources Canada's altimetry system designed to better meet the users' needs for elevation



- data and products. The CDEM stems from the existing Canadian Digital Elevation Data (CDED).
- 90-meter SRTM data will be use for the Alaska portion of the domain or if needed otherwise to fill missing data <http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1>
 - Terrain grid will be obtained using TERREL version 3.69, level 110330.

Land-use: Baseline Thematic Mapping Present Land Use Version 1 Spatial Layer will be downloaded from the British Columbia Government archives <https://apps.gov.bc.ca/pub/dwds/home.so>

- These land use maps will be processed on seasonal basis (winter without snow on the ground and summer with lush vegetation) using the following months-to-season distribution: winter months are January, February, March, April, October, November and December; summer months are May, June, July, August, and September. The domain is located near the northern Pacific coast and hence experiences very little of continuous snow on the ground.
- For purposes of Bowen ratio calculation the modelling year 2012 should be considered as wet year.
- The BTM land use categories will be mapped to the CALMET categories using Table 9.10 in the BC Modelling Guideline.
- Fractional land-use categories will be calculated for each grid cell using CTGPROC version 3.5, level 110403.
- In addition coastline maps will be downloaded and included in the processing. Coastline files will downloaded from “GSHHG - A Global Self-consistent, Hierarchical, High-resolution Geography Database” before <http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html>). Trinity will evaluate the coastline data accuracy against aerial imagery and provide these QA/QC plots to MOE in order to reach agreement on the use of the sub-grid thermal boundary layer (TIBL)

Calculation of the surface micrometeorological parameters will be complete with MAKEGEO version 3.2, level 110401.

Key CALMET Switch Settings: Trinity will follow the BC Guidelines for setting up CALMET and use the following values for the parameters left to be determined by modelers



Input Parameter and Definition	Default Value	Selected Value	Selection Description
RMAX1: Maximum radius (km) of influence over land in the surface layer	No default	! RMAX1 = 5. !	No more than 4 WRF cells
RMAX2: Maximum radius (km) of influence over land aloft	No default	! RMAX2 = 10. !	No more than 4 WRF cells
RMAX3: Maximum radius (km) of influence over water	No default	! RMAX3 = 40!	Approximately 1/2 domain width
RMIN: Minimum radius (km) of influence used in the wind field interpolation	Default: 0.1	! RMIN = 0.1!	
TERRAD: Radius (km) of influence of terrain features	No default	! TERRAD = 4. !	Approximately 4 CALMET grid cells; the smallest recognizable terrain features ~2km
R1: Distance (km) from an observation station at which the observation and first guess field are equally weighted at surface level	No default	! R1 = 2. !	2 CALMET grid cells
R2: Distance (km) from an observation station at which the observation and first guess field are equally weighted aloft	No default	! R2 = 8. !	2 WRF grid cells
Radius of influence for temperature interpolation	Default: 500	! TRADKM = 4!	4 CALMET grid cells

These CALMET parameter values will be tested over the entire grid for 2 days (one during the summer and one during the winter) to ensure that the wind fields are smooth no sudden convergence/ divergence is occurring on selected grid points. A second test will be performed to compare CALMET winds and temperature from WRF data without observations compared to selected surface observation stations at a grid point nearest to the station to produce the annual and seasonal wind roses and confirm that the observed fields are realistically captured by the WRF model. Based on these tests, up to two alternative CALMET control files (with alternate switch settings) will also be run for the two sample days in order to verify the most representative CALMET control settings.



Approved CALPUFF Modelling Protocol:

Model selection: CALPUFF version 6.42, Level 110325. (Recompiled to expand grid cell domain to accommodate meteorological domain)

Post-Processors:

CALPOST version 6.292, level 110406

POSTUTIL version 1.641, level 110225

APPEND version 2.36, level 110301

Domain and Coordinate System: As presented in CALMET protocol. UTM, zone 9, datum WGS-84

CALPUFF Key Switches and Settings:

For the switches and settings not identified in the table below the default CALPUFF and MOE Guidelines Table 9.7 switch settings will be used.

Input Parameter and Definition	MOE Guideline Value	Selected Value	Selected Description
Method used to simulate building downwash?	MBDW= 2 (Prime)	MBDW=1 (ISC)	Downwash will only be turned on when a proponent directly provides BPIP data provided. BPIP data was provided by one proponent for ISC downwash only, so Prime was not used.
Chemical Transformation Scheme	MCHEM=1 (MESOPUFF II)	MCHEM=6 (RIVAD with ISORRPIA equilibrium)	The MCHEM = 6 option is selected for all but one modelling scenario, Scenario 4. MCHEM=6 incorporates an update to the RIVAD chemical mechanism for the transformation of SO2 and NO/NO2 to sulfates and nitrates/nitrites, respectively. This option also replaces MESOPUFFII CHEMEQ model with ISORRPIA model for inorganic gas-particle equilibrium and provides a new option for aqueous-phase transformation adapted from the RADM cloud implementation in CMAQ/SCICHEM. MCHEM 7 with CALTech SOA formation algorithm was <u>not</u> selected as data on primary speciated VOC emissions and organic carbon emissions is not readily available for all sources, therefore accounting for anthropogenic SOA formation is not feasible for this analysis.



Input Parameter and Definition	MOE Guideline Value	Selected Value	Selected Description
Chemical Transformation Scheme	MCHEM=1 (MESOPUFF II)	MCHEM=1 (MESOPUFF II)	MCHEM = 1 selected for Scenario 4 only.
Aqueous phase transformation flag	MAQCHEM=0 (Not modelled)	MAQCHEM = 1	MAQCHEM is only used when MCHEM = 6 or 7. Transformation rates and wet scavenging coefficients are adjusted for in-cloud aqueous phase reactions.
Liquid Water Content Flag	N/A	MLWC=0	Data only required if MAQCHEM=1. Water content estimated from cloud cover and presence of precipitation = 0. Gridded cloud water data read from CALMET water content output files = 1. (SEE NOTE 1)
Method used to compute dispersion coefficients	MDISP = 2 near-field, MDISP = 3 long-range	MDISP=2	Option 2 indicates dispersion coefficients from internally calculated sigma v, sigma w using micrometeorological variables (u*, w*, L, etc.). This is the same option as KAA.
Probability Distribution Function used for dispersion under convective conditions	MPDF=1 if MDISP = 2 MPDF=0 if MDISP = 1	MPDF = 1	Yes (1) if MDISP = 2 (simulates AERMOD-type dispersion, averaging the balance between up- and down-drafts in vertical column).
Sub-Grid TIBL module for shore line?	MSGTIBL=0 (No)	MSGTIBL=1 (Yes)	Due to the proximity of the coast line the Sub grid TIBL will be used. Note that the SGTIBL option currently holds a place-holder value while the coastline input file is being developed.

NOTE 1: MCHEM=6 (RIVAD with ISORRPIA) is being tested with and without the use of liquid water content data from CALMET. Initial tests indicate successful runs are achieved if MLWC = 0, but not if MLWC = 1. If the MLWC = 1 option can be run successfully, this will be the recommended setting. If any runtime issues arise that are not resolved with a reasonable effort, the use of MCHEM=3 (RIVAD/ARM3) or MCHEM=1 may be discussed to determine the most appropriate path forward.

Additional CALPUFF Data Inputs Based on Switches and Settings Selected:

MOZ (MCHEM=1 or 6) = Use monthly data

BCKO3 (MCHEM=1 or 6) = For Scenario F_M 80 ppb was used for all months. For Scenario F_R monthly average monitor data was provided by MOE for the Prince Rupert area. In calendar order the ppb values for each month are: 36, 46, 53, 58, 62, 65, 65, 60, 50, 40, 36, 36.



MNH3 (MCHEM= 6) = Use monthly background values.

MAVGNH3 (MCHEM= 6) = NOT be required with MHN3 set to monthly background NH3 values.

BCKNH3 (MCHEM=1 or 6) = 0.5 ppb. The IWAQM Phase 2 report default for forest land is 0.5 ppb. Since 59% of the domain is forest land we are proposing the 0.5 ppb value to represent background NH3 (See image below for graph of LU data).

RNITE1 (MCHEM=1 or 6) = default at 0.2 %/hour

RNITE2 (MCHEM=1) = default at 2.0 %/hour

RNITE3 (MCHEM=1) = default at 2.0 %/hour

MH2O2 (MCHEM= 6) = use monthly background H2O2 value

BCKH2O2 (MCHEM=6) = default at 1 ppb for each month

NO2/NOx Ratios for RIVAD

NOx emissions will be speciated into NO and NO2 emissions based on in-stack ratio data.

All sources except turbines will assume 10% NO2 and 90% NO (i.e. 0.1 in-stack NO2/NOx ratio).

Turbines with DLE (or SoLoNox) will use data from Solar indicated at 30% NO2 (or a 0.3 in stack NO2/NOx ratio)

Data for in-stack ratios for turbines with SCR also uses the 0.3 in stack NO2/NOx ratio



2.2 CALMET Methodology

2.2.1 Introduction

As part of an overall strategic modelling analysis in support of the Prince Rupert Airshed Study (PRAS), Trinity Consultants (Trinity) has been contracted by MOE and ESSA Technologies Ltd. (ESSA) to assist with the generation of CALMET meteorological files. CALMET data files were developed as part of a complex study aiming to evaluate the air quality conditions from the perspective of human health in the Prince Rupert Airshed domain.

Meteorology plays a major role in determining air quality changes caused by the operation of emission sources. Both the wind and atmospheric stability greatly affect dispersion conditions. Local influences due to terrain and land-cover factors can also be important. For dispersion modelling, the CALMET meteorological model was used in conjunction with the CALPUFF air dispersion model. Meteorological input data for CALMET consisted of surface (over-land and over-water) and upper air data for the period January 1 - December 31, 2012 as well as the gridded fields produced by the mesoscale model.

The CALMET surface layer characterization was resolved in part with compatible data from meteorological stations available within the modelling domain. Upper air observations from the single station within the domain were included.

All observation stations are placed near populated areas and do not provide regular and sufficient coverage of the modelling domain. Therefore, the Weather Research and Forecasting (WRF) numerical weather prediction system was used to produce mesoscale meteorological fields and enhance the depiction of the meteorological conditions.

The following sections outline the methodology employed for this CALMET processing:

- Domain and Coordinate System
- Weather Research and Forecasting (WRF) Model
- Terrain Elevation Data
- Land-use Data
- Over-land Surface Meteorological Data
- Upper-air Meteorological Data
- Over-water Surface Meteorological Data
- CALMET Modelling Options
- CALMET Sensitivity Testing
- CALMET Representativeness
- Conclusion

2.2.2 Domain and Coordinate System

The CALMET modelling domain shown in Figure A2.2-1 was defined to encompass the study area with minimum of 50 km buffer in each direction. The CALMET domain was constructed as a rectangular Cartesian grid, which covers a 202-by-283 kilometer (km) area at resolution of 1 km and extends 4 kms in the vertical direction. It was determined that the height of 4 km is



sufficient to resolve the atmospheric boundary layer, where the plume dispersion occurs. The vertical span of the domain was split into eleven (11) layers defined by the following heights: 0, 20, 40, 80, 160, 300, 600, 1000, 1500, 2200, 3000, and 4000 metres.

The southwest corner of the CALMET grid was selected as Easting 305.6 (km), Northing 5897.6 (km) in Universal Transverse Mercator (UTM) Zone 9, World Geodesic System 1984 (WGS-84) coordinates.

The CALPUFF FAQ¹ states that “[f]or applications in the middle latitudes, the distortion due to use of UTM coordinates will generally become significant for modeling domains exceeding 200 kilometers on a side.” Since Prince Rupert is at the northern edge of the “middle latitudes” belt, a smaller threshold would apply. The full CALMET and CALPUFF domain is larger than 200 km. However, the study area is 101 km east-west by 182 km north-south; therefore, results would not be expected to be significantly affected by using the UTM coordinate system. Small effects may be seen near the boundaries of the domain, but would not likely be significant in the context of 1 km spaced receptors in these regions. The advantage of using the UTM coordinate system is that the various disciplines using the results and most reviewers are familiar with UTM coordinates, and can easily map those coordinates to user-friendly programs, such as Google Earth.

Figure A2.2-1 shows the study area marked with the red diamond-like shape, the CALMET domain outlined in blue for which terrain elevation is provided, and the coastline. The blue dots mark the grid point locations of the WRF Model at surface level.

¹ <http://www.src.com/calpuff/FAQ-answers.htm#1.1.5>



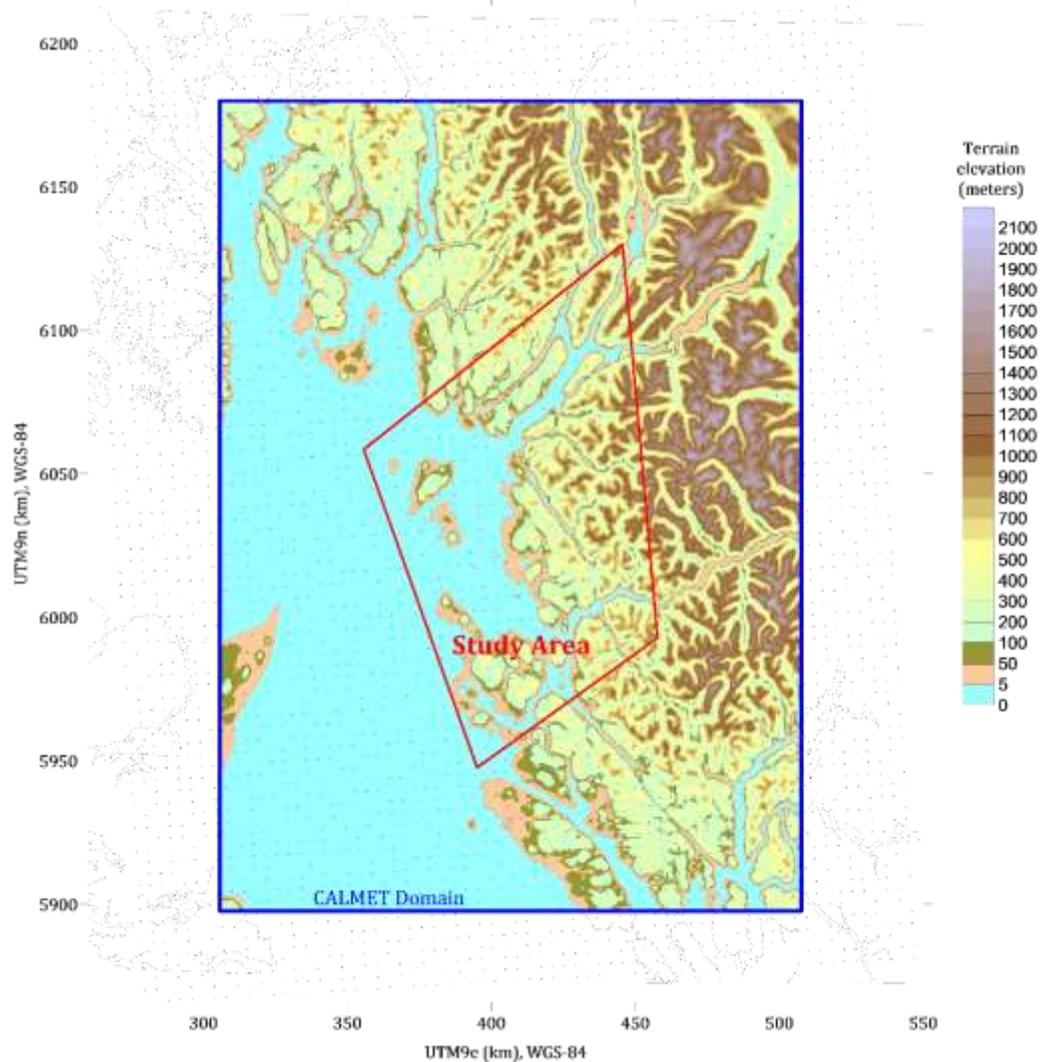


Figure A2.2-1: WRF, CALMET domains, and study area over terrain map.

2.2.3 Weather Research and Forecast (WRF) Model

The 2012 WRF data set for use in this CALMET application was provided by MOE². The WRF data set contains 12 files each covering one calendar month. The beginning and ending time were shifted to accommodate the time difference between local time zone (UTC-8) and GMT, the native WRF time zone. WRF domain extends from longitude -132.8° in the west to -128.3° in the east and from latitude 52.9° at the southern extent to 56.1° at the northern extent at grid resolution of 4 km. The domain is divided into 40 vertical layers reaching out to the 100 mB level. The WRF data set was used to generate the diagnostic meteorological fields and as the main source of precipitation data for the domain.

² Prepared by Li Huang, Air Quality Meteorologist, MOE and mailed to Trinity 20 January 2015.

2.2.4 Terrain Elevation Data

Terrain elevation for CALMET was obtained using the TERREL processor version 3.69 level 110330. The model was executed with terrain maps provided by the Consultative Group on International Agricultural Research (CGIAR) and the Consortium for Spatial Information (CSI) website³. Data were collected as part of the Shuttle Radar Topographic Mission (SRTM) and processed by CSI into 5° x 5° tiles at 90 metre resolution. The data were provided to TERREL in GeoTIFF format and further interpolated over the CALMET grid. Figure A2.2-1 shows the terrain elevations within the domain represented by the shaded area.

The SRTM data were used only for the geo-processing of the CALMET domain; the elevations of the discrete receptors and emission sources were extracted from the Canadian Digital Elevation Data (CDED) archive provided by the Department of Natural Resources of Canada⁴.

Initially the SRTM terrain elevation data set was the last choice to resolve the terrain of the CALMET domain. It was intended to provide data only for the Alaskan part of the domain. DEM data were downloaded from the GEOBASE of Canada database as well as from the USGS archives. After processing these data sets, it was found that the domain elevations were not well resolved, especially the coastal areas. Some of the islands included in the study area were completely submerged. Therefore, it was decided to use the SRTM data to resolve the entire CALMET domain. Such treatment provides smooth and seamless representation of the terrain. The SRTM data used in CALMET are part of Version 4 Archive and include high resolution DEM data incorporated in them, with corrections made for the previously identified error of reporting elevations near the top of canopies.

Several tests were also performed by extracting locations in the vicinity of Prince Rupert and comparing them to Google Earth – they showed satisfactory matching levels.

In addition to the SRTM data, coastline data of full resolution grade were used to better outline the sea-land boundary. The coast line data were obtained from the Global Self-consistent, Hierarchical, High-resolution Geography (GSHHG) Database supported by the National Geographic Data Center at NOAA⁵.

The GSHHG is a high-resolution geography data set, amalgamated from two databases in the public domain: World Vector Shorelines (WVS) and CIA World Data Bank II (WDBII). The former is the basis for shorelines while the latter is the basis for lakes, although there are instances where differences in coastline representations necessitated adding WDBII islands to GSHHG. The WDBII source also provides all political borders and rivers. GSHHG data have undergone extensive processing and should be free of internal inconsistencies such as erratic

³ <http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1>

⁴ <http://geogratis.gc.ca/site/eng/extraction>

⁵ <http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html>



points and crossing segments. The shorelines are constructed entirely from hierarchically arranged closed polygons.

The GSHHG geography data come in five different resolutions: crude (c); low (l); intermediate (i); high (h); and full (f). Shorelines are further organized into four hierarchical levels: boundary between land and ocean (L1); boundary between lake and land (L2); boundary between island-in-lake and lake (L3); and boundary between pond-in-island and island (L4).

2.2.5 Land Use Data

Land characteristics in the domain were extracted using the CALMET pre-processor CTGPROC version 3.5 level 110403. The input land use maps were obtained from British Columbia Geographic Data Center⁶ and from the United States Geological Survey (USGS)⁷ websites in GeoTIFF format. The British Columbia Baseline Thematic Mapping (BMT) provided land cover maps of resolution 30 metres, which were used to resolve the Canadian part of the domain. The USGS maps are part of the 2001 National Land Cover Database (NLCD), have grid resolution of 30 metres and were used to resolve the Alaskan part of the modelling domain.

The two data sets use different categorization schemes to classify the land features, and neither scheme is native to CTGPROC at this time. Therefore the two data sets were extracted with ArcGIS and remapped on 100-metre grid, then each classification scheme was translated to the default CALMET scheme of 38 categories. The size of the domain did not allow for bulk processing at higher resolution – the files were exceeding manageable size and requiring processing time not available for this project. Additionally, the CALMET grid cells are of 1 km size, and 100-meter resolution of the input data is sufficient to provide detail on the CALMET grid, i.e., using approximately 100 input grid cells to evaluate the land characteristics of one CALMET grid cell. The CTGPROC utility was initialized with files of generic type constructed of three variable types – X-coordinate, Y-coordinate and LU-code. Table A2.2-1 provides the translation mechanism for both – the BMT and the NLCD maps.

The land use characteristics of the CALMET domain are shown on Figure A2.2-2.

Table A2.2-1: BTM and 2001 NLCD land cover categories translated to CALMET 38 category set.

B.C. LU Code	B.C. Land Use Category	CALMET LU Code	CALMET Land Use Category
From BC Modelling Guideline			
2	Agriculture	21	Agricultural - cropland or pasture
3	Barren Surfaces	74	Barren - bare exposed rock
4	Fresh Water	52	Water - Lakes
5	Mining	75	Barren - Strip Mines, Quarries, and gravel pits
6	Old Forest	43	Mixed Forest Land

⁶ <http://www.data.gov.bc.ca/dbc/geographic/index.page?WT.svl=Topnav>

⁷ <http://earthexplorer.usgs.gov/>



B.C. LU Code	B.C. Land Use Category	CALMET LU Code	CALMET Land Use Category
7	Recently Logged	33	Mixed Rangeland
8	Recreation Activities	43	Mixed Forest Land
9	Residential Agriculture Mixtures	21	Agricultural Land
10	Selectively Logged	43	Mixed Forest Land
11	Urban	11	Residential
12	Wetlands	62	Non-forested Wetland
13	Young Forest	43	Mixed Forest Land
Additional not in Guideline			
	Sub alpine Avalanche Chutes	91	Perennial snow fields
	Alpine	83	Bare Ground Tundra
	Glaciers and Snow	92	Glaciers
	Shrubs	32	Shrub and Brush Rangeland
	Estuaries	54	Bays and Estuaries
	Salt Water	55	Large Water Body
	Recently Burned	43	Mixed Forest Land
	Range Lands	33	Rangeland
USGS 2001 LU Code	USGS 2001 Categories	CALMET LU Code	CALMET 38 Input Categories
11	Open water	55	Ocean
12	Perennial Ice/Snow	91	Perennial Snowfields
21	Developed, Open Space	11	Residential
22	Developed, Low Intensity	16	Mixed Urban or Build-up
23	Developed, Medium Intensity	12	Commercial & Services
24	Developed, High Intensity	15	Industrial & Commercial Complexes
31	Barren Land	74	Bare Exposed Rock
32	Quarries/Strip Mines/Gravel Pits	75	Strip Mines, Quarries, Gravel Pits
33	Transitional	76	Transitional Areas
41	Deciduous Forest	41	Deciduous Forest
42	Evergreen Forest	42	Evergreen Forest
43	Mixed Forest	43	Mixed Forest
51	Dwarf Shrub; 52 - Shrub/Scrub	32	Shrub and Brush Range Land
61	Orchards/Vineyards/Other	22	Orchards, Groves, Vineyards, Nurseries, etc.
71	Grassland/Herbaceous	31	Herbaceous Rangeland
81	Pasture/Hay	21	Cropland and Pastures
82	Cultivated Crops	24	Other Agricultural Land
90	Woody Wetlands	61	Forested Wetlands
95	Emergent Herbaceous Wetlands	62	Non-forested Wetlands



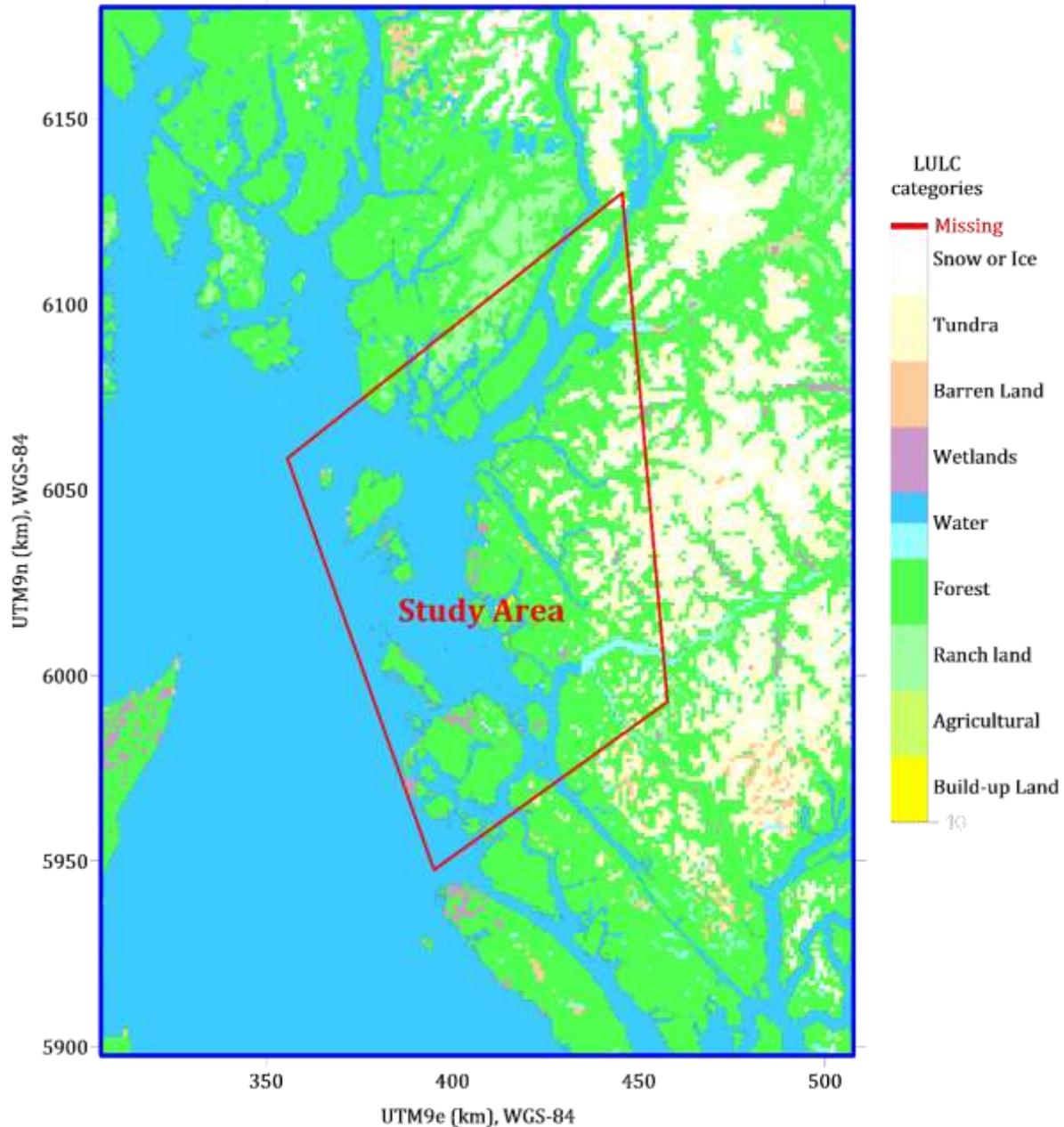


Figure A2.2-2: Land use characteristics within CALMET domain.

MAKEGEO is the final geophysical processor; it reads the fractional land use and terrain elevation data and calculates the set of surface micro-meteorological parameters needed in calculation of some of the CALMET meteorological variables as well as some dispersion characteristics at CALPUFF stage. These are: surface roughness length; Bowen ratio; albedo; leaf area index; soil heat flux parameter; and anthropogenic heat flux.

MAKEGEO version 3.2, level 110401 was used in preparation of the geo-physical data.

In this study the seasonal variation of the surface micro-meteorological was accounted for. After investigating a variety of maps (monthly albedo, leaf area index, etc.) provided by NASA via their Moderate Resolution Imaging Spectroradiometer (MODIS)⁸ program, it was concluded that there are two clearly distinguished seasons in the CALMET domain – winter without continuous snow cover and summer with lush vegetation.

It was established that for purposes of the Bowen ratio variations, 2012 was a year of wet moisture conditions.

The process of assigning seasonal values to the albedo, Bowen ratio and surface roughness length was based on the procedures approved by USEPA and published in the “AERSURFACE User’s Guide”, revised 16 January 2013, Tables A-1, A-2, and A-3. The values for leaf area index, soil heat flux parameter, and anthropogenic heat flux were based on the CALMET default values, and further modified to better describe the domain based on the MODIS images.

Table A2.2-2 lists the resulting values of the surface micro-meteorological parameters corresponding to each land-use category by season.

Table A2.2-2: Surface micro-meteorological parameter values for each land-use category by season.

38 Input LU Category	Input LU ID	Z ₀ (m)	Albedo (0 to 1)	Bowen Ratio	Soil HF Param.	Anthropogenic HF (W/m ²)	LAI	Output LU ID	Output LU Category
Winter values for wet moisture conditions									
Residential	11	0.300	0.18	0.60	0.2	0	0.5	10	Urban Build-up Land
Commercial & Services	12	0.700	0.18	1.00	0.25	0	0.2	10	
Industrial	13	1.000	0.18	1.00	0.25	0	0.2	10	
Transportation, Communication & Utilities	14	1.000	0.18	1.00	0.25	0	0.2	10	
Industrial & Commercial Complexes	15	1.000	0.18	1.00	0.25	0	0.2	10	
Mixed Urban or Build-up	16	1.000	0.18	1.00	0.25	0	0.2	10	
Other Urban or Build-up	17	1.000	0.18	1.00	0.25	0	0.2	10	
Cropland and Pastures	21	0.020	0.18	0.40	0.15	0	1.5	-20	Agricultural Land (-20 for irrigated land)
Orchards, Groves, Vineyards, Nurseries, Ornamental Horticultural Areas	22	0.100	0.18	0.40	0.15	0	1.5	-20	
Confined Feeding Operations	23	0.300	0.18	0.60	0.15	0	1.5	-20	
Other Agricultural Land	24	0.020	0.18	0.40	0.15	0	1.5	-20	
Herbaceous Rangeland	31	0.010	0.20	0.50	0.15	0	0.5	30	Ranch land
Shrub and Brush Range Land	32	0.300	0.18	1.00	0.15	0	0.5	30	
Mixed Rangeland (recently logged)	33	0.6	0.19	0.68	0.15	0	2.75	30	

⁸ <http://neo.sci.gsfc.nasa.gov/view.php?datasetId=MCD43C3> M. BSA



38 Input LU Category	Input LU ID	Z ₀ (m)	Albedo (0 to 1)	Bowen Ratio	Soil HF Param.	Anthropogenic HF (W/m ²)	LAI	Output LU ID	Output LU Category
Deciduous Forest	41	0.600	0.22	0.40	0.15	0	3	40	Forest
Evergreen Forest	42	1.300	0.17	0.30	0.15	0	7	40	
Mixed Forest	43	0.900	0.19	0.35	0.15	0	5	40	
Streams and Canals	51	0.001	0.10	0.10	1	0	0	51	Sweet water
Lakes	52	0.001	0.10	0.10	1	0	0	51	
Reservoirs	53	0.001	0.10	0.10	1	0	0	51	
Bay and Estuaries	54	0.001	0.10	0.10	1	0	0	54	Bays and Estuaries
Ocean	55	0.001	0.10	0.10	1	0	0	55	Ocean
Forested Wetlands	61	0.400	0.14	0.10	0.25	0	1	61	Forested Wetlands
Non-forested Wetlands	62	0.200	0.14	0.10	0.25	0	1	62	Non-forested Wetlands
Dry Salt Flats	71	0.050	0.20	1.00	0.15	0	0.05	70	Barren Land
Beaches	72	0.050	0.20	1.00	0.15	0	0.05	70	
Sandy Areas (not Beaches)	73	0.050	0.20	1.00	0.15	0	0.05	70	
Bare Exposed Rock	74	0.050	0.20	1.00	0.15	0	0.05	70	
Strip Mines, Quarries, Gravel Pits	75	0.300	0.20	1.00	0.15	0	0.05	70	
Transitional Areas	76	0.200	0.18	0.70	0.15	0	0.05	70	
Mixed Barren Land	77	0.200	0.18	0.70	0.15	0	0.05	70	
Shrub and Brush Tundra	81	0.200	0.50	0.50	0.15	0	0	80	Tundra
Herbaceous Tundra	82	0.200	0.50	0.50	0.15	0	0	80	
Bare Ground Tundra	83	0.200	0.50	0.50	0.15	0	0	80	
Wet Tundra	84	0.200	0.50	0.50	0.15	0	0	80	
Mixed Tundra	85	0.200	0.50	0.50	0.15	0	0	80	
Perennial Snowfields	91	0.002	0.70	0.50	0.15	0	0	90	Snow or Ice
Glaciers	92	0.002	0.70	0.50	0.15	0	0	90	

38 Input LU Category	Input LU ID	Z ₀ (m)	Albedo (0 to 1)	Bowen Ratio	Soil HF Param.	Anthropogenic HF (W/m ²)	LAI	Output LU ID	Output LU Category
Summer values for wet moisture conditions									
Residential	11	0.400	0.16	0.60	0.2	0	1	10	Urban Build-up Land
Commercial & Services	12	0.700	0.18	1.00	0.25	0	0.2	10	
Industrial	13	1.000	0.18	1.00	0.25	0	0.2	10	
Transportation, Communication & Utilities	14	1.000	0.18	1.00	0.25	0	0.2	10	
Industrial & Commercial Complexes	15	1.000	0.18	1.00	0.25	0	0.2	10	
Mixed Urban or Build-up	16	1.000	0.18	1.00	0.25	0	0.2	10	
Other Urban or Build-up	17	1.000	0.18	1.00	0.25	0	0.2	10	



38 Input LU Category	Input LU ID	Z ₀ (m)	Albedo (0 to 1)	Bowen Ratio	Soil HF Param.	Anthropogenic HF (W/m ²)	LAI	Output LU ID	Output LU Category
Cropland and Pastures	21	0.150	0.20	0.30	0.15	0	3	-20	Agricultural Land (-20 for irrigated land)
Orchards, Groves, Vineyards, Nurseries, Ornamental Horticultural Areas	22	0.300	0.18	0.30	0.15	0	3	-20	
Confined Feeding Operations	23	0.400	0.16	0.60	0.15	0	3	-20	
Other Agricultural Land	24	0.200	0.20	0.30	0.15	0	3	-20	
Herbaceous Rangeland	31	0.100	0.18	0.40	0.15	0	0.5	30	Ranch land
Shrub and Brush Range Land	32	0.300	0.18	0.80	0.15	0	0.5	30	
Mixed Rangeland (recently logged)	33	0.8	0.16	0.50	0.15	0	3.75	30	
Deciduous Forest	41	1.300	0.16	0.20	0.15	0	7	40	Forest
Evergreen Forest	42	1.300	0.12	0.20	0.15	0	7	40	
Mixed Forest	43	1.300	0.14	0.20	0.15	0	7	40	
Streams and Canals	51	0.001	0.10	0.10	1	0	0	51	Sweet water
Lakes	52	0.001	0.10	0.10	1	0	0	51	
Reservoirs	53	0.001	0.10	0.10	1	0	0	51	
Bay and Estuaries	54	0.001	0.10	0.10	1	0	0	54	Bays and Estuaries
Ocean	55	0.001	0.10	0.10	1	0	0	55	Ocean
Forested Wetlands	61	0.500	0.14	0.10	0.25	0	2	61	Forested Wetlands
Non-forested Wetlands	62	0.200	0.14	0.10	0.25	0	1	62	Non-forested Wetlands
Dry Salt Flats	71	0.050	0.20	1.00	0.15	0	0.05	70	Barren Land
Beaches	72	0.050	0.20	1.00	0.15	0	0.05	70	
Sandy Areas (not Beaches)	73	0.050	0.20	1.00	0.15	0	0.05	70	
Bare Exposed Rock	74	0.050	0.20	1.00	0.15	0	0.05	70	
Strip Mines, Quarries, Gravel Pits	75	0.300	0.20	1.00	0.15	0	0.05	70	
Transitional Areas	76	0.200	0.18	0.70	0.15	0	0.05	70	
Mixed Barren Land	77	0.200	0.18	0.70	0.15	0	0.05	70	
Shrub and Brush Tundra	81	0.200	0.30	0.50	0.15	0	0	80	Tundra
Herbaceous Tundra	82	0.200	0.30	0.50	0.15	0	0	80	
Bare Ground Tundra	83	0.200	0.30	0.50	0.15	0	0	80	
Wet Tundra	84	0.200	0.30	0.50	0.15	0	0	80	
Mixed Tundra	85	0.200	0.30	0.50	0.15	0	0	80	
Perennial Snowfields	91	0.002	0.60	0.50	0.15	0	0	90	Snow or Ice
Glaciers	92	0.002	0.60	0.50	0.15	0	0	90	



2.2.6 Over-land Surface Meteorological Data

In addition to the WRF meteorological data, surface observations from nine meteorological stations were included in this modelling exercise. Data for the Prince Rupert stations – the airport (CYPR) and Roosevelt Park School Met60 stations (PRSCH) – were provided by MOE.⁹

Additionally, surface hourly observations in TD-3505 format were obtained from the Integrated Surface Hourly Database (ISHD) supported by the US National Climatic Data Center (NCDC).¹⁰ Figure A2.2-3 shows the location of all meteorological stations used in this study; the surface stations are marked with pink diamonds. A description of the surface stations is provided in Table A2.2-3.

The Prince Rupert airport station was included twice in the modelling using data from all available sources. This action was needed due to the incompleteness of both data sets. The MOE set provided hourly records of wind, temperature, dew point temperature, relative humidity, station pressure, and visibility, but no cloud cover and ceiling height data. The NCDC data were available only every six hours and included cloud cover and ceiling height data.

Prince Rupert airport data were the only data that was additionally processed before inputting into SMERGE. The hours with variable winds were originally reported as having non-zero wind speed and missing wind direction. Such missing wind directions were linearly interpolated. The interpolation procedure included converting the winds in vector format with (u,v)-components and averaging over 10 previous and 10 past observations for any number of variable winds reported in sequence.

The Roosevelt Park School station is part of the MOE monitoring network in the Skeena region. This meteorological station collects data for wind speed and direction, wind direction standard deviation, temperature, relative humidity, and station pressure. The data coverage for 2012 was from June 17 to December 31. The wind direction standard deviation records were not used in this modelling effort due to the partial year coverage.

The observations for the nine surface stations were processed with SMERGE version 5.7 level 121203.

⁹ <http://envistaweb.env.gov.bc.ca/>

¹⁰ <ftp://ftp.ncdc.noaa.gov/pub/data/noaa/>



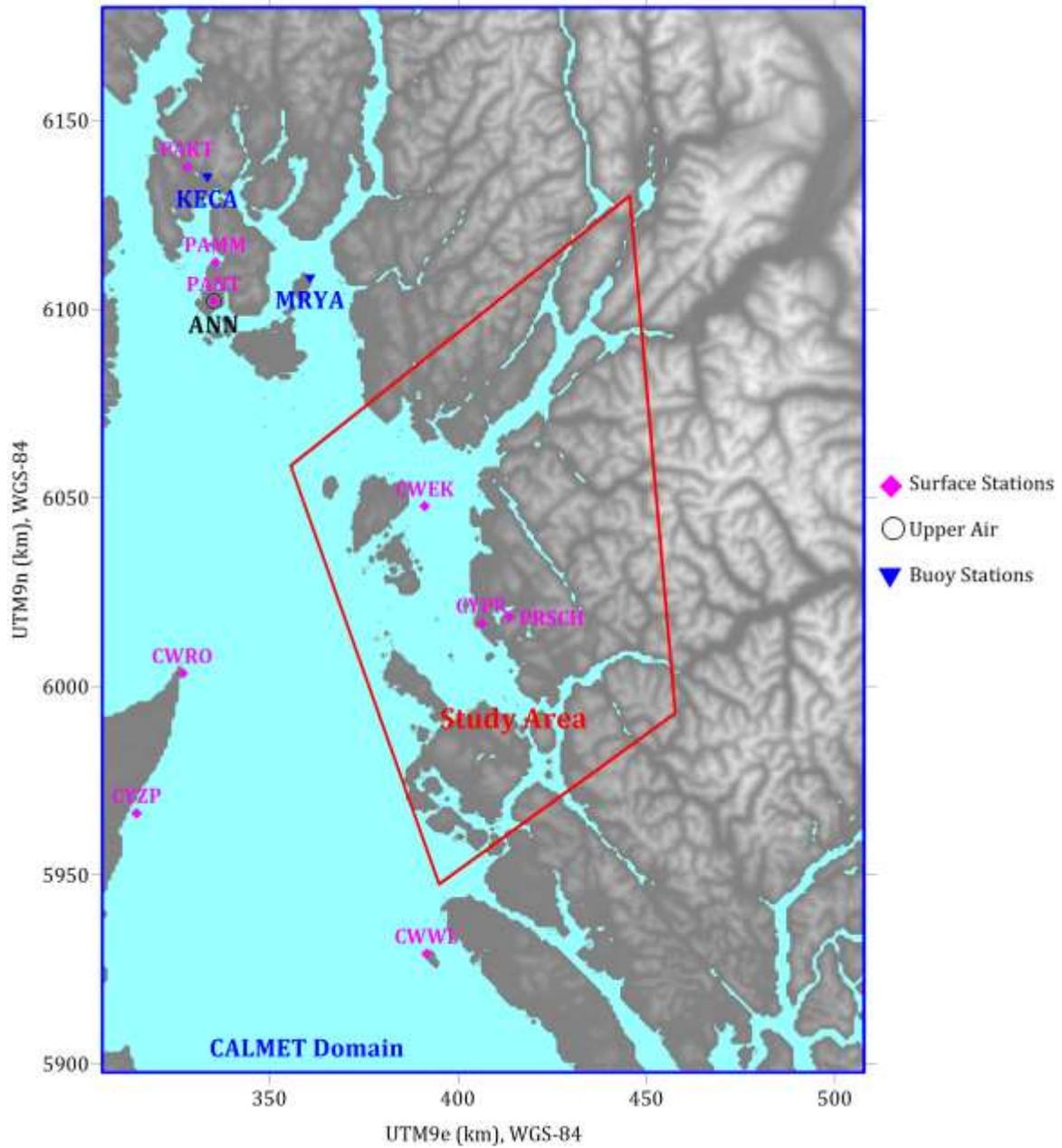


Figure A2.2-3: Meteorological stations included in the CALMET modeling effort.

Table A2.2-3: Description of the surface stations included in the CALMET modeling effort.

UTM9 East (km)	UTM9 North (km)	Latitude (degrees)	Longitude (degrees)	Elevation (m)	Call Sign	USAF	Location
406.269	6016.745	54.290	-130.440	35.4	PRAP	710221	PRINCE RUPERT AIRPORT
413.665	6018.424	54.306	-130.327	80.0	PRSC	710222	SCHOOL MET60
328.143	6137.754	55.356	-131.711	23.2	PAKT	703950	KETCHIKAN INTL AIRPORT
335.264	6102.058	55.038	-131.578	33.2	PANT	703980	ANNETTE ISLAND AIRPORT
335.646	6112.404	55.131	-131.578	0.0	PAMM	703985	METLAKATLA SEAPANE BAS
314.806	5966.387	53.813	-131.813	6.4	CYZP	711010	SANDSPIT
391.187	6047.801	54.566	-130.683	8.0	CWEK	714760	GREY ISLET
326.939	6003.457	54.150	-131.650	7.0	CWRO	714770	ROSE SPIT
391.684	5929.135	53.500	-130.633	15.0	CWWL	714840	BONILLA ISLAND

2.2.7 Upper-air Meteorological Data

Twice-daily radiosonde observations from Annette Island upper air station were obtained from the NCDC Earth System Research Laboratory (ESRL) website.¹¹ The data set includes all available soundings and was downloaded in the Original Forecast Systems Laboratory (FSL) format.

Annette Island upper air station (ANN) is located at latitude 55.03N and longitude 131.57W in the vicinity of the surface station. It is marked on Figure A2.2-3 with a black circle.

There was one missing sounding and there were 10 hours during which an element at the top layer (500 mB) was missing. The missing sounding at 2012 05 02 hour 00 was substituted with the existing sounding for 2012 05 01 hour 22.

The missing top layer values were extrapolated using the routine embedded in READ62.

The raw radiosonde observations were processed with READ62 version 5.661 level 110225.

¹¹ <http://www.esrl.noaa.gov/raobs/>



2.2.8 Over-water Meteorological Data

The aerodynamic and thermal properties of water surfaces require a different method for calculating the boundary layer parameters in the marine environment. A profile technique, using air-sea temperature differences, is used in CALMET to compute the micro-meteorological parameters in the marine boundary layer. The WRF dataset was used as the primary source for these over-water data, with buoy stations added to nudge the model to preserve the local weather pattern in the northern coastal area.

Three buoy stations were located within the CALMET domain of this project, none of which is operating within the boundaries of the study area.

After analyzing the observations from the buoy stations, it was determined that only two of them provide data of sufficient quality for modelling. Initially the North Hecate buoy (HECA) was considered along with Ketchikan and Mary Island buoys. However, after performing quality control testing (including mapping hourly surface winds, temperatures, and mixing heights), it was revealed that including HECA observations created large gradients around the station location in the surface fields, expressed with well-defined “bull’s eyes” in the ocean. Moreover, the fact that the station has missing data creates the effect of “pulsing” when the observations are present. The quality control test to investigate the effect of including the buoy station was performed for January 7, 2012. It was concluded that HECA should be excluded from the final modelling. The stations included in the modelling are listed and described in Table A2.2-4.

Table A2.2-4: List of the over-water meteorological station providing data for 2012.

Station Name	LAT	LON	Elevation (m)	Modelling ID	Air Temperature Sensor Height (m)	Water Temperature Sensor Depth (m)	Anemometer Height (m)
Ketchikan	55.331	-131.625	4.6	KECA	7.68	3.47	8.2
Mary Island	55.099	-131.182	4.0	MRYA	7.68	3.47	4

Buoy observations were obtained from the US National Data Buoy Center (NDBC)¹² and processed into SEA.DAT files using the BUOY utility version 1.3.0, level 140116.

2.2.9 CALMET Modelling Options

The latest available version of CALMET (version 6.4 level 121203) was used in the final stage of the meteorological data processing. In this final stage, CALMET combines the geophysical data (MAKEGEO output), the surface and upper air observations, and WRF’s meteorological fields together and computes the values of the output meteorological variables for each grid cell and each hour. The modelling period – January to December 2012 – was split into twelve periods each corresponding to one calendar month. The domain time zone was set to Pacific (UTC-8).

For most of the input parameters, Trinity selected the values recommended in the “*Guidelines for Air Quality Modelling in British Columbia*”. Table A2.2-5 summarizes some of the key input

¹² <http://www.ndbc.noaa.gov/>



parameter values selected for CALMET processing. Most of these key input parameters are determined based on user selection. The notes in the column marked as “Selection Description” indicate the basis for each input.

Table A2.2-5: Summary of key input parameter values for CALMET.

Input Parameter and Definition	MOE Default Value	Selected Value	Selection Description
Extrapolate surface wind observations to upper layers	-4	! IEXTRP = -4. !	similarity theory used; data from upper air stations are ignored in the first layer
I PROG: Use gridded prognostic wind field model outputs as input to the diagnostic wind field model	2, 4 or 14	! I PROG = 14!	use winds from MM5/3D.DAT file as initial guess field
Use varying radius of influence?	T	! LVARY = T !	Yes, if no stations are found within RMAX's, then the closest station will be used
RMAX1: Maximum radius (km) of influence over land in the surface layer	varies	! RMAX1 = 5. !	1.25 WRF grid cells
RMAX2: Maximum radius (km) of influence over land aloft	varies	! RMAX2 = 10. !	2.5 WRF grid cells
RMAX3: Maximum radius (km) of influence over water	varies	! RMAX3 = 40. !	Approximately ¼ of domain length
TERRAD: Radius (km) of influence of terrain features	varies	! TERRAD = 4. !	Four (4) CALMET grid cells
R1: Distance (km) from an observation station at which the observation and first guess field are equally weighted at surface level	varies	! R1 = 2. !	Two (2) CALMET grid cells
R2: Distance (km) from an observation station at which the observation and first guess field are equally weighted aloft	varies	! R2 = 8. !	Two (2) WRF grid cells
Radius of influence for temperature interpolation	Default: 500	! TRADKM = 4!	Four (4) CALMET grid cells

2.2.10 CALMET Sensitivity Testing

As part of the determination of the final set of CALMET input parameters, a series of sensitivity tests was performed in order to establish the most representative set of values for the project-specific geophysical setting. In these tests, the radii of influence were varied until the natural smoothness of the meteorological fields (and particularly winds) was captured. Additionally, the effect of the WRF data was tracked by setting simulation with and without the WRF data set. In other words, as part of studying the effect of the radii of influence and establishing the most appropriate values for this CALMET domain, the model was run in the two limiting cases – no-observation (NOOBS) mode (with WRF data only) and no WRF data (only observations) – as well as with several combinations of different values for the radii of influence variables.

The wind field smoothness tests were based on visual inspection of the wind field snapshots for different hours capturing the entire grid. Sharp changes of the wind direction causing convergence (divergence) at localized grid cells not followed by divergence (convergence) and inconsistent with the overall pattern of domain circulation, were considered an indicator for the



R1 and R2 adjustment. An example of the resulting surface wind field, temperature, and mixing height fields for four different simulation settings is shown in Figure A2.2-4 (a, b, c, d) and Figure A2.2-5 (a, b, c, d). The hour in this example is hour 9 on August 28th, 2012, and represents a typical situation of light wind conditions.

In this example, the radius of influence of the surface station R1 was set to 2 km and 12 km, the radius of influence of the upper air stations was set to 8 and 12 km. The four scenarios under considerations were:

- a. Only WRF data included in the CALMET input and small (compared to WRF data grid spacing of 4 km) radii of influence – R1= 2 km, R2 = 8 km
- b. Hybrid inputs¹³ with small radii of influence. R1 is kept 2 km, and R2 = 8 km but surface and upper air observations were included in addition to the WRF data
- c. Hybrid inputs with large radii of influence. Simulation included data from observations and WRF but the radii of influence were increased to R1 = 12 km, and R2 = 12 km
- d. Observations only were used in the CALMET simulation with radii of influence set to R1 = 12 km, and R2 = 12 km respectively. For this case, additional stations outside the CALMET domain were included. Such observation station selection is typical where no mesoscale model data are available in order to better resolve the meteorology of the domain

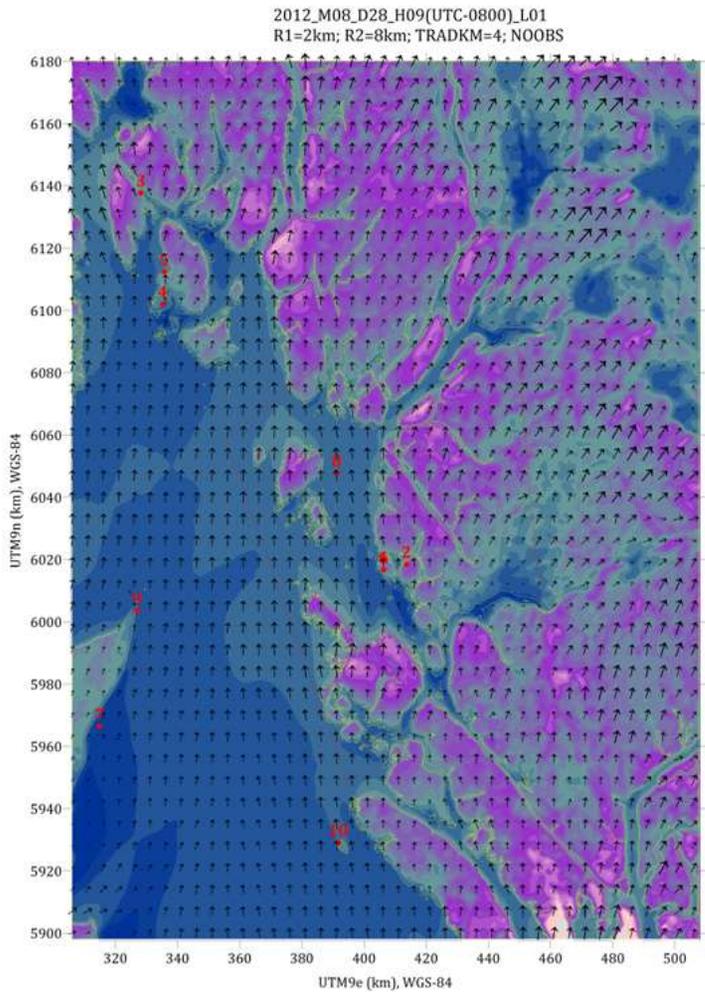
All four scenarios capture the general southerly flow of the hour. The winds resolved with WRF data are in general higher in the areas far from the observation stations. Similarly the overland mixing heights are higher in the same regions.

The temperature fields are better resolved when WRF data are included, specifically in the northeast regions of the domain where higher terrain is prevailing.

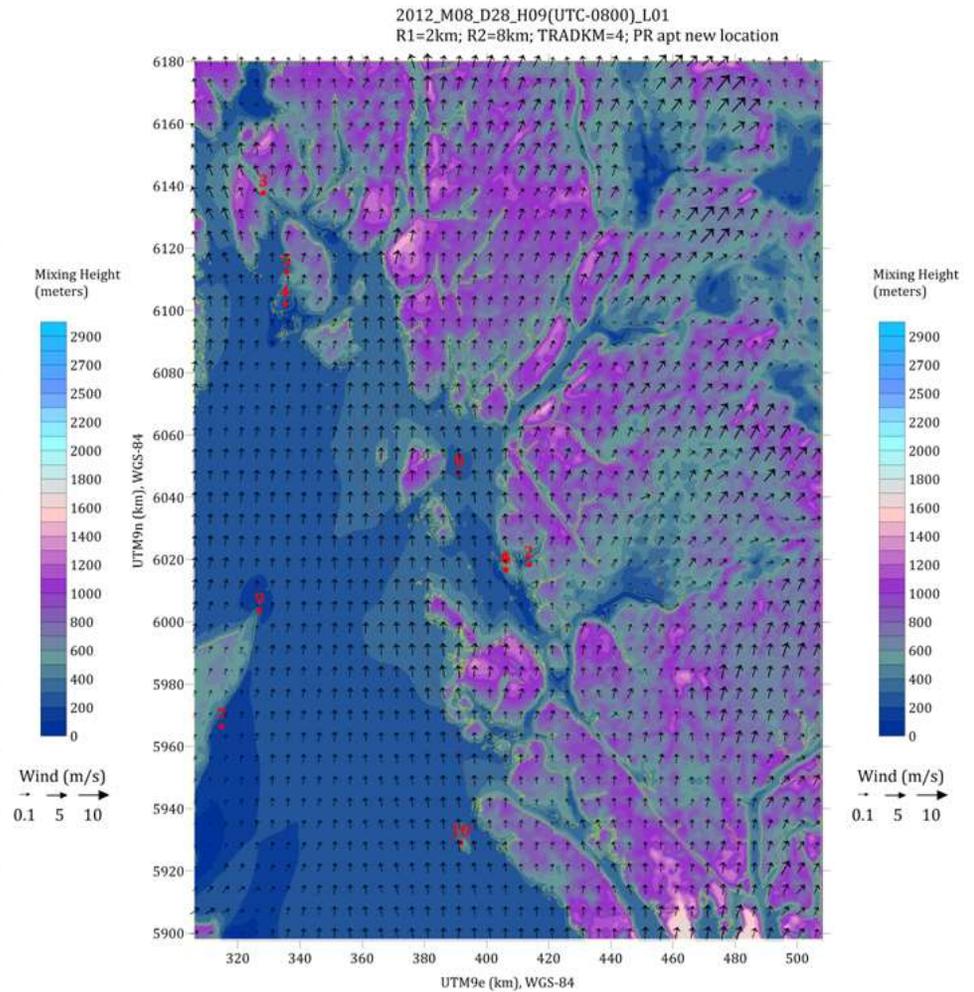
The final selection for this CALMET modelling was scenario b) – a combination of WRF and observations balanced with relatively small radii of influence, which did enough data smoothing to prevent individual stations from creating sharp gradients in the meteorological fields and yet keep the uniqueness of each observation station.

¹³ The term “hybrid inputs” used in the description of the CALMET inputs should be understood as combining the WRF-generated data with surface and upper air observations from stations within the domain. In the final CALMET runs, the WRF data and observations were merged to develop the modelling fields of all atmospheric variables needed for the dispersion modelling.



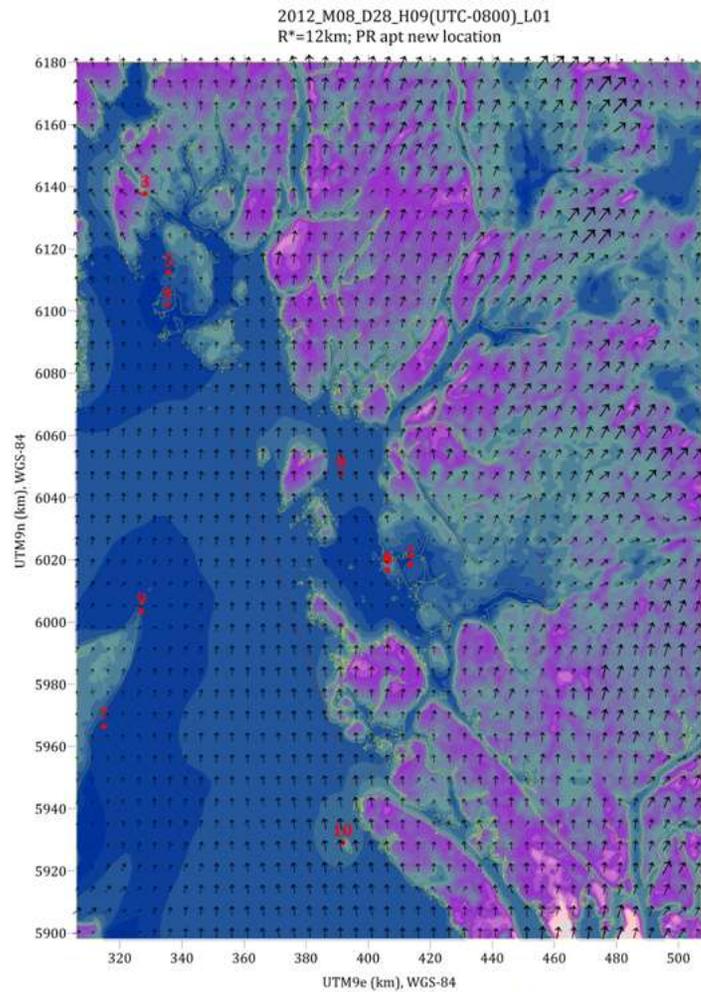


a) Only WRF data used with small R1 and R2

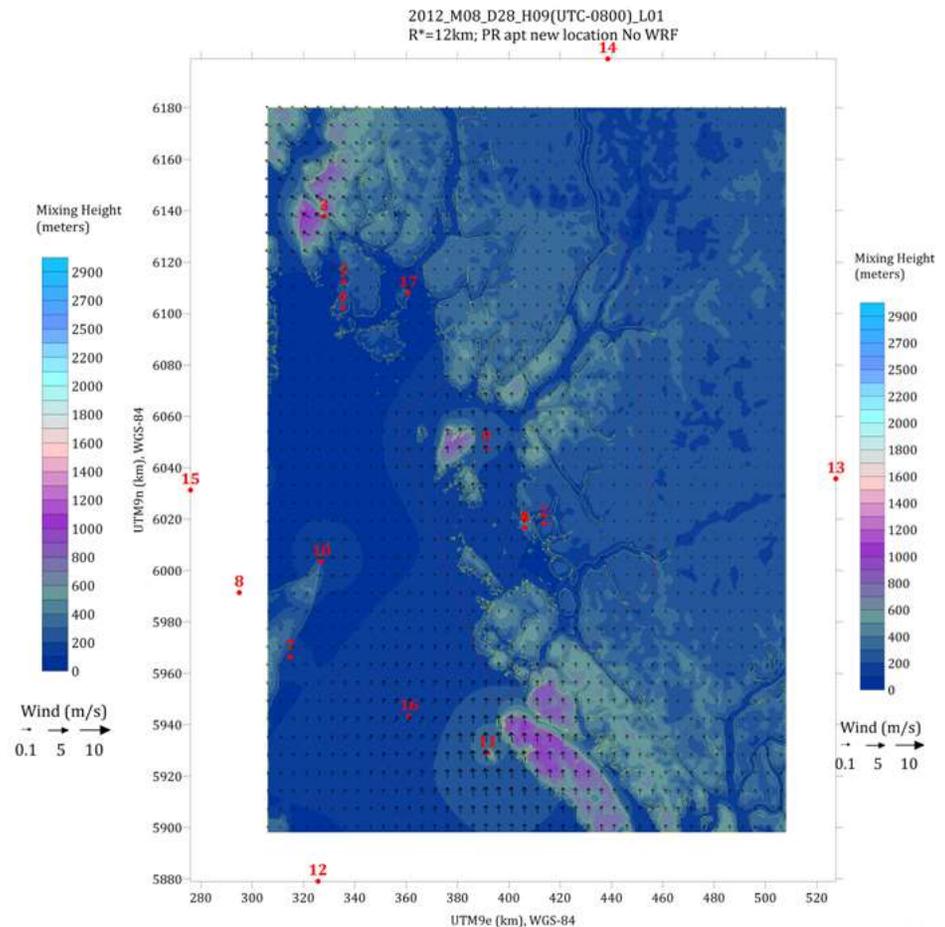


b) Hybrid mode with small R1 and R2





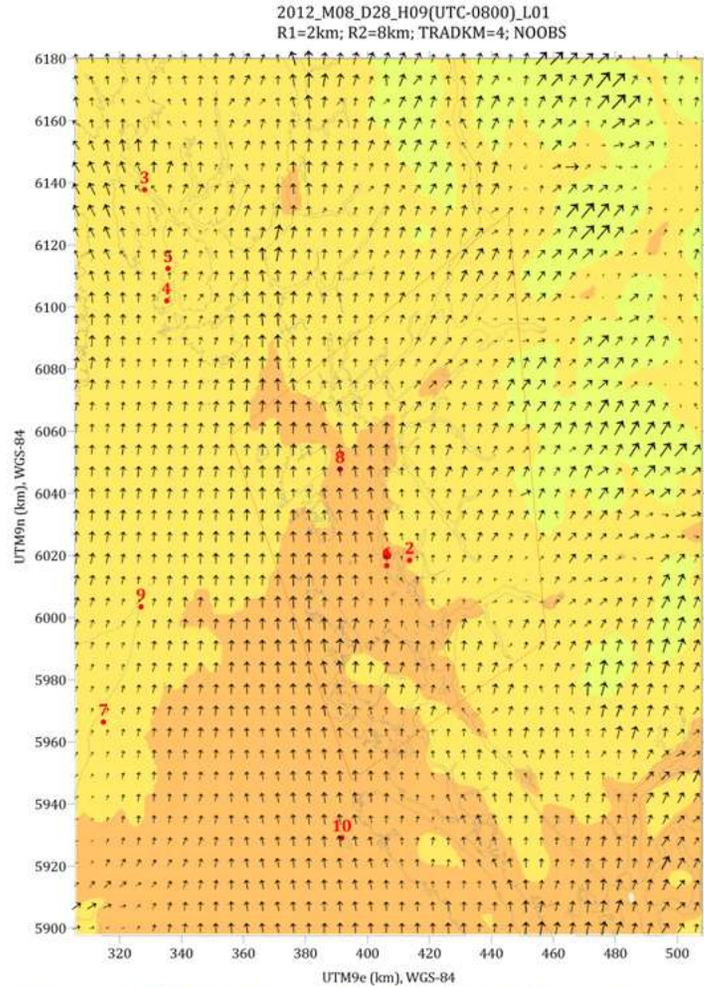
c) Hybrid mode with small R1 and R2



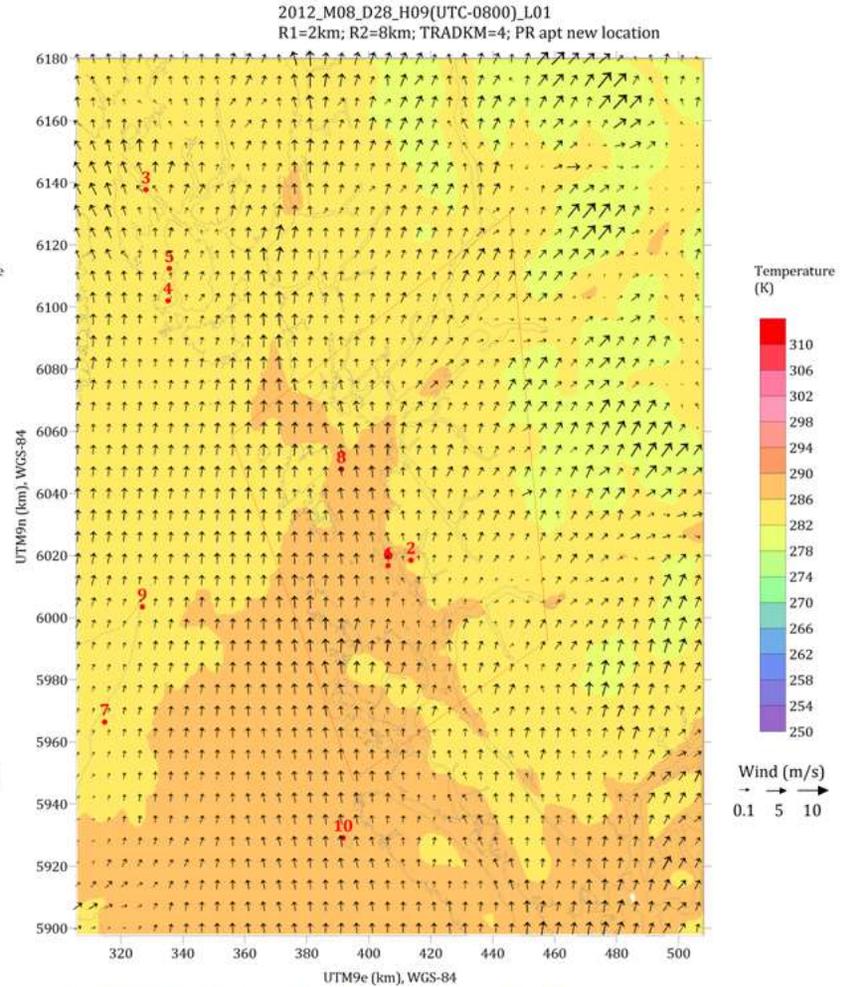
d) Only observations were used with large R1 and R2

Figure A2.2-4: Domain wind field snapshot superimposed over the mixing height field for daytime light winds hour comparing four setup situations.



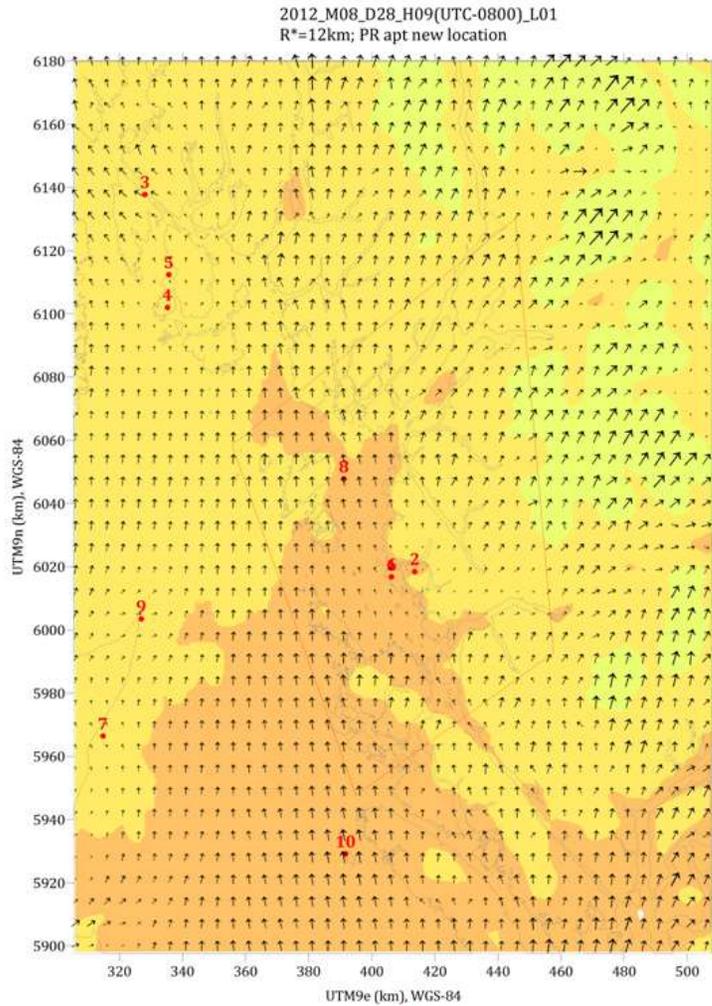


a) Only WRF data used with small R1 and R2

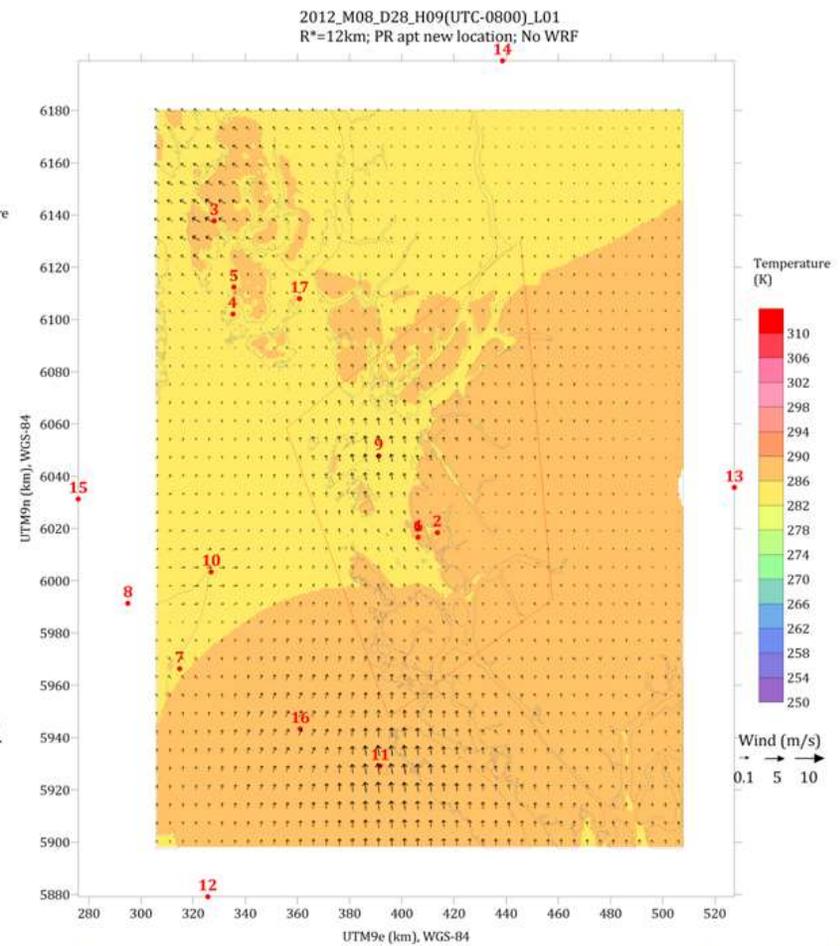


b) Hybrid mode with small R1 and R2





c) Hybrid mode with small R1 and R2



d) Only observations were used with large R1 and R2

Figure A2.2-5: Domain wind field snapshot superimposed over the temperature field.



2.2.11 CALMET Representativeness

Representativeness analysis was based on comparing the CALMET predicted meteorological variables to the observations. Of main interest were the surface temperature and wind time series. For this test the observations at the Roosevelt Park School Met60 station and Prince Rupert Airport were compared to their corresponding computed values from the nearest CALMET grid point. The CALMET data from which the grid point was extracted include the surface station. Part of the test was to show that CALMET is set up adequately to preserve the local stations' weather patterns. Both locations were selected because they are central to the study area and in the vicinity of the emission sources. The CALMET grid point nearest to the school is located approximately 500 m southeast of the station, and the nearest CALMET grid point to the airport is 400 m to the northwest of the station. The relative position of the points in consideration is shown on Figure A2.2-6:

- CALMET (101, 120) – 406.1 km E, 6017.1 km N
- Prince Rupert Airport – 406.3 km E, 6016.7 km N
- CALMET (109, 121) – 414.1 km E, 6018.1 km N
- Roosevelt Park School – 413.7 km E, 6018.4 km N

The extracted time series for the school station extends from June 17 to December 31, 2012 – the period for which observations are available. The airport time series covers the entire year of 2012. Surface data from the observations were compared to the first CALMET layer data.

The subsequent statistical analysis showed a high level of correlation between the observations and CALMET data:

- Prince Rupert airport: 98% (wind speed), 96% (temperature)
- Roosevelt Park School: 98% (wind speed), 96% (temperature)

The corresponding time series and quantile-quantile plots are presented on Figure A2.2-7 and Figure A2.2-8. For both locations, CALMET is under-predicting the high and over-predicting the low temperatures by nearly 4°K. The black line on the Q-Q plots represents the line of perfect match; the dotted red line represents linear approximation of the data fit.



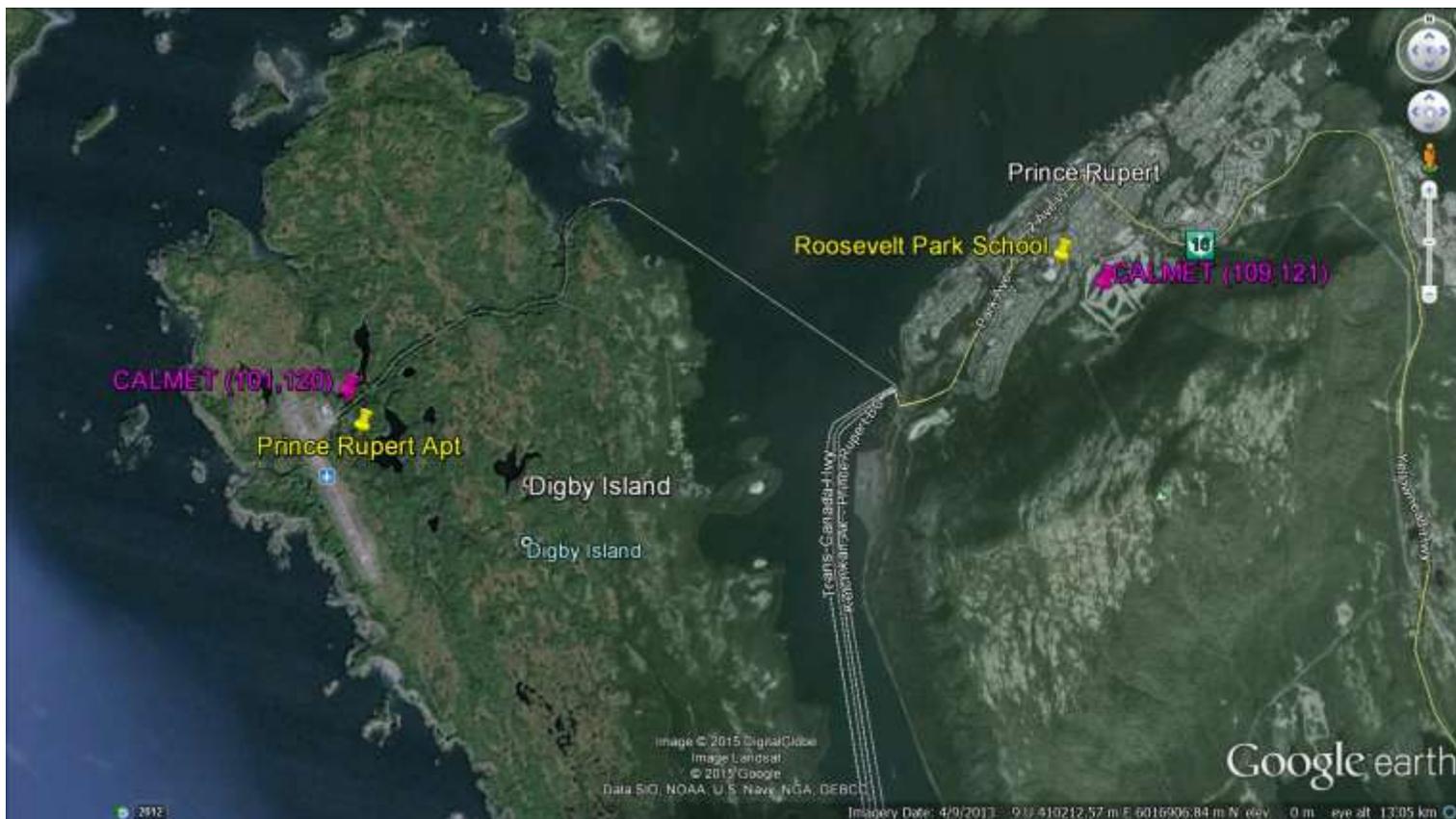


Figure A2.2-6: Relative position of the Prince Rupert observations stations and their corresponding nearest CALMET grid points.

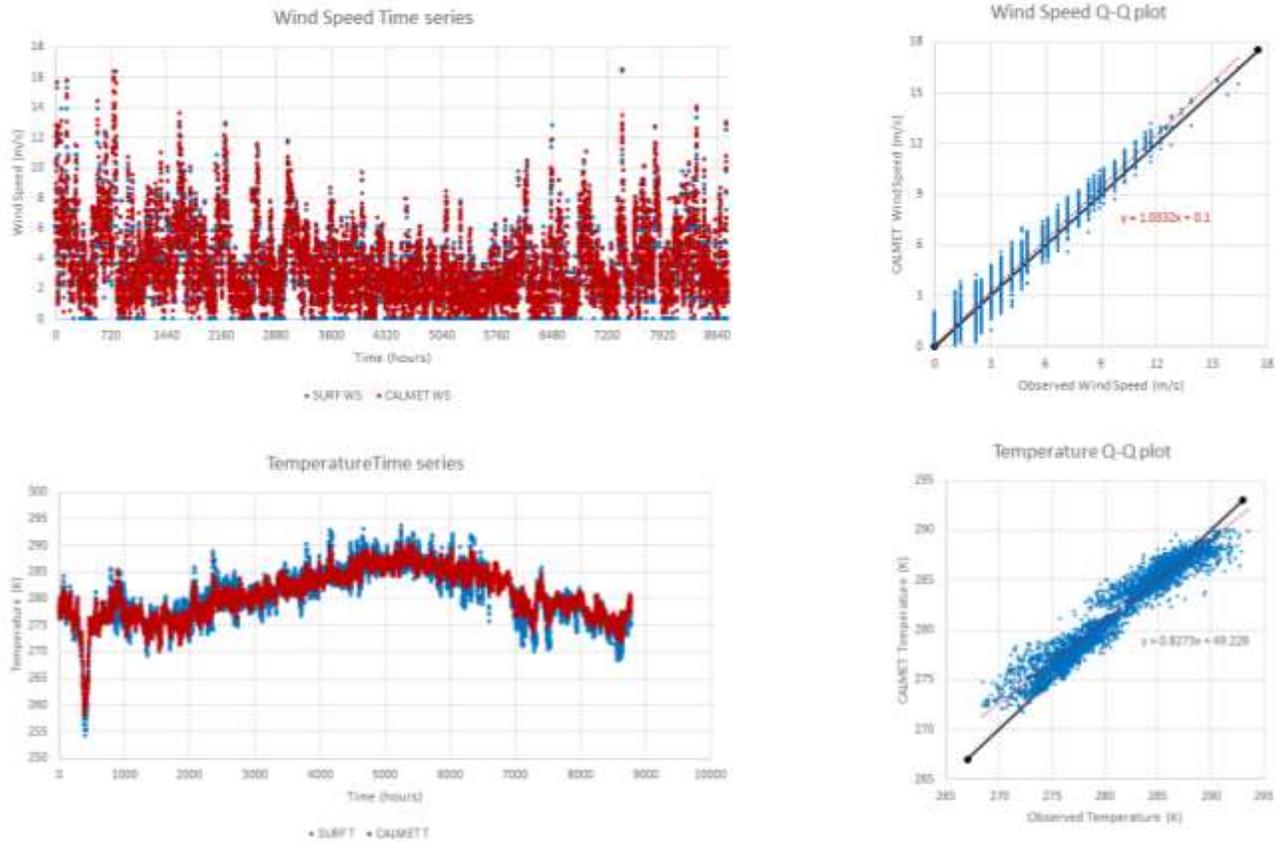


Figure A2.2-7: Correlation between Prince Rupert Airport and CALMET (101,120) Grid Point Data time series for wind speed and temperature variables for modelling year 2012.



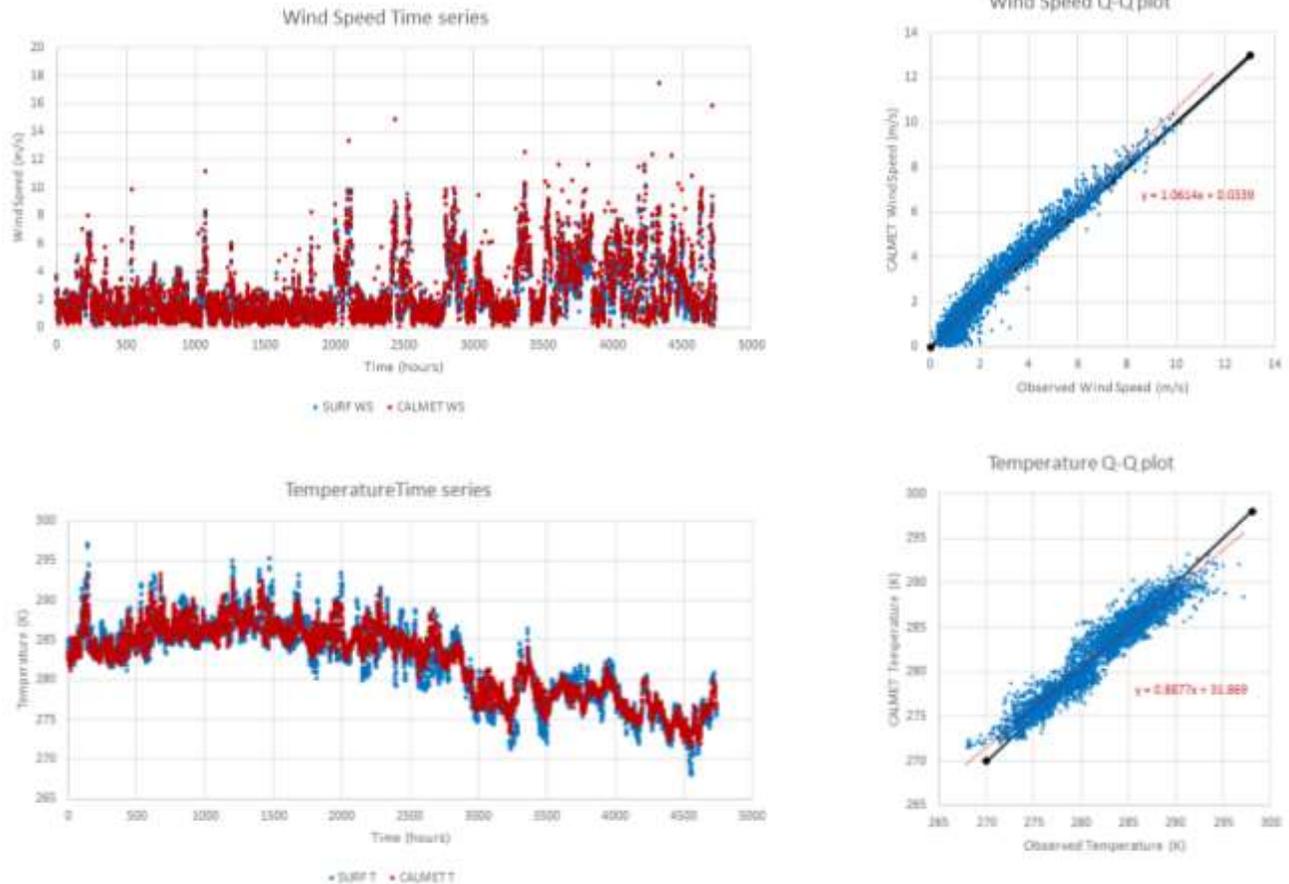


Figure A2.2-8: Correlation between Roosevelt Park School Met_60 Station and CALMET (109,121) Grid Point Data time series for wind speed and temperature variables for the period June-December 2012.

Additionally, the wind roses at the two sets of locations are compared on Figure A2.2-9 (a, b, c) and Figure A2.2-10 (a, b, c, d, e).

The predominant wind direction at the school station locations in the second half of 2012 is southeast – more than 15% relatively strong winds blow from that direction. Other frequent wind directions are the easterly and the westerly. CALMET is picking some more winds from the east (12%) than they were observed (8%), but is under-predicting the east-northeasterly wind by the same amount. Similarly the southwesterly winds are slightly under-predicted and the west-southwesterly winds are slightly over-predicted. Both model and observations are registering low-frequency of northerly winds. CALMET is showing higher percentage (7.7%) of calm events compare to the 4% reported by observations. On the other hand, there are approximately 5% of missing data in the observation set which were interpolated from the WRF data in the CALMET set.

The airport locations are west of the school and more exposed to the open ocean, but the prevailing winds are still from the southwest. Another very frequent direction is south-southeast and the least frequent direction is northerly. The wind pattern of the observed winds is well depicted by CALMET.

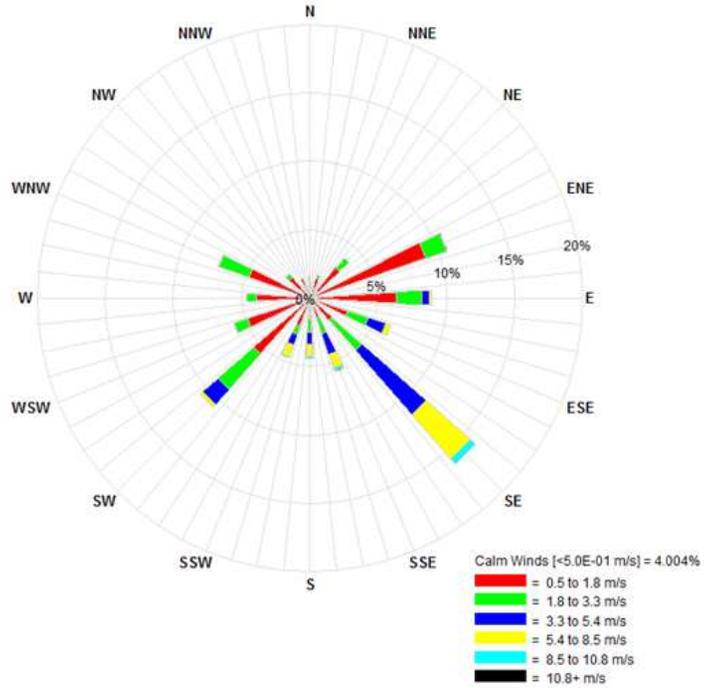


a) Semi-annual wind rose (June to December 2012)

(11) - SURF.DAT: Station ID = 710222

Height = 20.00 m; [Jun 17, 2012 - 10:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]

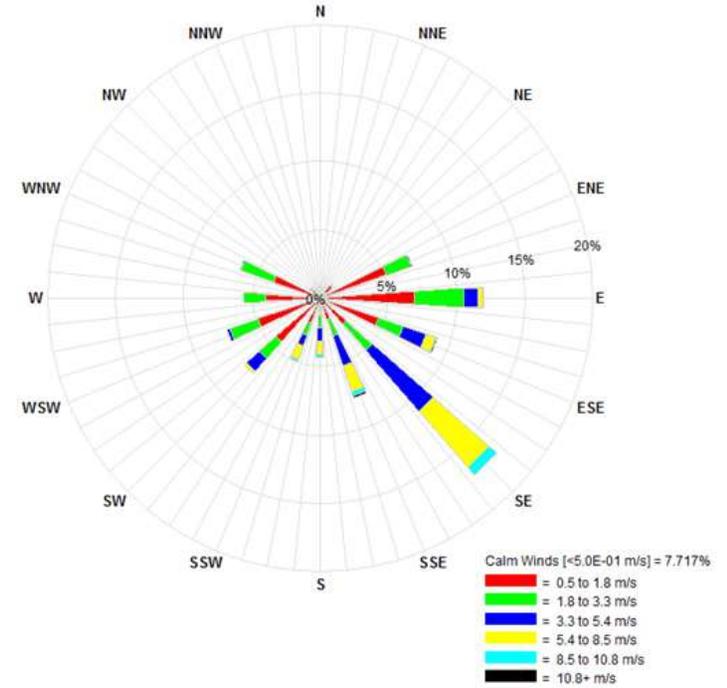
Annual(Jun to Dec): Total Periods = 4743; Valid Periods = 4545 (95.8%); Calm Wind Periods = 182



(108120) - CALMET.DAT: Nearest Grid Pt [(I,J)=(109.000, 121.000)] [(X,Y)km=(414.100, 6018.100) in MODEL Projection]

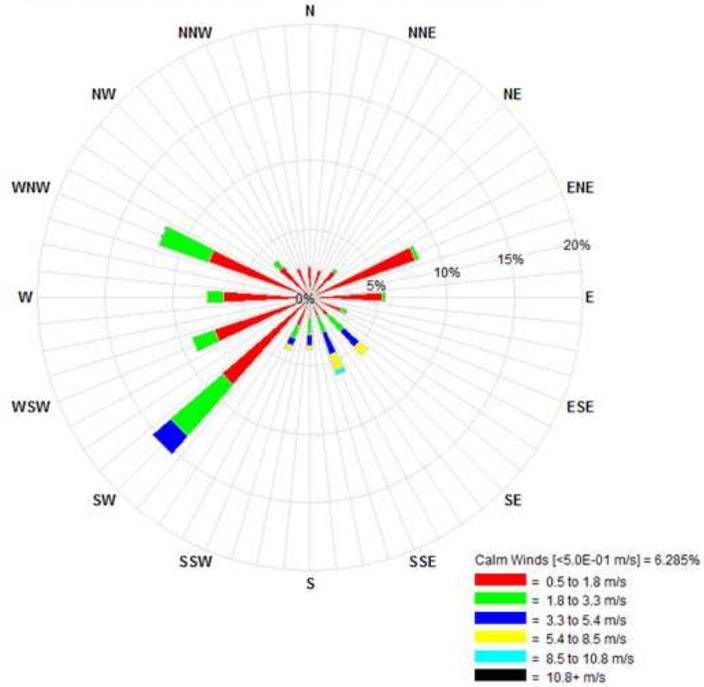
Height = 20.00 m; [Jun 17, 2012 - 10:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]

Annual(Jan to Dec): Total Periods = 4743; Valid Periods = 4743 (100%); Calm Wind Periods = 366

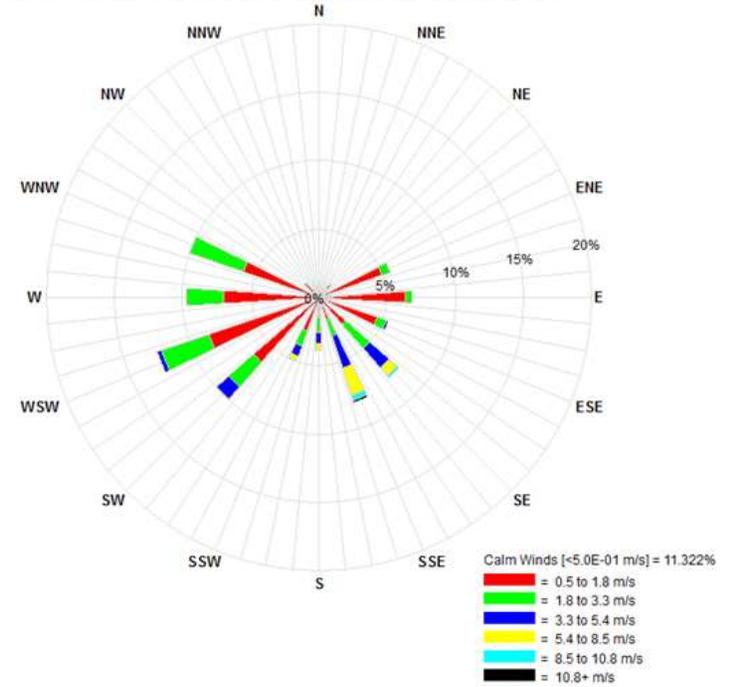


b) Quarterly wind rose (July, August, September)

SURF.DAT: Station ID = 710222
Height = 20.00 m; [Jan 1, 2012 - 1:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]
Q3(Jul,Aug,Sep): Total Periods = 2208; Valid Periods = 2116 (95.8%); Calm Wind Periods = 133



(108120) - CALMET.DAT: Nearest Grid Pt [(I,J)=(109.000, 121.000)] [(X,Y)km=(414.100, 6018.100) in MODEL Projection]
Height = 20.00 m; [Jun 17, 2012 - 10:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]
Q3(Jul,Aug,Sep): Total Periods = 2208; Valid Periods = 2208 (100%); Calm Wind Periods = 250



c) Quarterly wind rose (October, November, December)

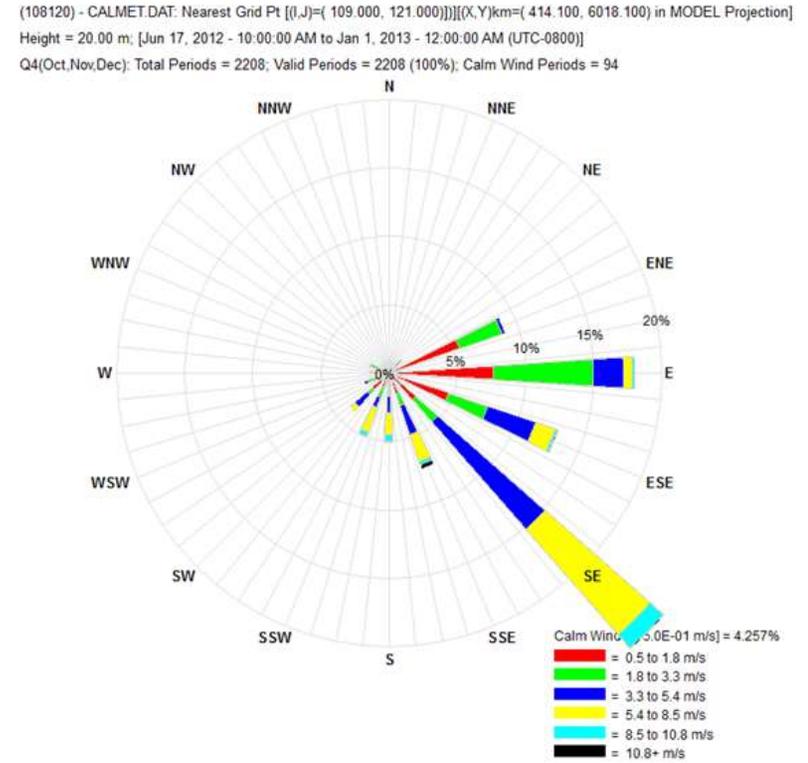
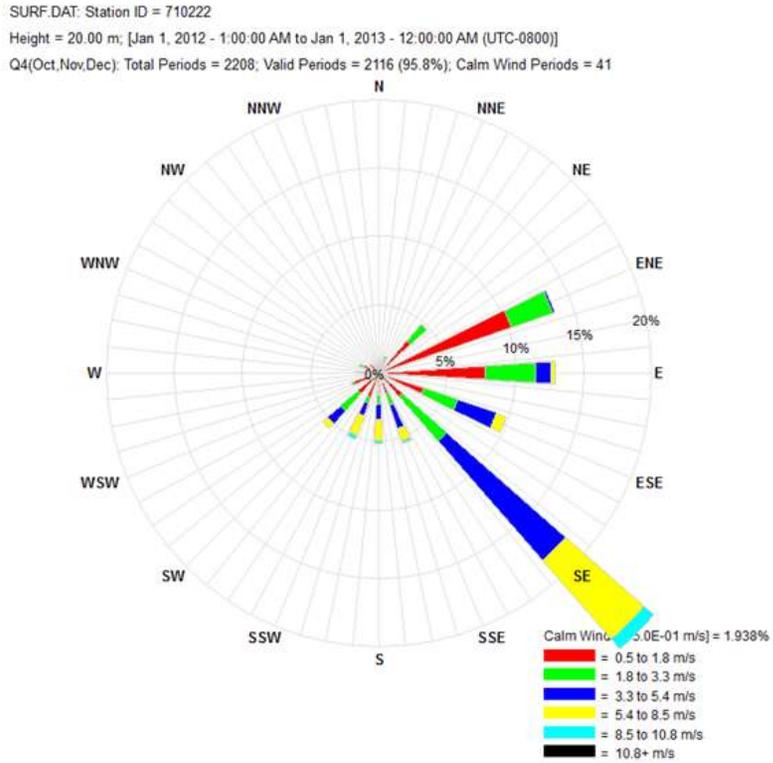
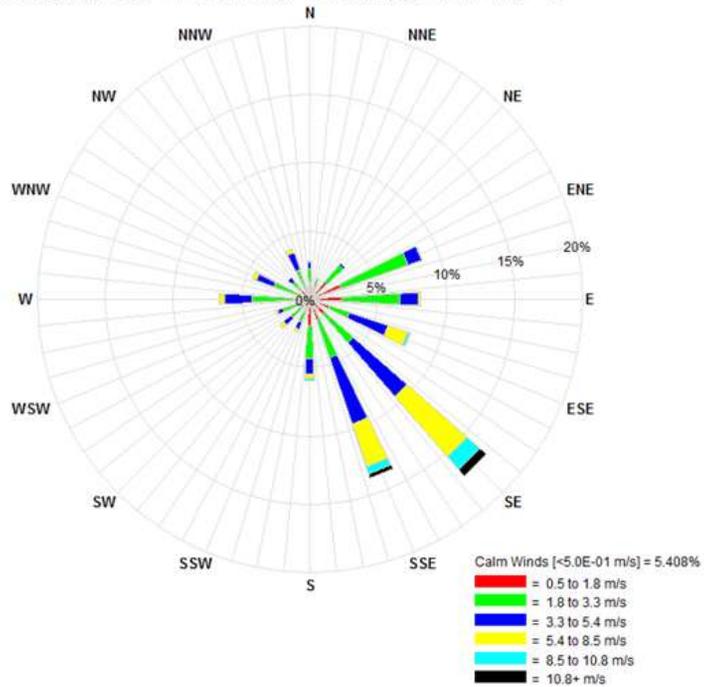


Figure A2.2-9: Wind roses comparison between Roosevelt Park School station and CALMET (109,121) grid point: one semi-annual rose for the period of June – December 2012; two quarterly roses Q3 (JUL, AUG, SEP) and Q4 (OCT, NOV, DEC).

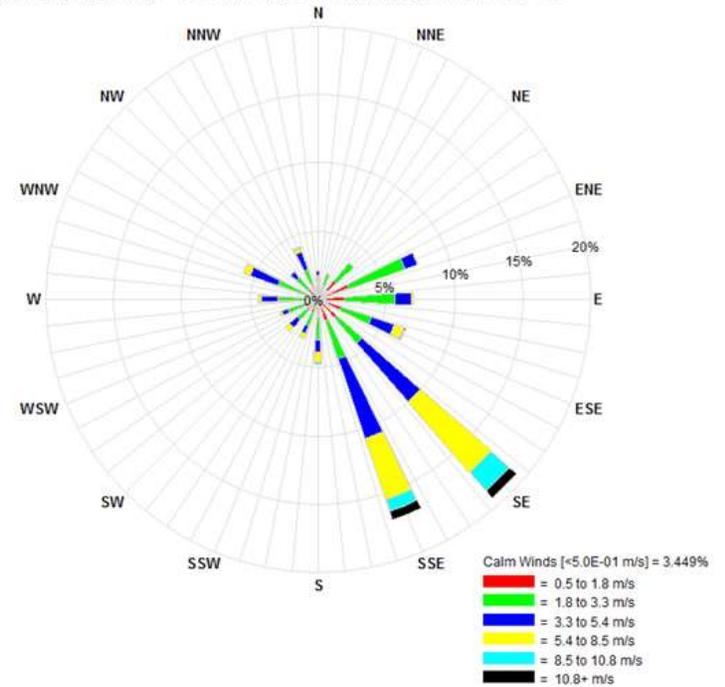


a) Annual wind rose (January to December 2012)

SURF.DAT: Station ID = 710221
Height = 10.00 m; [Jan 1, 2012 - 1:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]
Annual(Jan to Dec): Total Periods = 8784; Valid Periods = 8710 (99.2%); Calm Wind Periods = 471

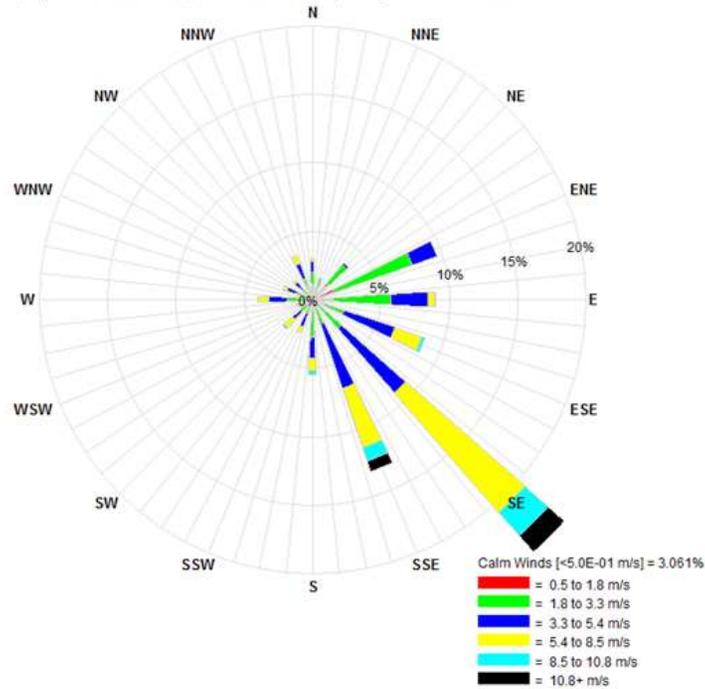


(101120) - CALMET.DAT: Nearest Grid Pt [(I,J)=(101.000, 120.000)] [(X,Y)km=(406.100, 6017.100) in MODEL Projection]
Height = 10.00 m; [Jan 1, 2012 - 1:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]
Annual(Jan to Dec): Total Periods = 8784; Valid Periods = 8784 (100%); Calm Wind Periods = 303

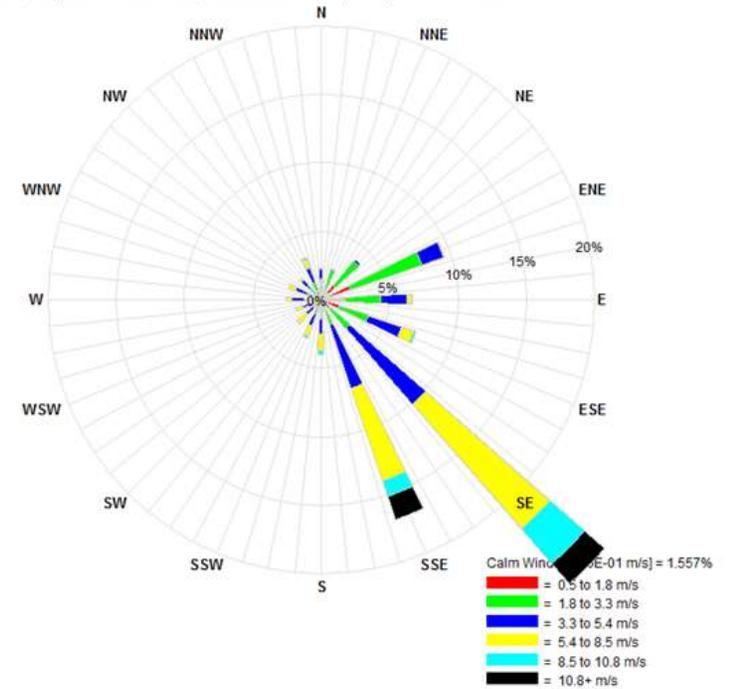


b) Quarterly wind rose (January, February, March)

SURF.DAT: Station ID = 710221
 Height = 10.00 m; [Jan 1, 2012 - 1:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]
 Q1(Jan, Feb, Mar): Total Periods = 2184; Valid Periods = 2156 (98.7%); Calm Wind Periods = 66

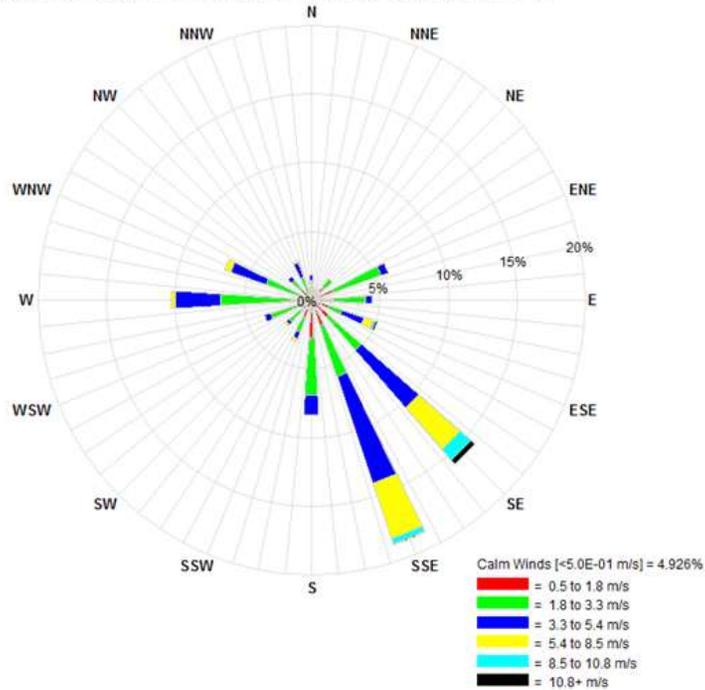


(101120) - CALMET.DAT: Nearest Grid Pt [(I,J)=(101.000, 120.000)] [(X,Y)km=(406.100, 6017.100) in MODEL Projection]
 Height = 10.00 m; [Jan 1, 2012 - 1:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]
 Q1(Jan, Feb, Mar): Total Periods = 2184; Valid Periods = 2184 (100%); Calm Wind Periods = 34

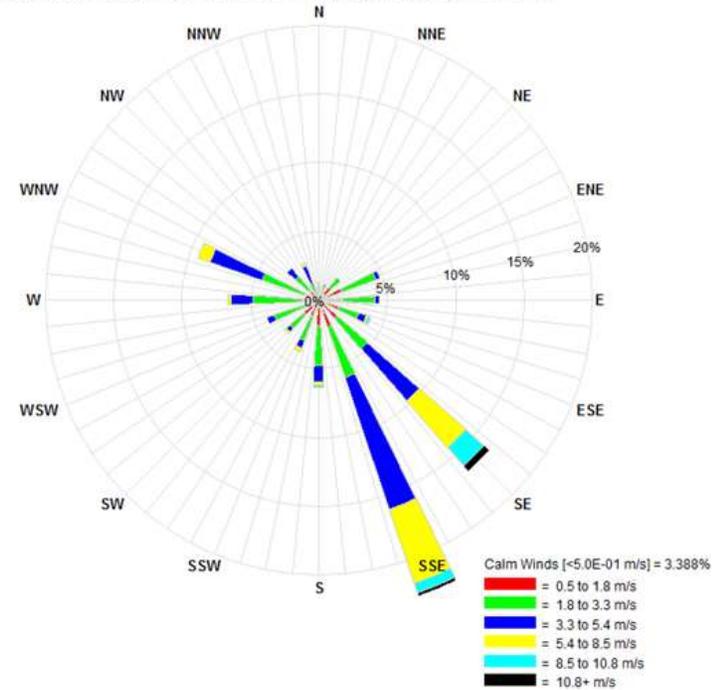


c) Quarterly wind rose (April, May, June)

SURF.DAT: Station ID = 710221
Height = 10.00 m; [Jan 1, 2012 - 1:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]
Q2(Apr,May,Jun): Total Periods = 2184; Valid Periods = 2172 (99.5%); Calm Wind Periods = 107

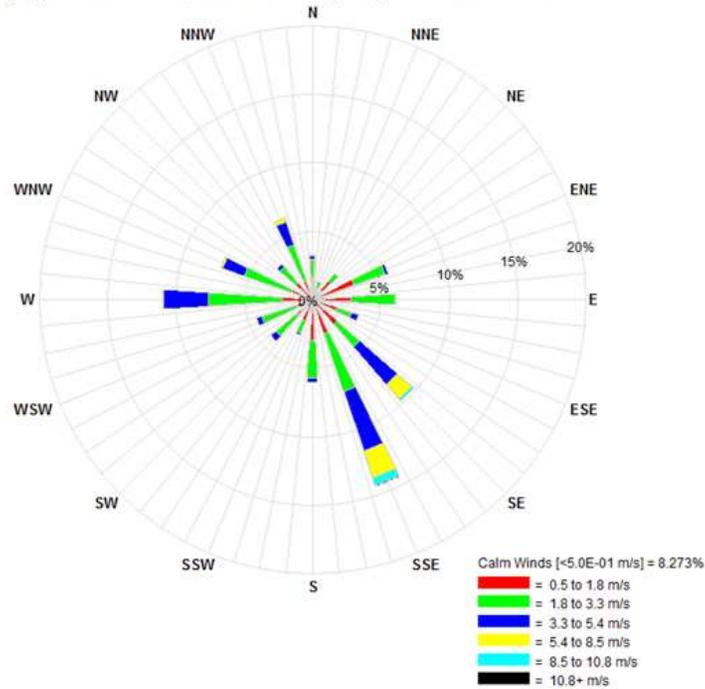


(101120) - CALMET.DAT: Nearest Grid Pt [(I,J)=(101.000, 120.000)] [(X,Y)km=(406.100, 6017.100) in MODEL Projection]
Height = 10.00 m; [Jan 1, 2012 - 1:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]
Q2(Apr,May,Jun): Total Periods = 2184; Valid Periods = 2184 (100%); Calm Wind Periods = 74

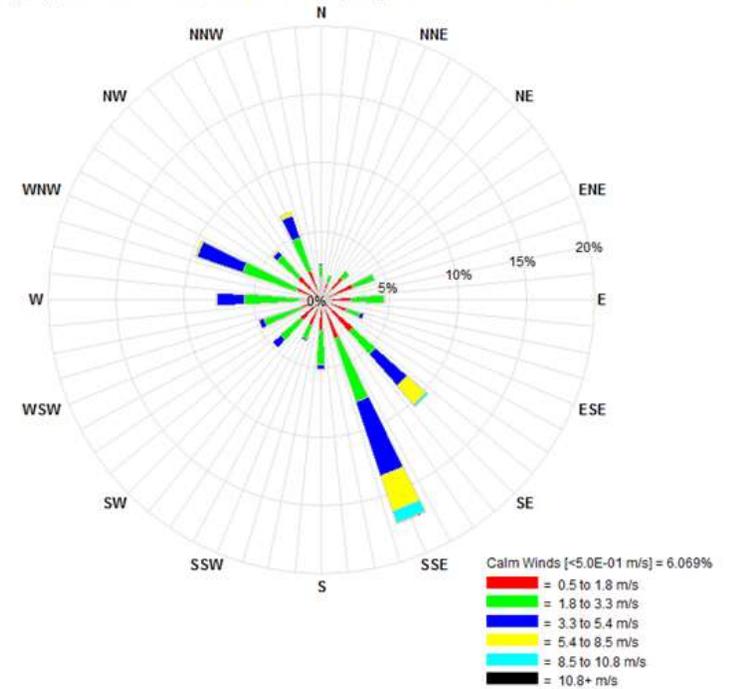


d) Quarterly wind rose (July, August, September)

SURF.DAT: Station ID = 710221
 Height = 10.00 m; [Jan 1, 2012 - 1:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]
 Q3(Jul,Aug,Sep): Total Periods = 2208; Valid Periods = 2200 (99.6%); Calm Wind Periods = 182



(101120) - CALMET.DAT: Nearest Grid Pt [(I,J)=(101.000, 120.000)] [(X,Y)km=(406.100, 6017.100) in MODEL Projection]
 Height = 10.00 m; [Jan 1, 2012 - 1:00:00 AM to Jan 1, 2013 - 12:00:00 AM (UTC-0800)]
 Q3(Jul,Aug,Sep): Total Periods = 2208; Valid Periods = 2208 (100%); Calm Wind Periods = 134



e) Quarterly wind rose (October, November, December)

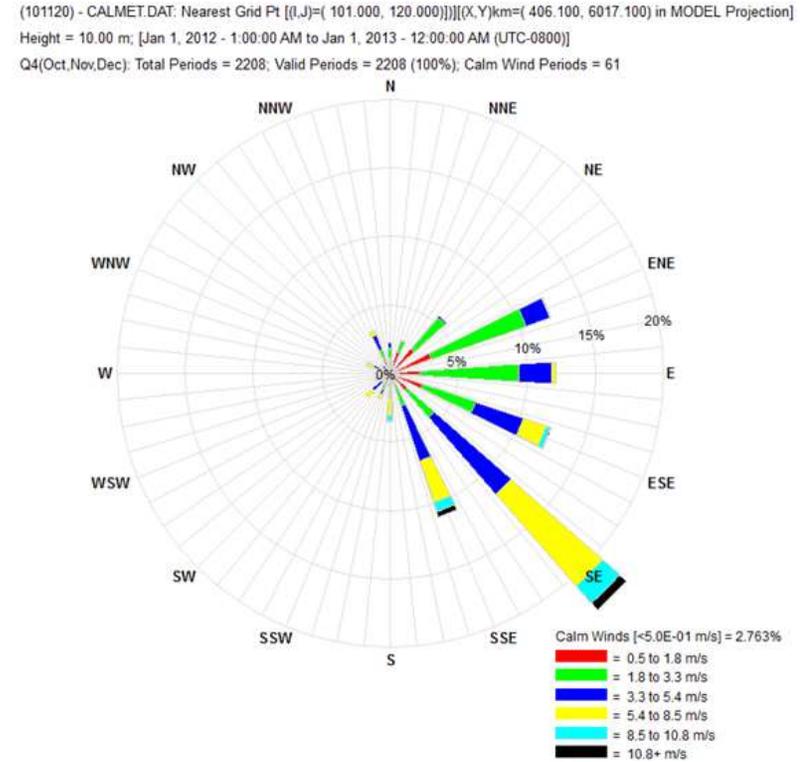
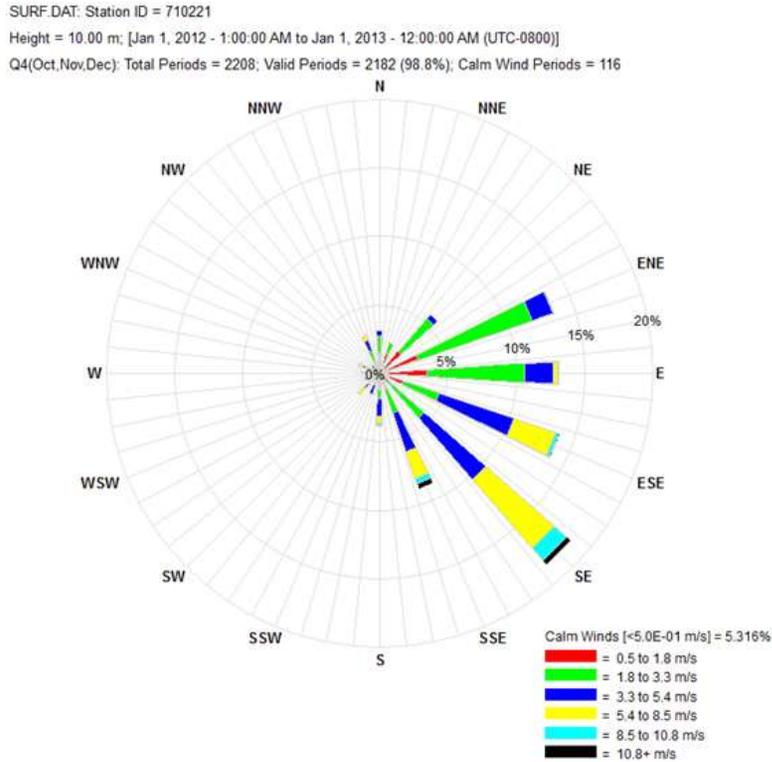


Figure A2.2-10: Wind roses comparison between Prince Rupert Airport station and CALMET (101,120) grid point: 2012 annual wind rose; four quarterly roses Q1 (JAN, FEB, MAR), Q2 (APR, MAY, JUN), Q3 (JUL, AUG, SEP) and Q4 (OCT, NOV, DEC).



2.2.12 Conclusions

The hybrid meteorological fields produced from observations and prognostic model data appear to be representative for the region, and the coastal flow is depicted realistically. The correlation between the observed and modelled fields is considered sufficiently high to justify the use of the selected model parameters as a final set.



2.3 Modelling Source Parameters

This section removed from report to protect proprietary information of proponent/permit holder.



2.4 Modelling QA/QC Log & Scenario Layer Summary

CALPUFF Input Files								Post-Processing & Results v1.0				
Scenario (New)	Scenario (old)	Facility	File Name	Set up Status	Modeler	QA Status	QA'er	File/task	Set up Status	Modeler	QA Status	QA'er
A	1	Pacific Northwest LNG	PNWE.*	2/20/2015	AVJ	2/26/2015	HC	APPEND	3/9/2015	AVJ	3/9/2015	HC
A	1	Prince Rupert LNG	PR_TO.*	2/24/2015	AVJ	2/26/2015	HC	POSTUTIL_Dep	3/9/2015	AVJ	3/9/2015	HC
A	1	Woodside Grassy Point LNG	WGE.*	2/20/2015	AVJ	2/26/2015	HC	POSTUTIL_Con	3/9/2015	HC	3/10/2015	AVJ
A	1	WCC LNG	WCCE.*	2/20/2015	AVJ	2/26/2015	HC	CALPOST_Dep	3/9/2015	AVJ	3/10/2015	HC
A	1	Aurora LNG (Digby Island)	ADIE.*	2/20/2015	AVJ	2/26/2015	HC	CALPOST_Con	3/11/2015	HC	3/11/2015	AVJ
A	1	Watson Island LNG	WIE.*	2/20/2015	AVJ	2/26/2015	HC	Total Deposition_1_2015-0309	3/9/2015	HC	3/9/2015	AVJ
A	1	LNG - Marine	SHFL_1	2/24/2015	HC	2/27/2015	AVJ	Human Health_1_2015-0310	3/10/2015	HC	3/11/2015	AVJ
A	1	LNG - Marine	SHFL_2	2/24/2015	HC	2/27/2015	AVJ	Veg Results_1_2015-0311	3/11/2015	HC	3/13/2015	AVJ
A	1	LNG - Marine	SHFL_3	2/24/2015	HC	2/27/2015	AVJ	Total Deposition_1_2015-0317	3/17/2015	HC	3/17/2015	AVJ
A	1	LNG - Marine	LPFL_1	2/24/2015	HC	2/27/2015	AVJ					
A	1	LNG - Marine	LPFL_2	2/24/2015	HC	2/27/2015	AVJ					
A	1	LNG - Marine	LPFL_3	2/24/2015	HC	2/27/2015	AVJ					
A	1	BC Hydro	BCHR.*	2/20/2015	AVJ	2/26/2015	HC					
A	1	Terminals - Stationary	PortR.*	2/23/2015	AVJ	2/26/2015	HC					
A	1	Terminals - Marine (Part 1)	TL1.*	2/24/2015	HC	2/26/2015	AVJ					
A	1	Terminals - Marine (Part 2)	TL2.*	2/24/2015	HC	2/26/2015	AVJ					
A	1	Terminals - Rail (Area)	RLA.*	2/23/2015	HC	2/27/2015	AH					
A	1	Terminals - Rail (Line Part 1)	RLine1.*	2/25/2015	HC	2/27/2015	AH					
A	1	Terminals - Rail (Line Part 2)	RLine2.*	2/25/2015	HC	2/27/2015	AH					
A	1	Terminals - Rail (Line Part 3)	RLine3.*	2/25/2015	HC	2/27/2015	AH					
A	1	Terminals - Rail (Line Part 4)	RLine4.*	2/25/2015	HC	2/27/2015	AH					
A	1	Terminals - Rail (Line Part 5)	RLine5.*	2/25/2015	HC	2/27/2015	AH					
A	1	Terminals - Rail (Line Part 6)	RLine6.*	2/25/2015	HC	2/27/2015	AH					
A	1	Terminals - Rail (Line Part 7)	RLine7.*	2/25/2015	HC	2/27/2015	AH					
A	1	Terminals - Rail (Line Part 8)	RLine8.*	2/25/2015	HC	2/27/2015	AH					
A	1	Terminals - Rail (Line Part 9)	RLine9.*	2/25/2015	HC	2/27/2015	AH					
F_R	2	Pacific Northwest LNG	PNWDR.*	2/20/2015	AVJ	2/26/2015	HC	APPEND	N/A	N/A	N/A	N/A
F_R	2	Prince Rupert LNG	PRDR_1.*	2/24/2015	AVJ	2/26/2015	HC	POSTUTIL_Dep	3/9/2015	AVJ	3/9/2015	HC
F_R	2	Prince Rupert LNG	PRDR_2.*	2/24/2015	AVJ	2/26/2015	HC	POSTUTIL_Con	3/9/2015	HC	3/10/2015	AVJ
F_R	2	Prince Rupert LNG	PR_TO.*	NA	NA	NA	NA	CALPOST_Dep	3/9/2015	AVJ	3/10/2015	HC
F_R	2	Woodside Grassy Point LNG	WGDR.*	2/20/2015	AVJ	2/26/2015	HC	CALPOST_Con	3/11/2015	HC	3/10/2015	AVJ
F_R	2	WCC LNG	WCCDR.*	2/20/2015	AVJ	2/26/2015	HC	Total Deposition_2_2015-0309	3/9/2015	HC	3/9/2015	AVJ
F_R	2	Aurora LNG (Digby Island)	ADIDR.*	2/20/2015	AVJ	2/26/2015	HC	Human Health_2_2015-0310	3/10/2015	HC	3/11/2015	AVJ
F_R	2	Watson Island LNG	WIDR.*	2/20/2015	AVJ	2/26/2015	HC	Veg Results_2_2015-0311	3/11/2015	HC	3/13/2015	AVJ
F_R	2	LNG - Marine (6 Parts)	LNGFL.*	NA	NA	NA	NA	Total Deposition_2_2015-0317	3/17/2015	HC	3/17/2015	AVJ
F_R	2	BC Hydro	BCHR.*	NA	NA	NA	NA					
F_R	2	Terminals - Stationary	PortR.*	NA	NA	NA	NA					
F_R	2	Terminals - Marine (2 Parts)	TL.*	NA	NA	NA	NA					
F_R	2	Terminals - Rail (Area)	RLA.*	NA	NA	NA	NA					
F_R	2	Terminals - Rail (9 Lines)	RLine.*	NA	NA	NA	NA					



2.5 Rail and Marine Transportation Emissions

2.5.1 Marine and Rail Emissions Calculations

Pacific Northwest LNG Emissions - Shipping

Table 1. LNG Carrier Operating Information

Parameter	Value	Units	Source/Basis
Main Engine Output Rating	37,320	kW	Pacific Northwest LNG Air Quality Technical Data Report
Main Engine Load Factor	65%	--	Engineering estimate based on travel speed versus carrier cruise speed
Facility Production Capacity	19,200,000	metric tpy	Pacific Northwest LNG Project Description
LNG Carrier Capacity	217,000	m ³	Pacific Northwest LNG Air Quality Technical Data Report
Maximum Speed Outside of Port Boundary	16	knots	Pacific Northwest LNG Project Description
Length of Shipping Route Outside of Port Boundary	34	km	Distance based on proposed shipping route and length to study area boundary.
Maximum Speed Within the Port Boundary	6	knots	Pacific Northwest LNG Environmental Assessment
Length of Shipping Route Within the Port Boundary	14	km	Distance based on proposed shipping route
Travel Time	2.5	hours	Calculated
Ships per Year	350	carriers/yr	Pacific Northwest LNG Air Quality Technical Data Report

Table 2. LNG Carrier Emissions during Travel - Main Engine

Pollutant	Emission Factor	Units	Source/Basis	Emissions per Unit		Combined Emissions (tonnes/yr)	Annual Average (g/s)
				(g/s)	(g/carrier)		
NO _x	13.2	g/kW-hr	Email from Kyle Beaulieu dated 12/11/2013, MGO-fired 4-stroke main engine, merchant (liquefied gas) vessel, 2015 inventory	88.95	785,436	274.9	8.7
SO ₂	0.42	g/kW-hr	Email from Kyle Beaulieu dated 12/11/2013, MGO-fired 4-stroke main engine, merchant (liquefied gas) vessel, 2015 inventory	2.83	24,991	8.7	0.3
PM ₁₀	0.28	g/kW-hr	Email from Kyle Beaulieu dated 12/11/2013, MGO-fired 4-stroke main engine, merchant (liquefied gas) vessel, 2015 inventory	1.92	16,938.6	5.9	0.2
PM _{2.5}	0.26	g/kW-hr	Email from Kyle Beaulieu dated 12/11/2013, MGO-fired 4-stroke main engine, merchant (liquefied gas) vessel, 2015 inventory	1.76	15,583.5	5.5	0.2



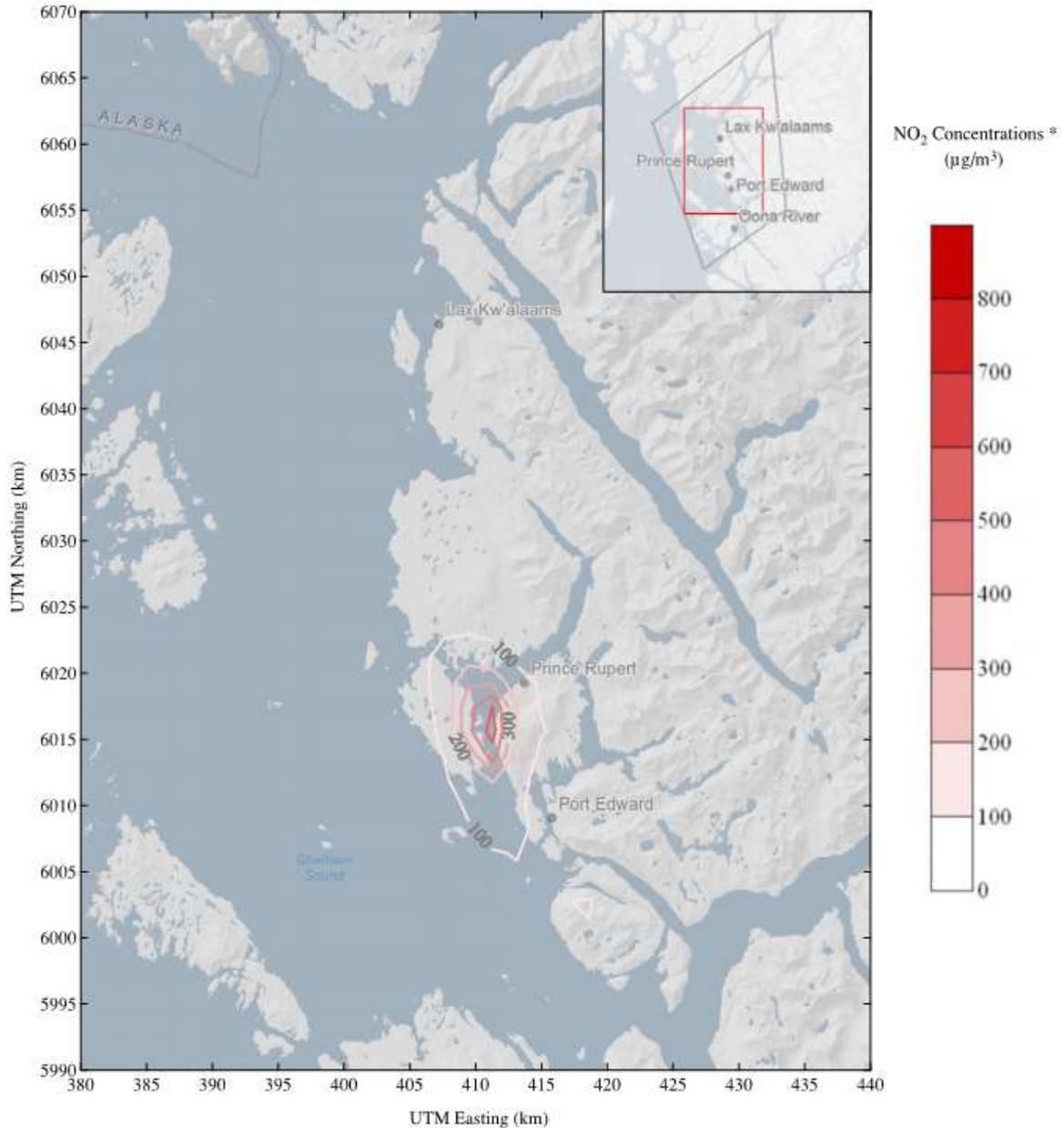
2.5.2 Provided or Referenced Data for Marine Emissions

This section removed from report to protect proprietary information of proponent/permit holder.



2.6 Concentration and Deposition Maps for Scenarios B to F_M

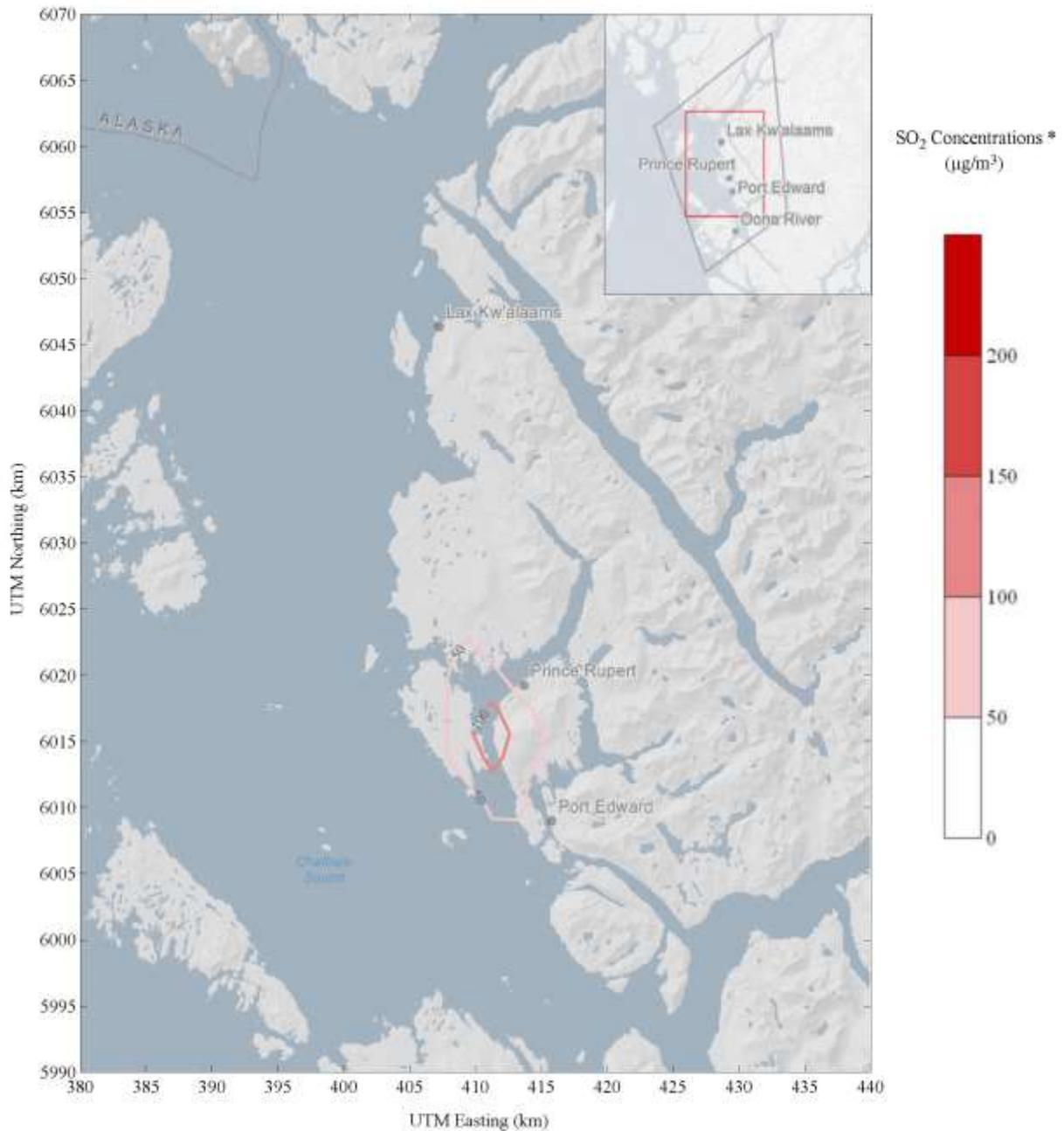
Prince Rupert Airshed Study 98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average 2012 Meteorological Year Scenario B



* The modelled NO₂ concentrations include a background concentration of 13.0 ppb (24.44 µg/m³).



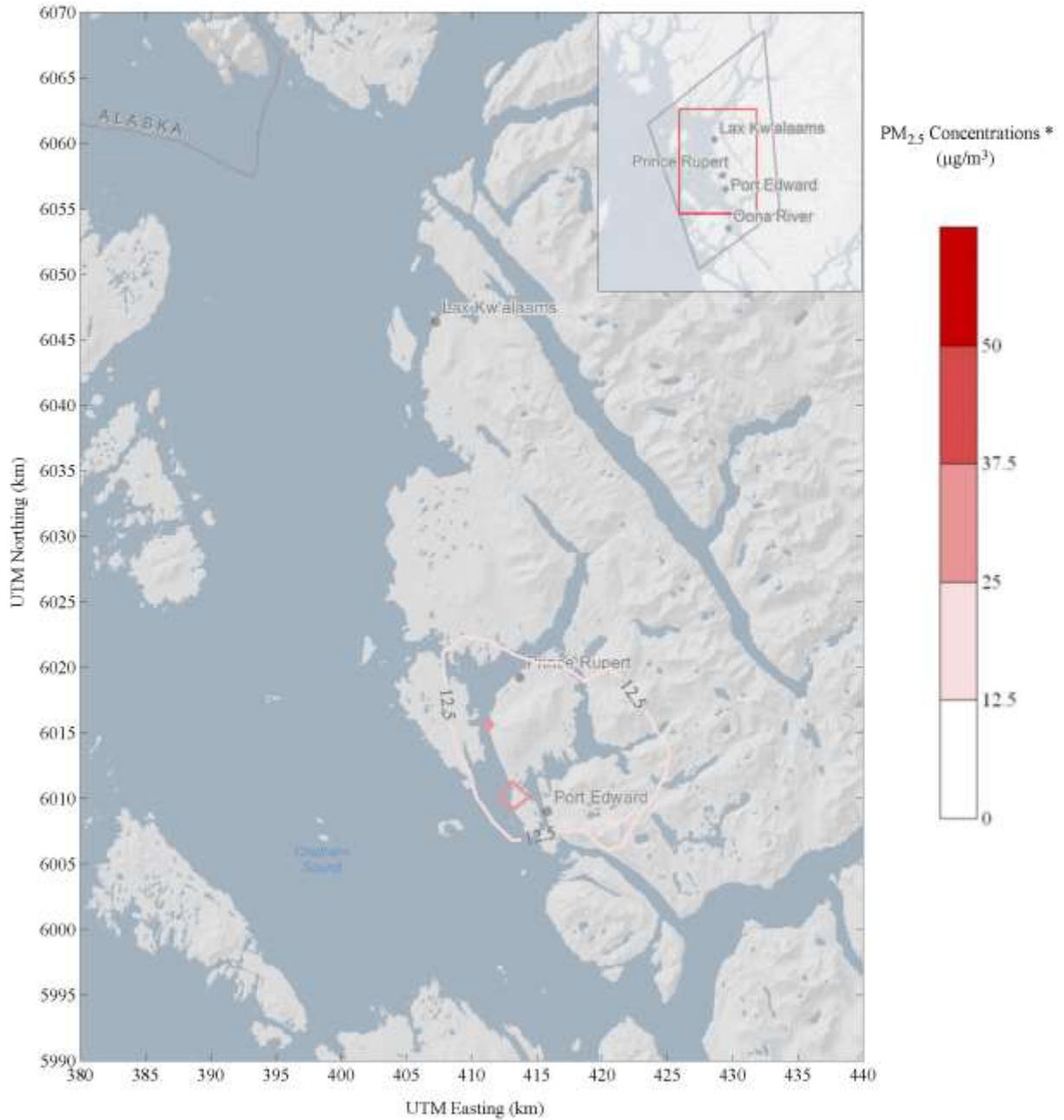
**Prince Rupert Airshed Study
99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario B**



* The modelled SO₂ concentrations include a background concentration of 4.0 ppb (10.67 µg/m³).



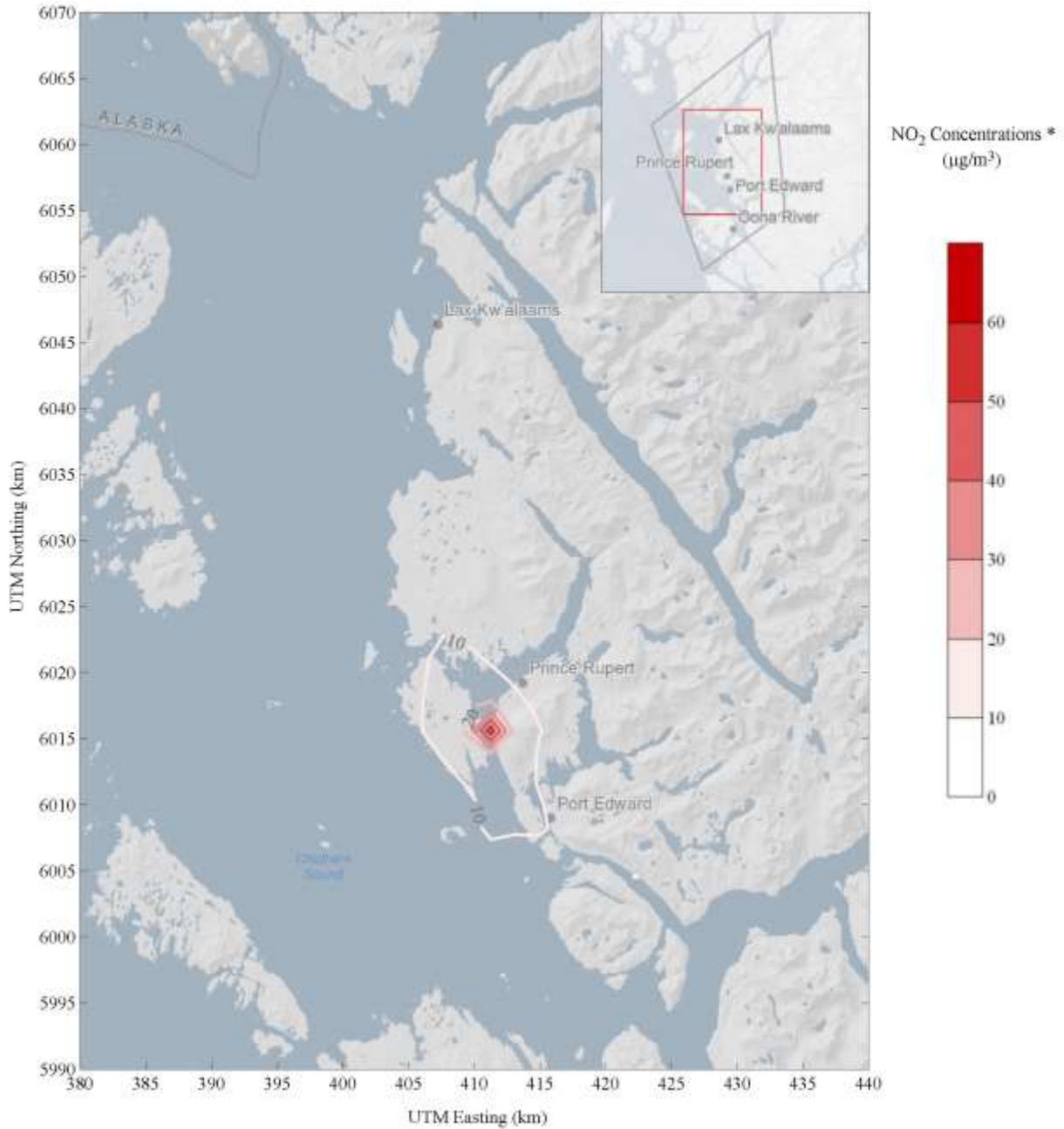
Prince Rupert Airshed Study
98th Percentile PM_{2.5} Concentrations, 24 hour Average
2012 Meteorological Year
Scenario B



* The modelled PM_{2.5} concentrations include a background concentration of 7.0 µg/m³.



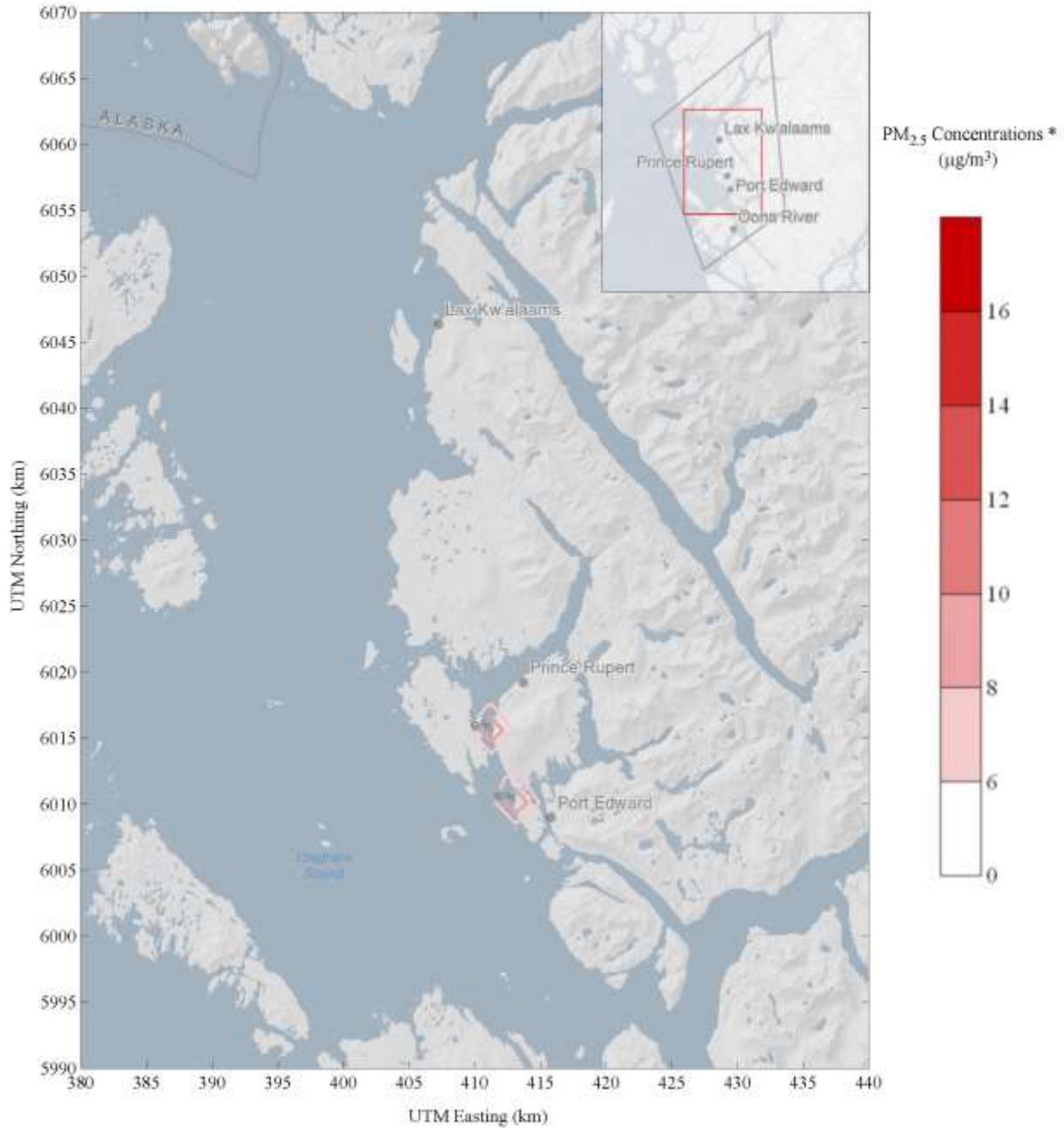
**Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario B**



* The modelled NO₂ concentrations include a background concentration of 3.0 ppb (5.64 µg/m³).



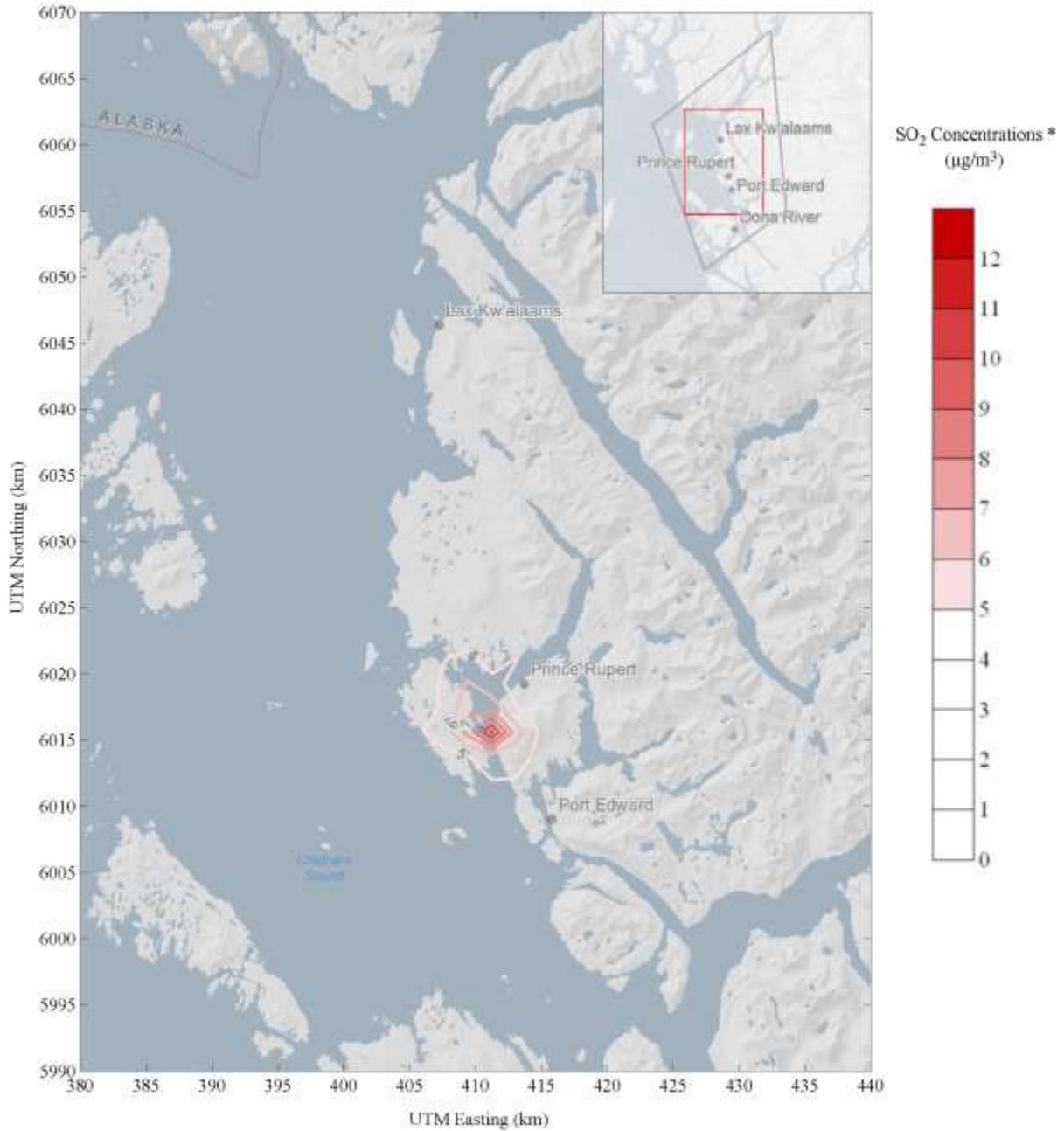
**Prince Rupert Airshed Study
PM_{2.5} Concentrations, Annual Average
2012 Meteorological Year
Scenario B**



* The modelled PM_{2.5} concentrations include a background concentration of 3.5 µg/m³.
Contour levels below the levels of 4 µg/m³ are not shown because they are very close to or below the background concentration.



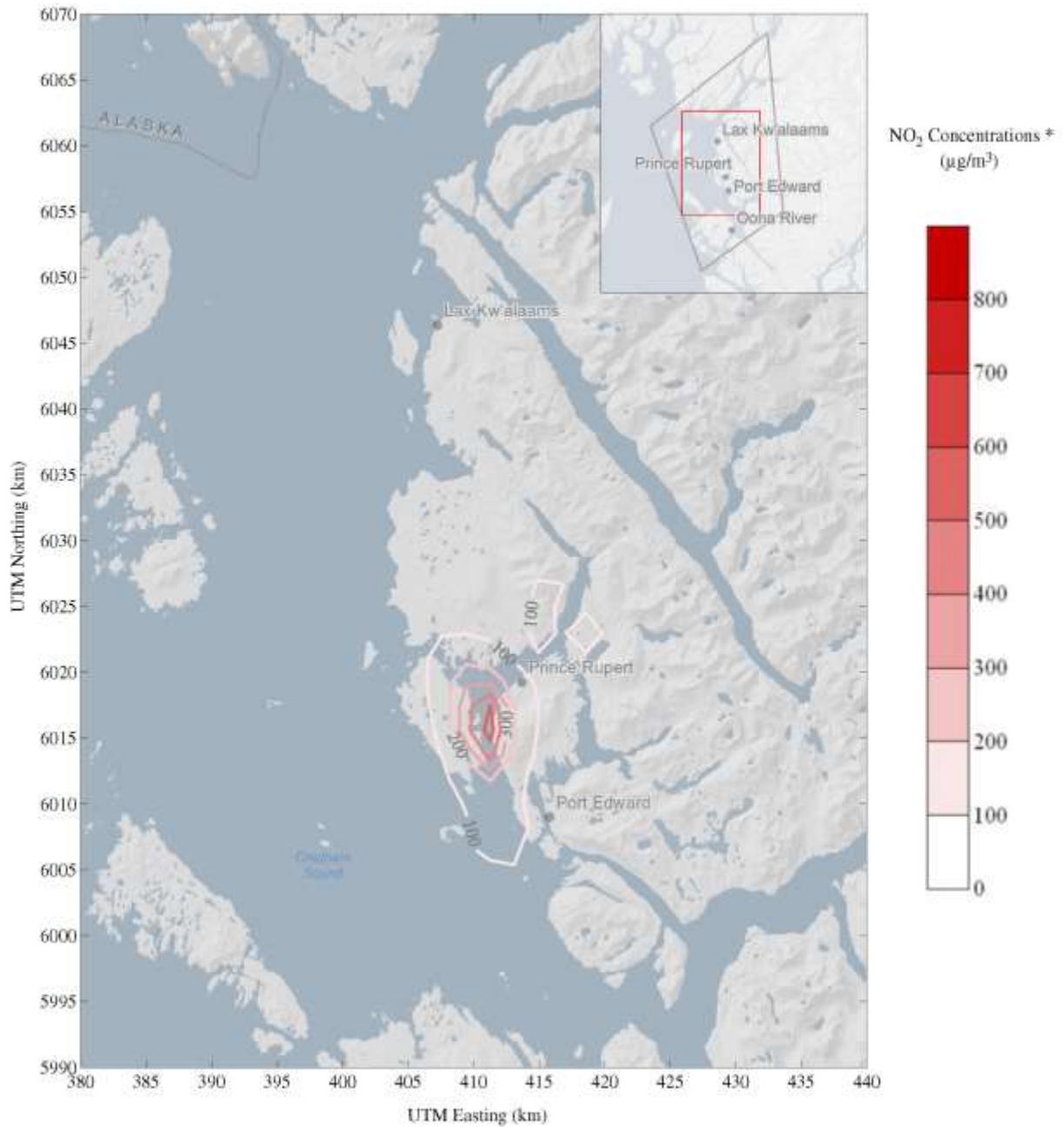
**Prince Rupert Airshed Study
SO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario B**



* The modelled SO₂ concentrations include a background concentration of 1.5 ppb (4.00 µg/m³).
Contour levels below the background concentration are shown as white.



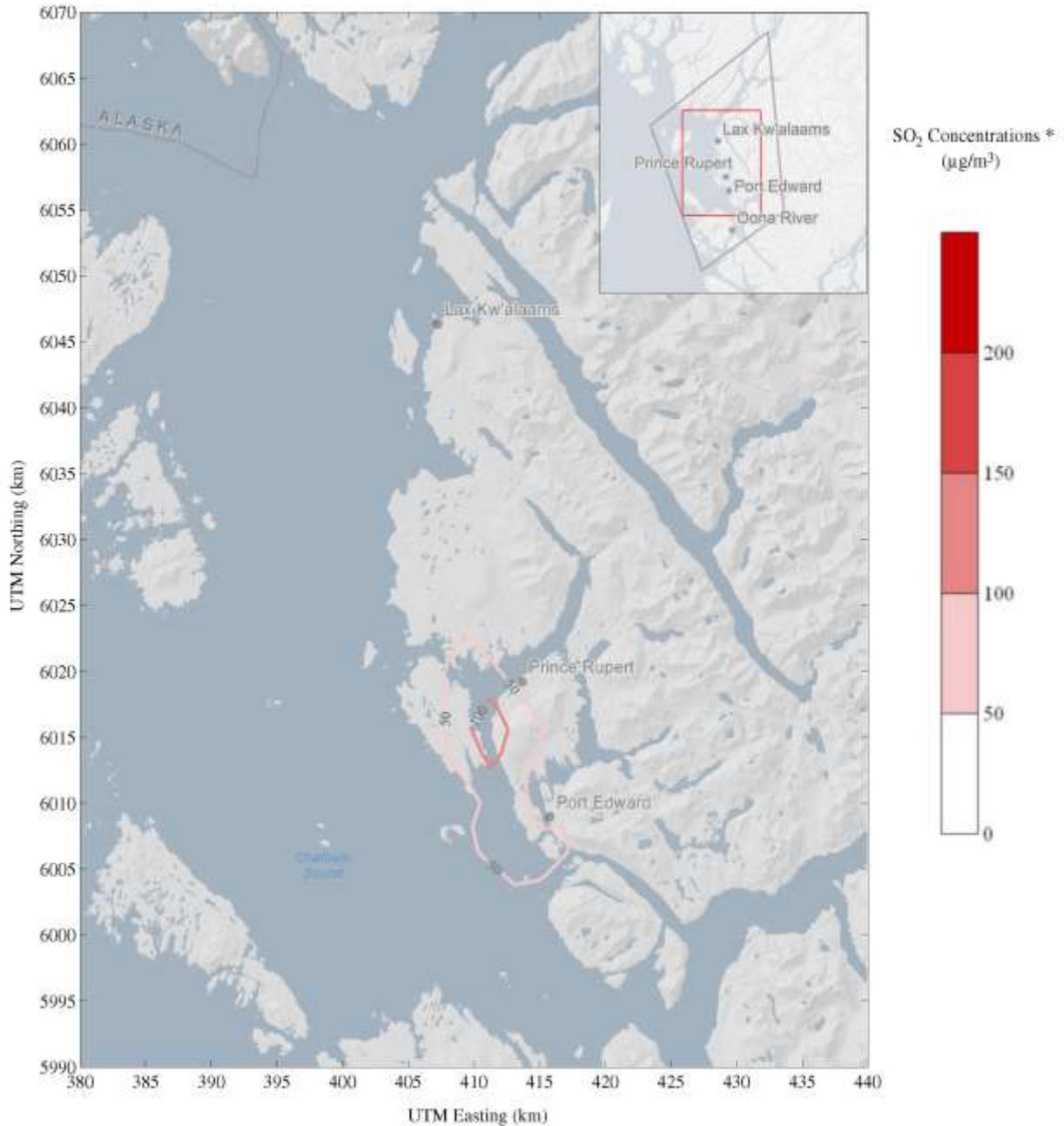
**Prince Rupert Airshed Study
98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario C**



* The modelled NO₂ concentrations include a background concentration of 13.0 ppb (24.44 µg/m³).



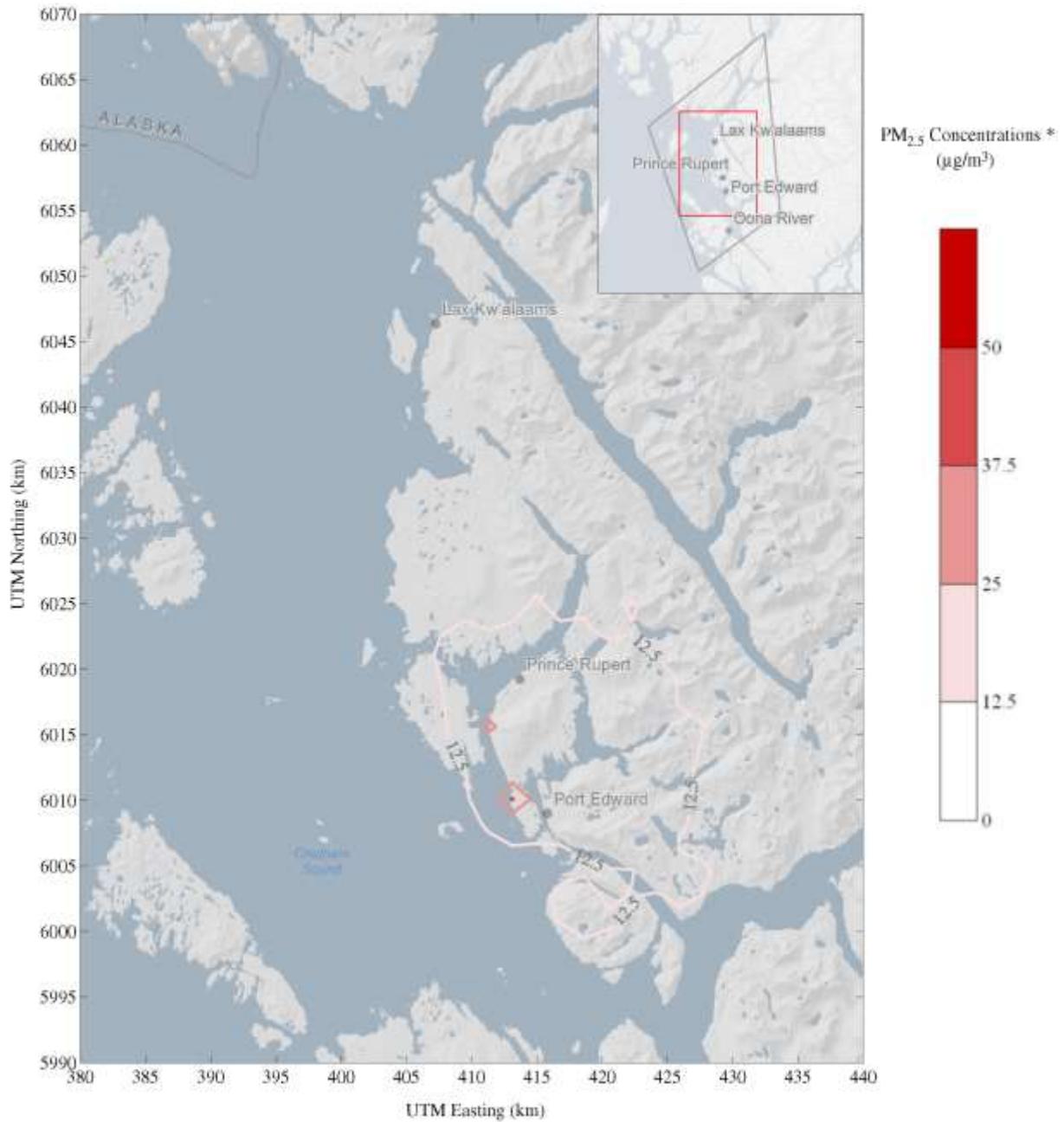
**Prince Rupert Airshed Study
99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario C**



* The modelled SO₂ concentrations include a background concentration of 4.0 ppb (10.67 µg/m³).



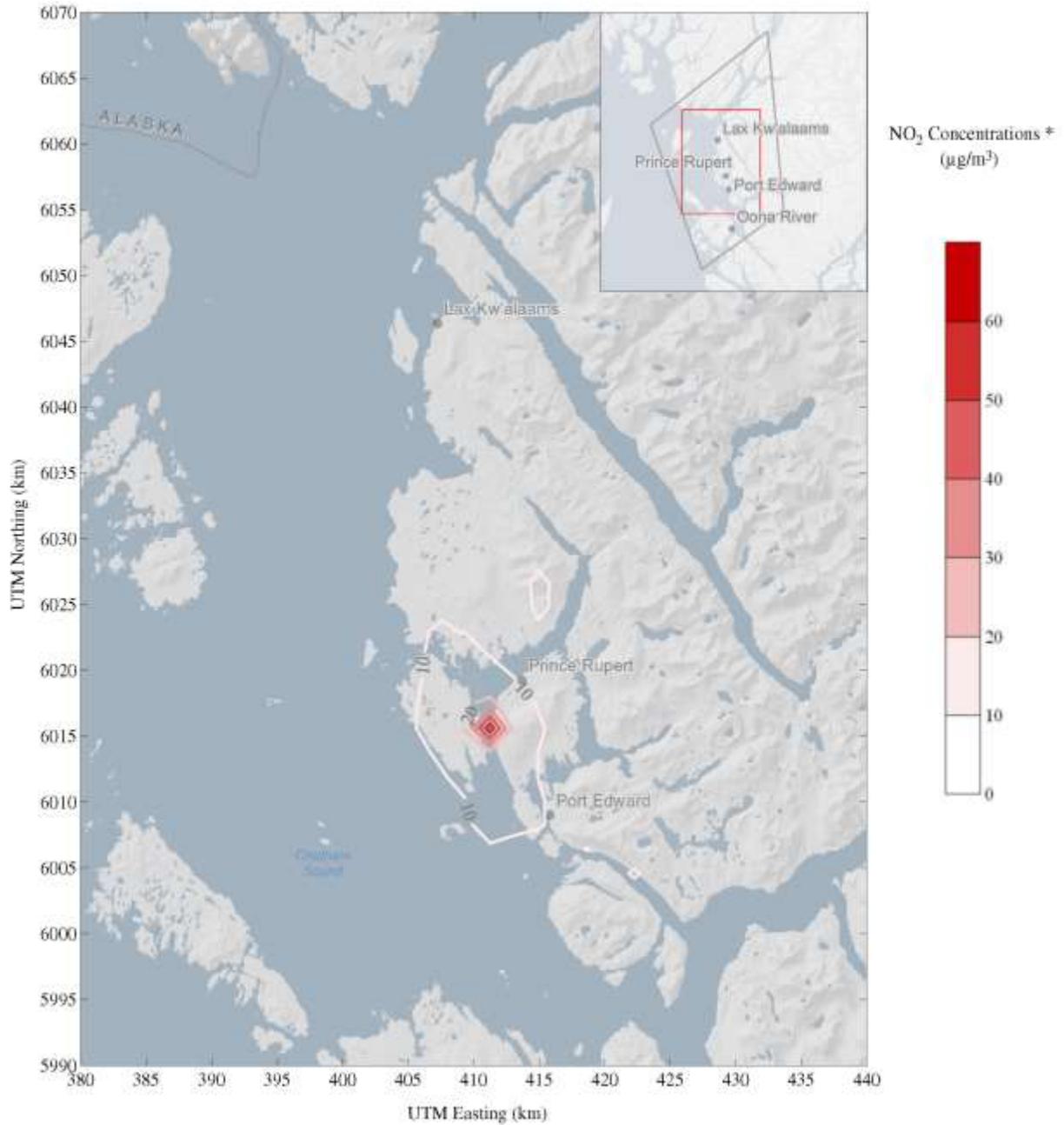
Prince Rupert Airshed Study
98th Percentile PM_{2.5} Concentrations, 24 hour Average
2012 Meteorological Year
Scenario C



* The modelled PM_{2.5} concentrations include a background concentration of 7.0 µg/m³.



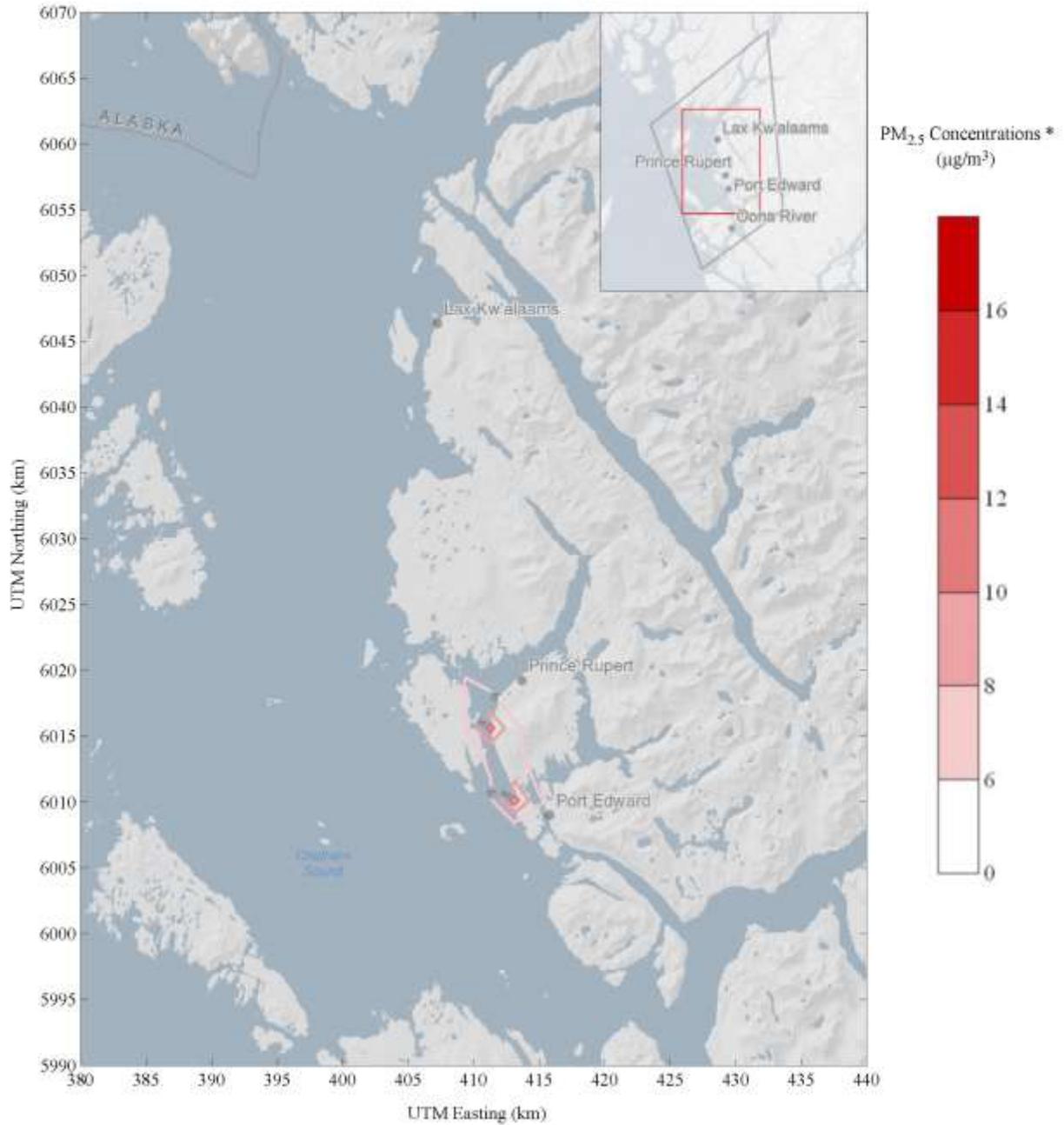
Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario C



* The modelled NO₂ concentrations include a background concentration of 3.0 ppb (5.64 µg/m³).

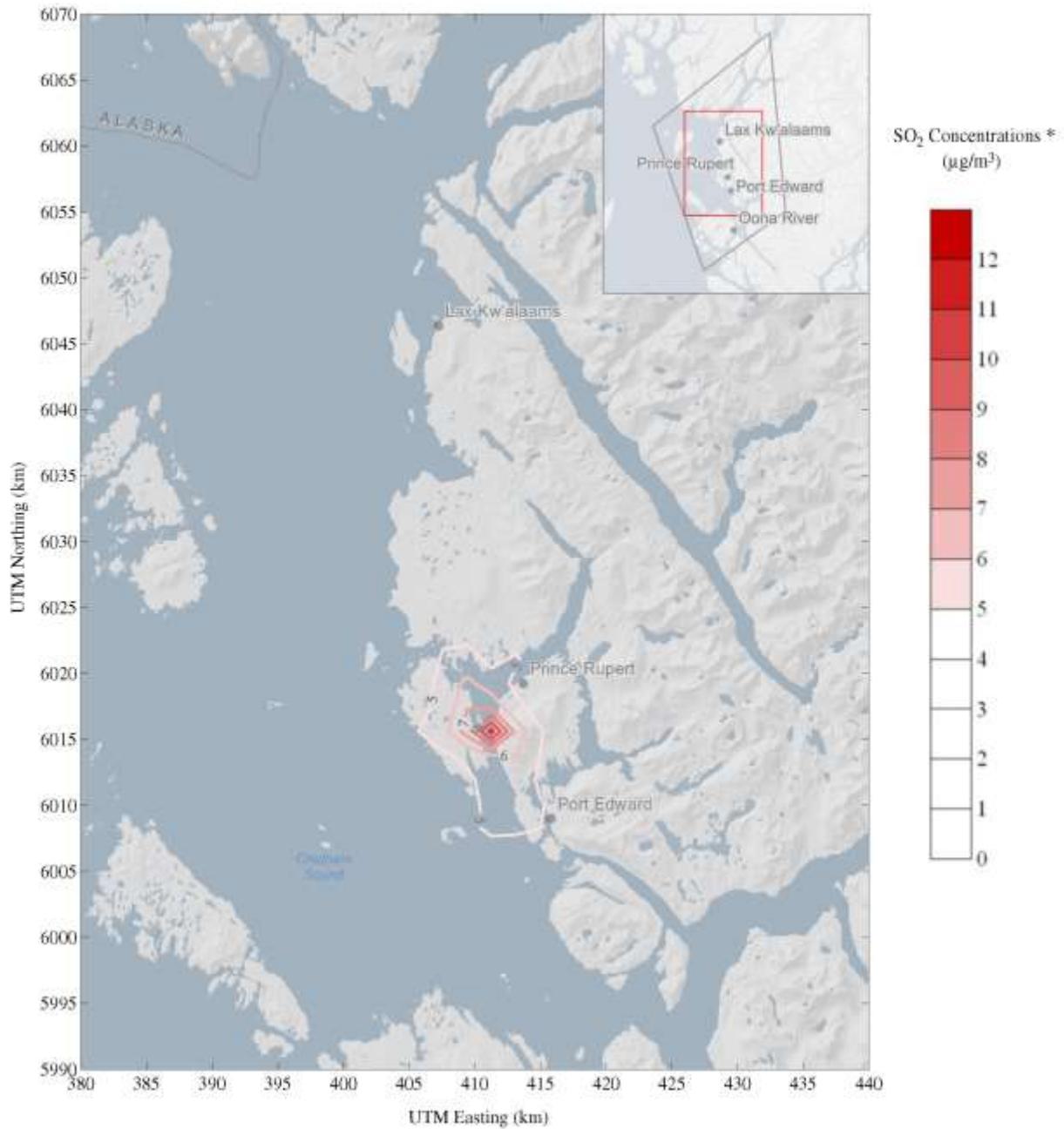


Prince Rupert Airshed Study PM_{2.5} Concentrations, Annual Average 2012 Meteorological Year Scenario C



* The modelled PM_{2.5} concentrations include a background concentration of 3.5 µg/m³.
Contour levels below the levels of 4 µg/m³ are not shown because they are very close to or below the background concentration.

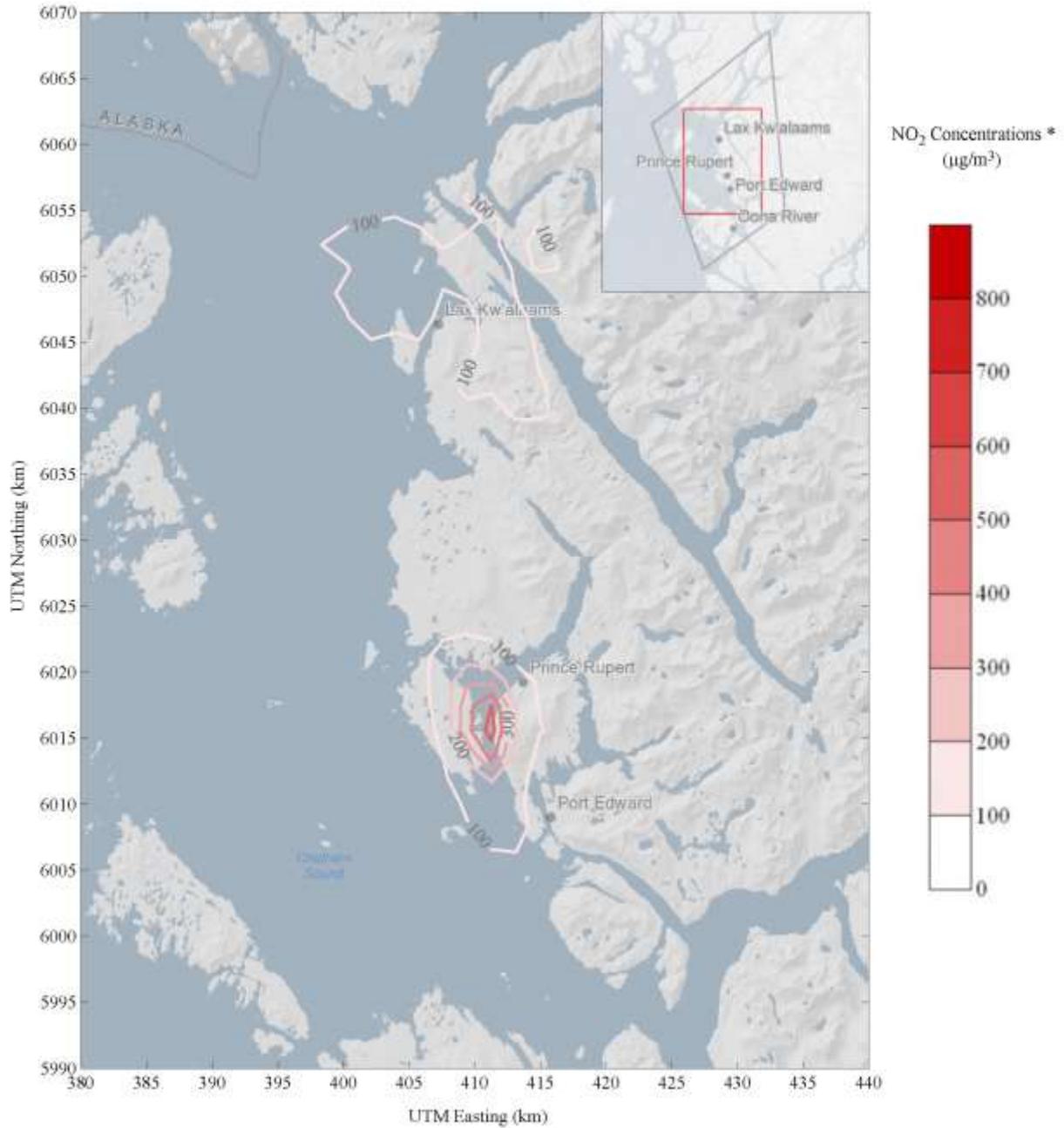
Prince Rupert Airshed Study
SO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario C



* The modelled SO₂ concentrations include a background concentration of 1.5 ppb (4.00 µg/m³).
Contour levels below the background concentration are shown as white.



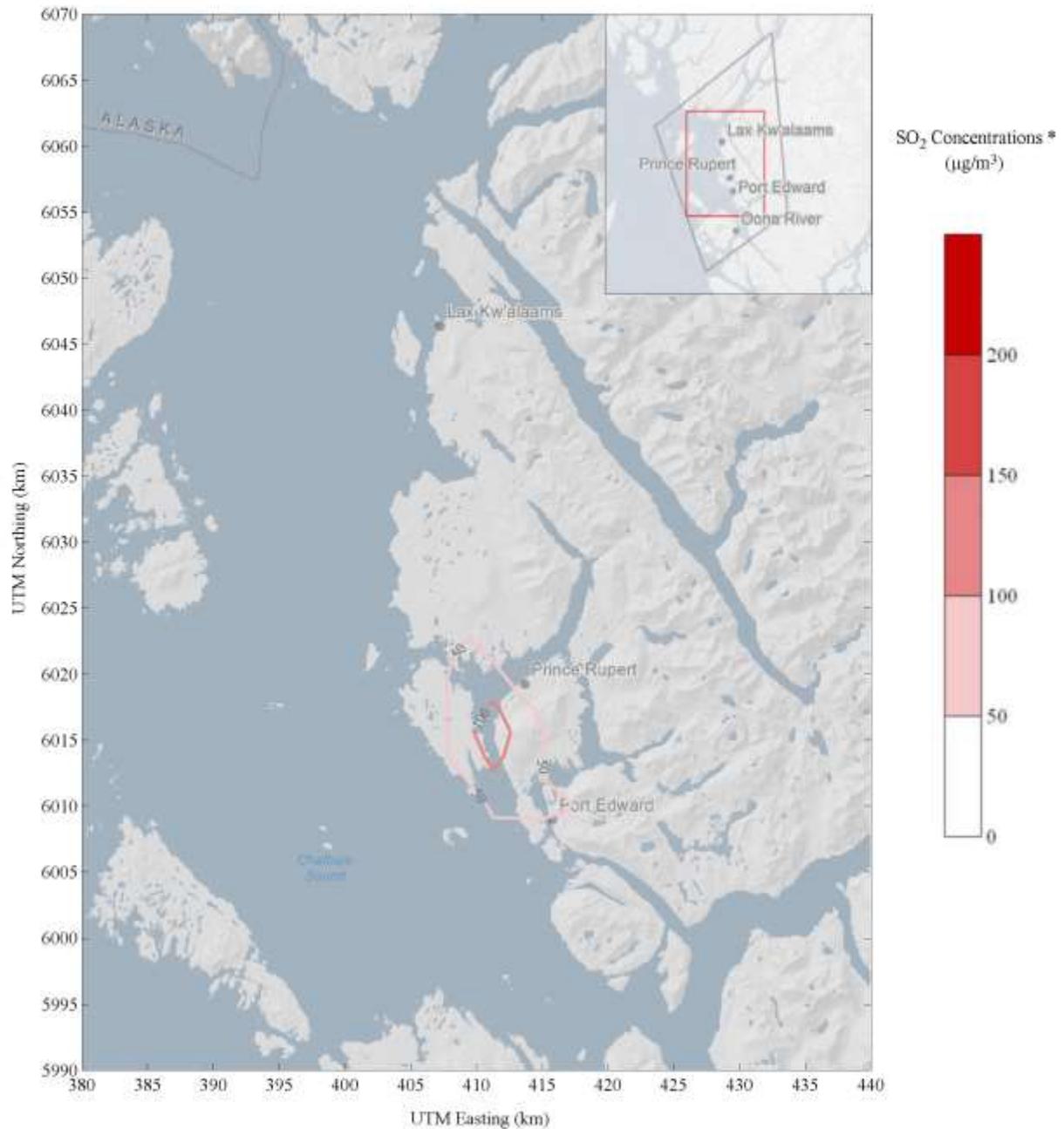
**Prince Rupert Airshed Study
98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario D**



* The modelled NO₂ concentrations include a background concentration of 13.0 ppb (24.44 µg/m³).



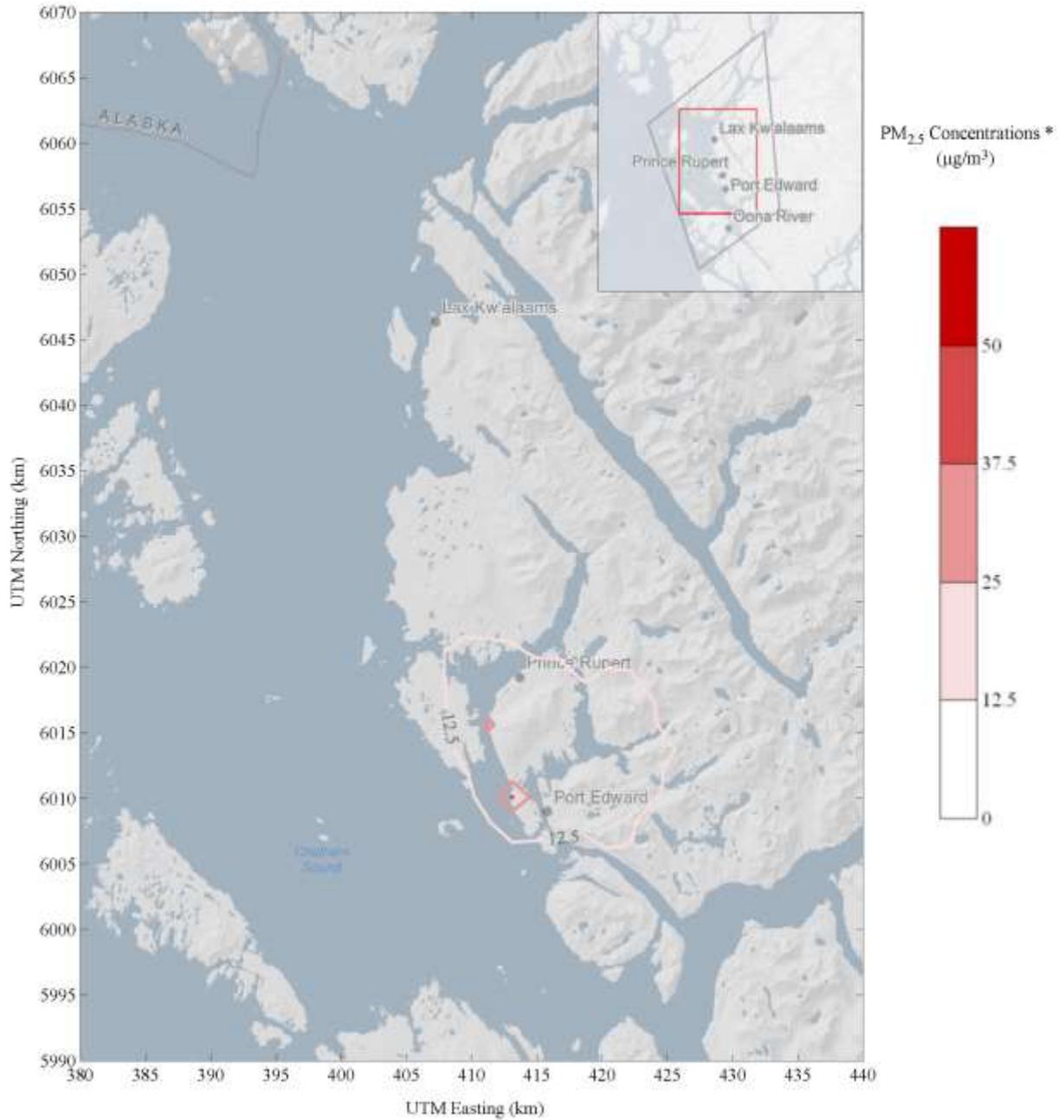
**Prince Rupert Airshed Study
99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario D**



* The modelled SO₂ concentrations include a background concentration of 4.0 ppb (10.67 µg/m³).



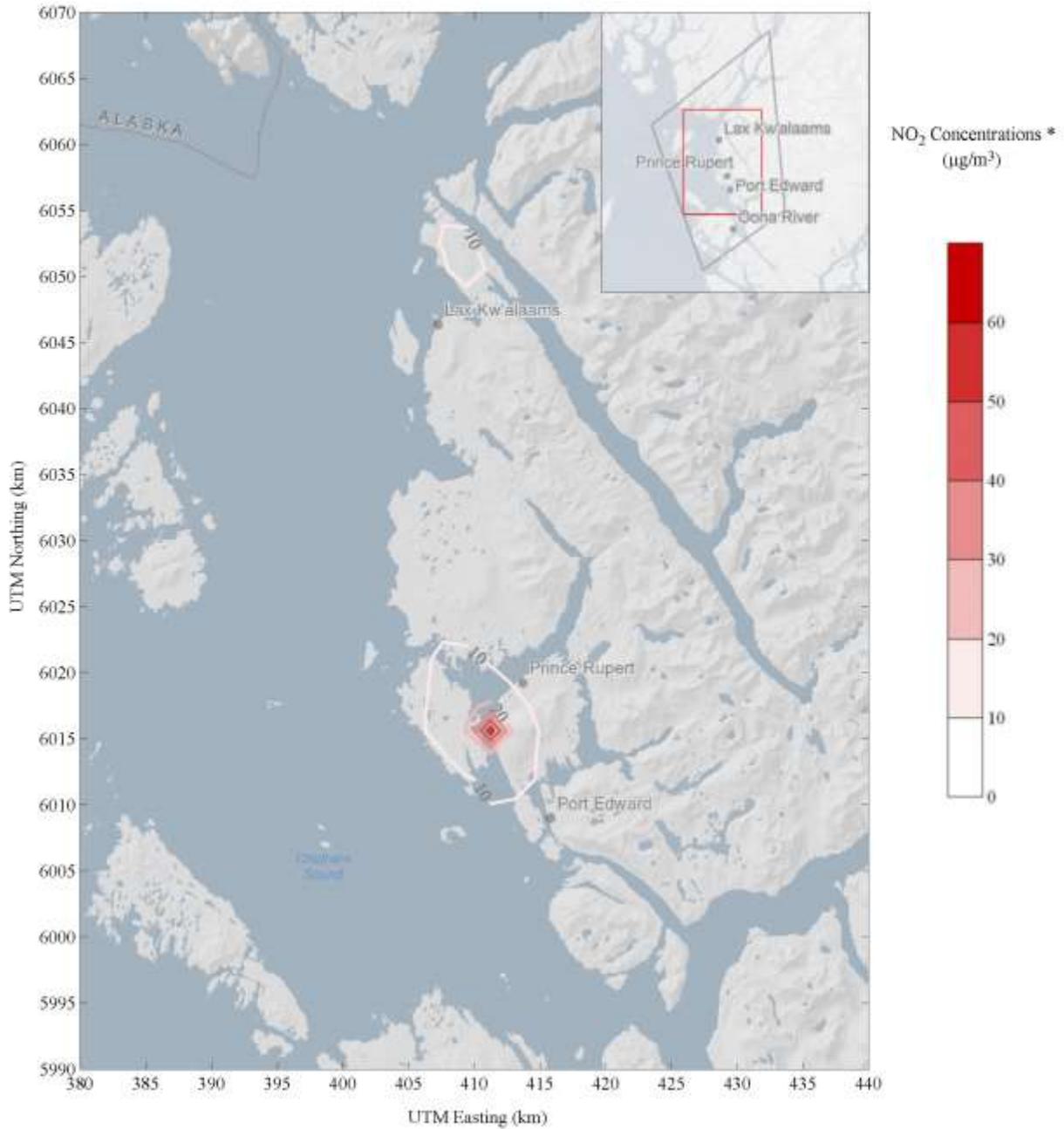
Prince Rupert Airshed Study
98th Percentile PM_{2.5} Concentrations, 24 hour Average
2012 Meteorological Year
Scenario D



* The modelled PM_{2.5} concentrations include a background concentration of 7.0 µg/m³.



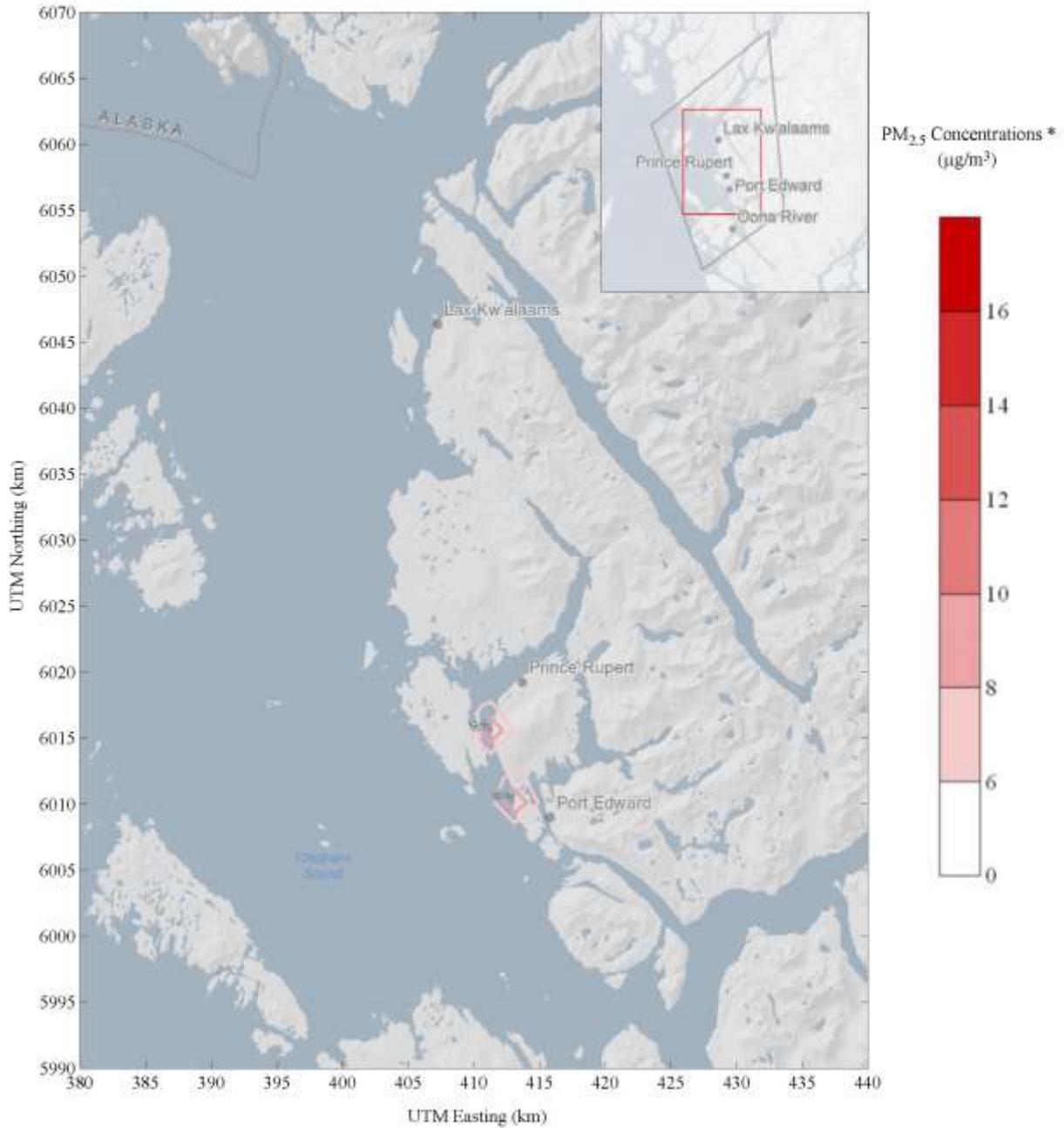
**Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario D**



* The modelled NO₂ concentrations include a background concentration of 3.0 ppb (5.64 µg/m³).



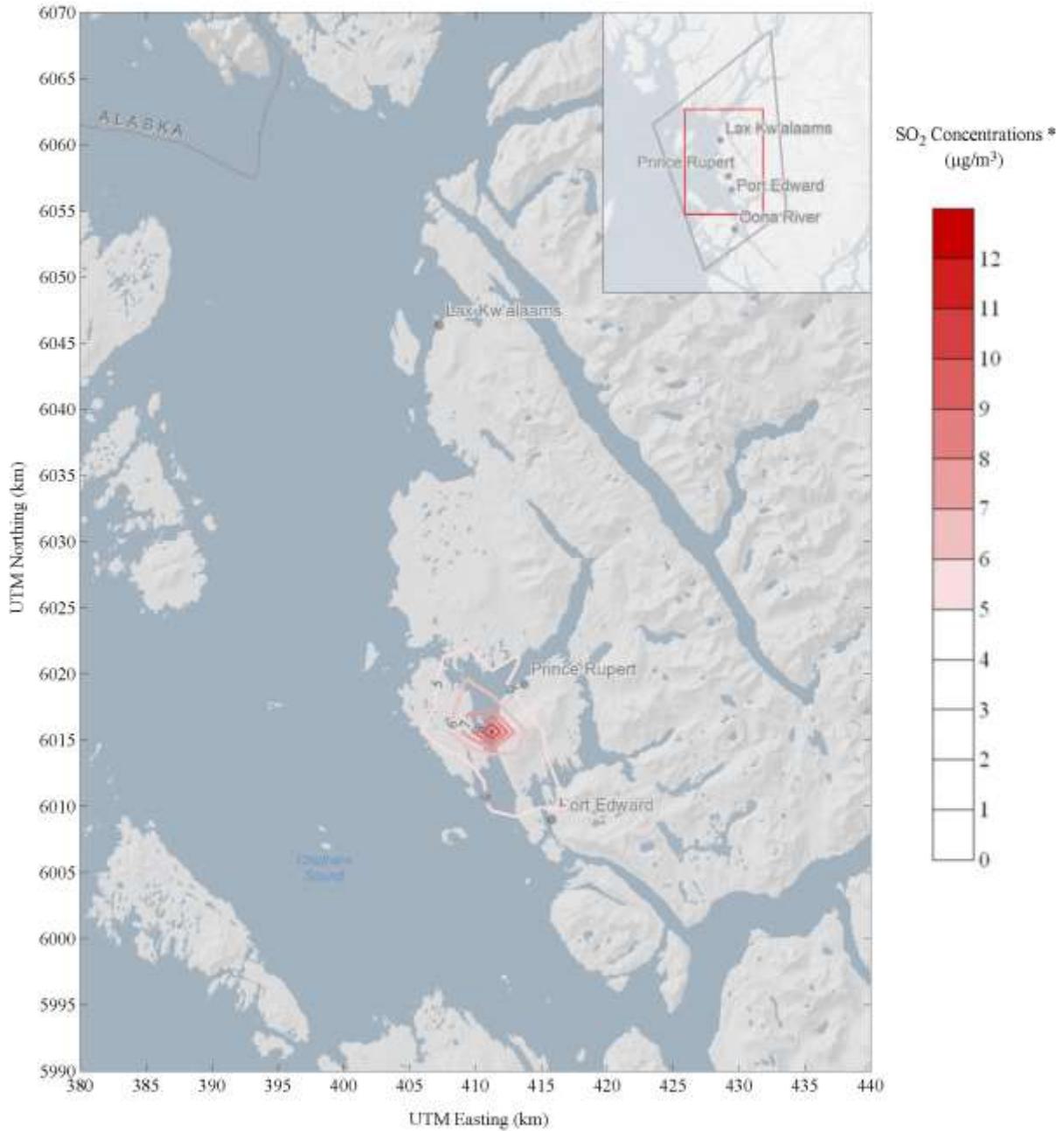
**Prince Rupert Airshed Study
PM_{2.5} Concentrations, Annual Average
2012 Meteorological Year
Scenario D**



* The modelled PM_{2.5} concentrations include a background concentration of 3.5 µg/m³.
Contour levels below the levels of 4 µg/m³ are not shown because they are very close to or below the background concentration.



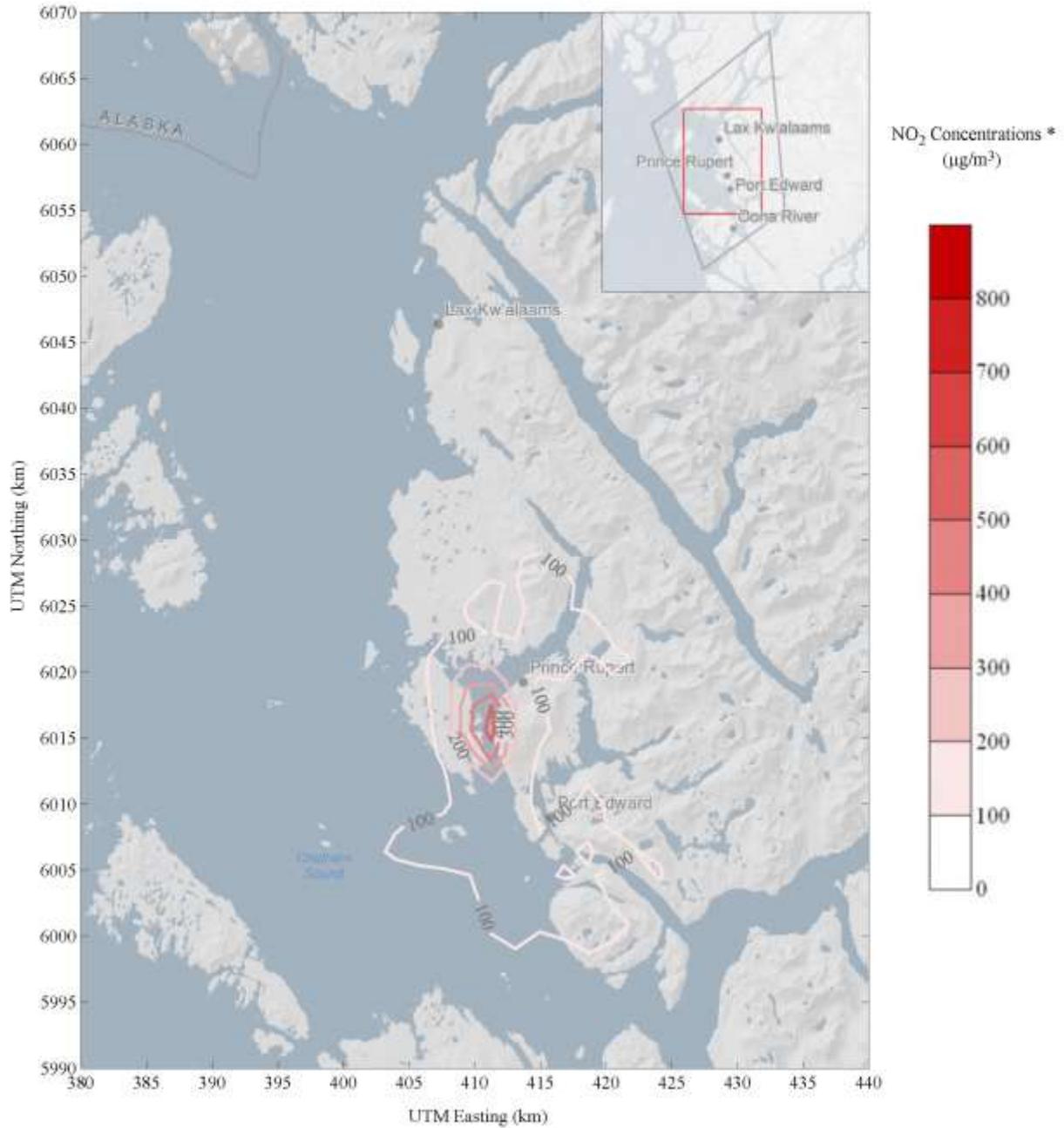
Prince Rupert Airshed Study
SO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario D



* The modelled SO₂ concentrations include a background concentration of 1.5 ppb (4.00 µg/m³).
Contour levels below the background concentration are shown as white.



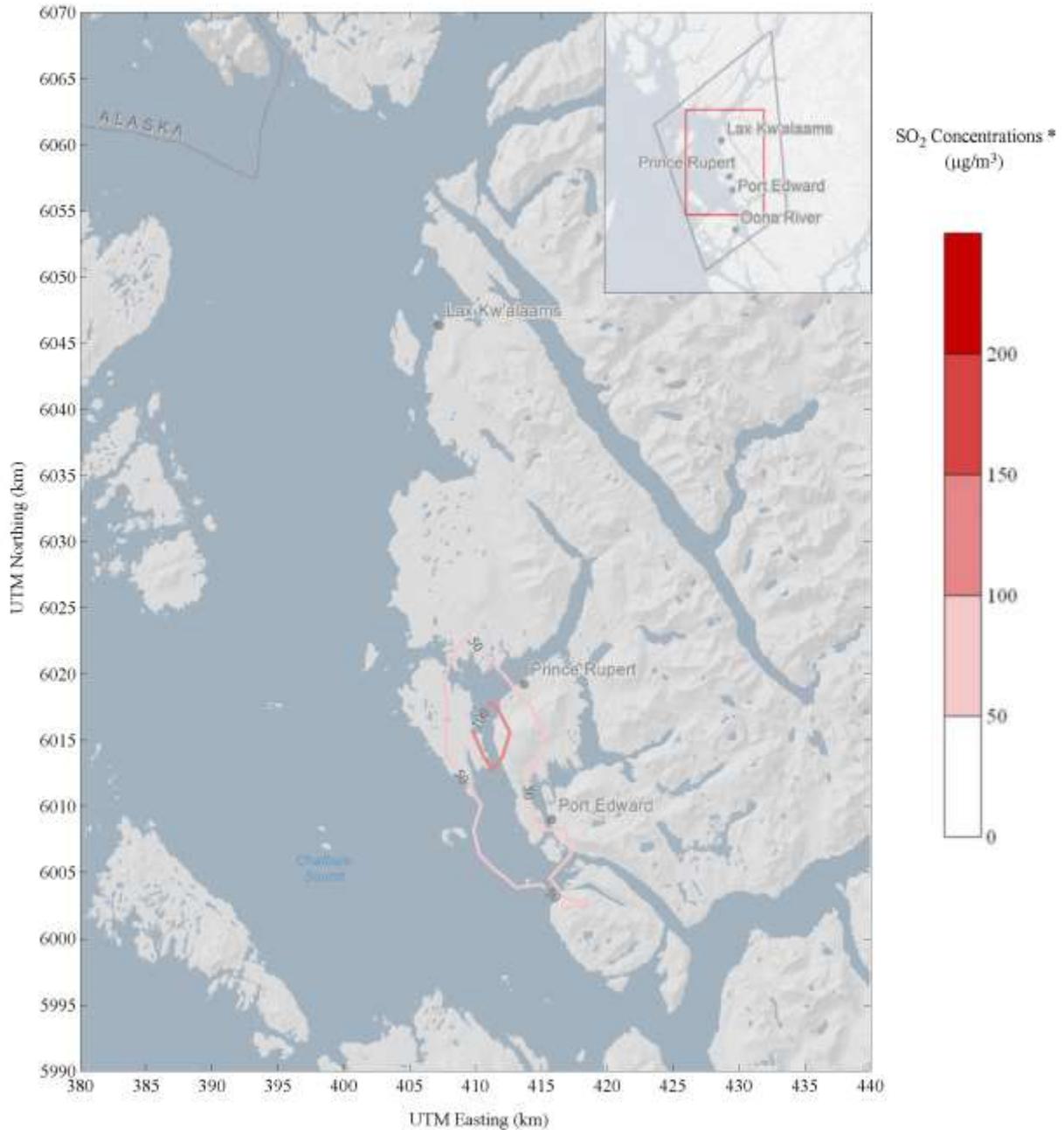
**Prince Rupert Airshed Study
98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario E**



* The modelled NO₂ concentrations include a background concentration of 13.0 ppb (24.44 µg/m³).



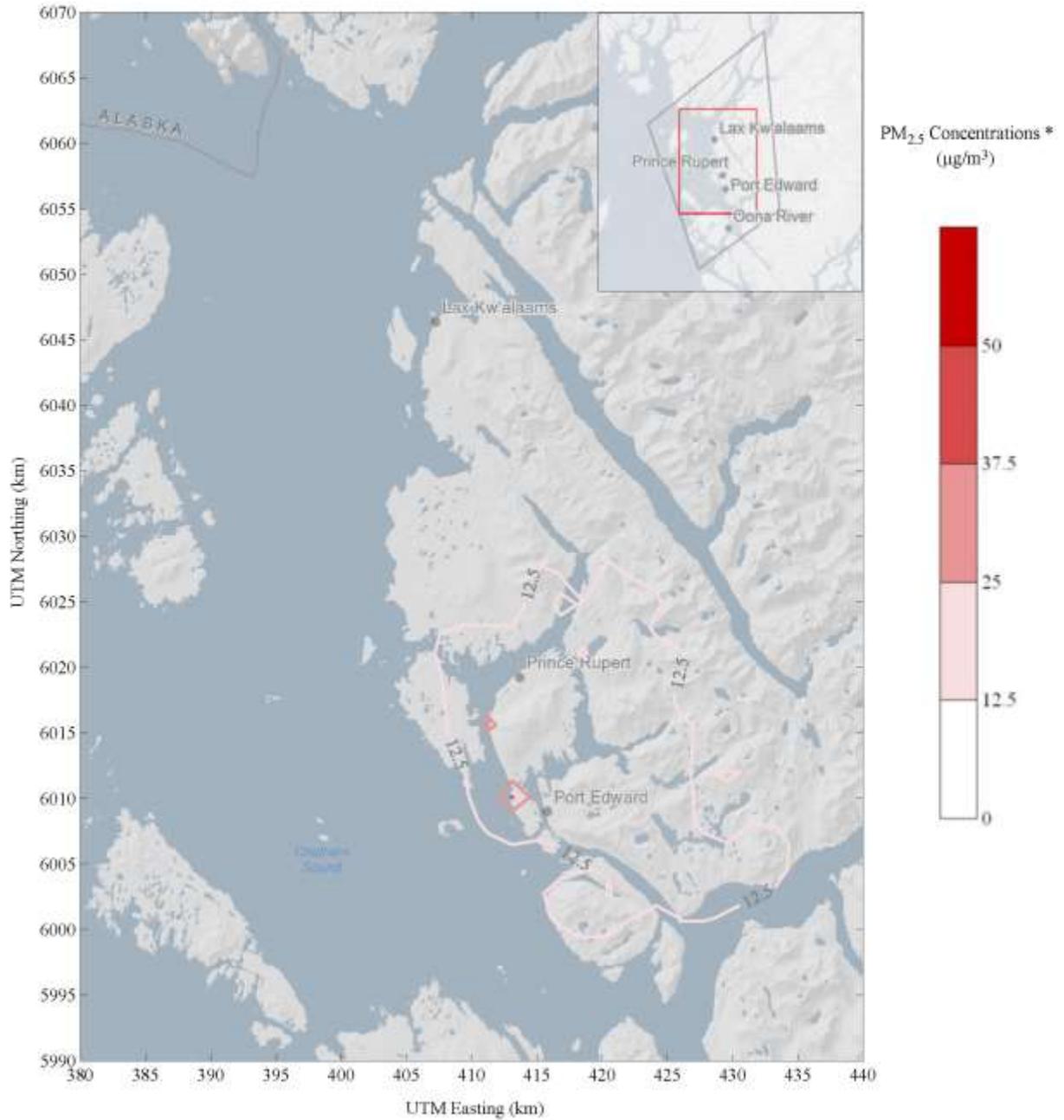
Prince Rupert Airshed Study
99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario E



* The modelled SO₂ concentrations include a background concentration of 4.0 ppb (10.67 µg/m³).

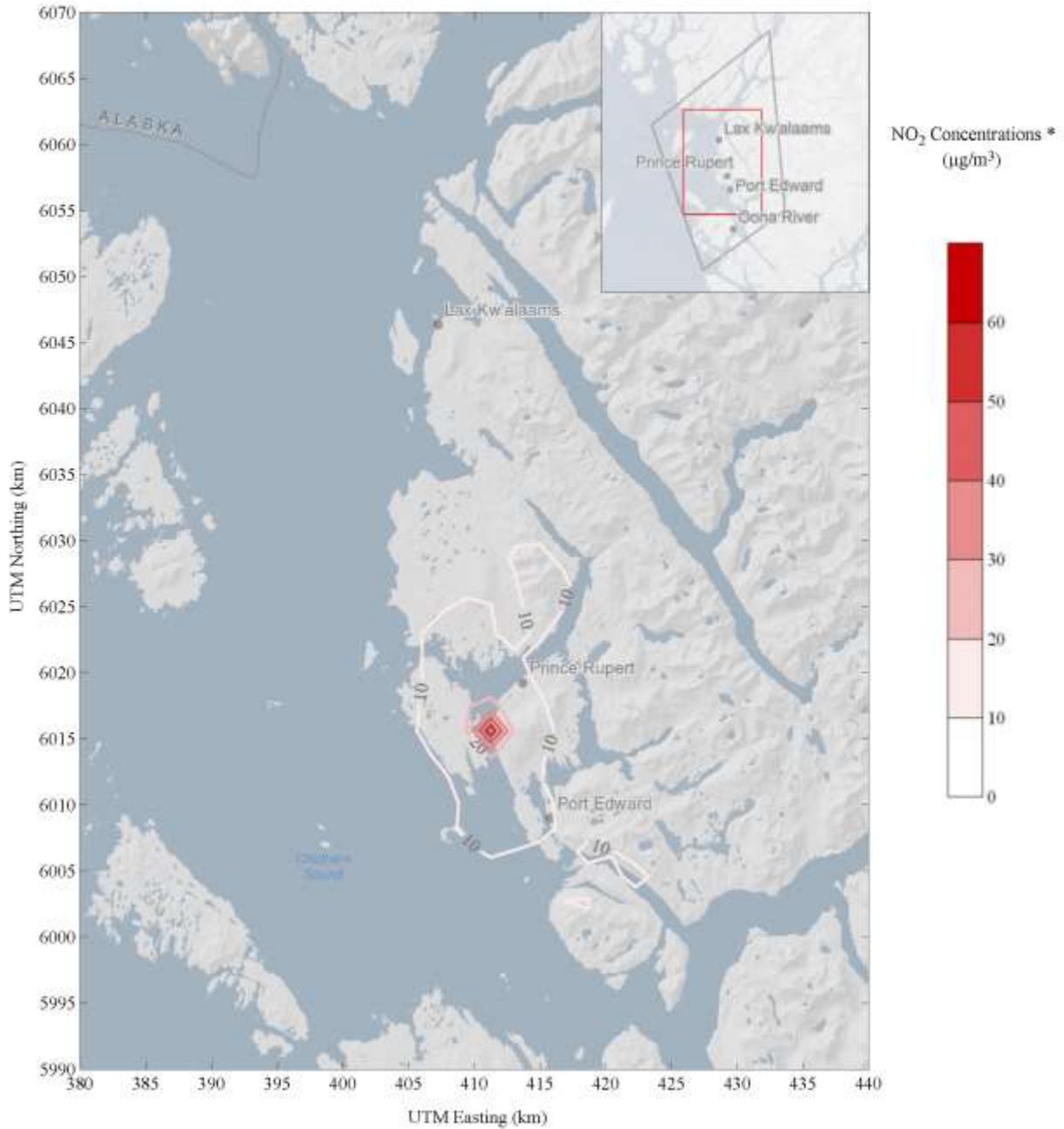


Prince Rupert Airshed Study
98th Percentile PM_{2.5} Concentrations, 24 hour Average
2012 Meteorological Year
Scenario E



* The modelled PM_{2.5} concentrations include a background concentration of 7.0 µg/m³.

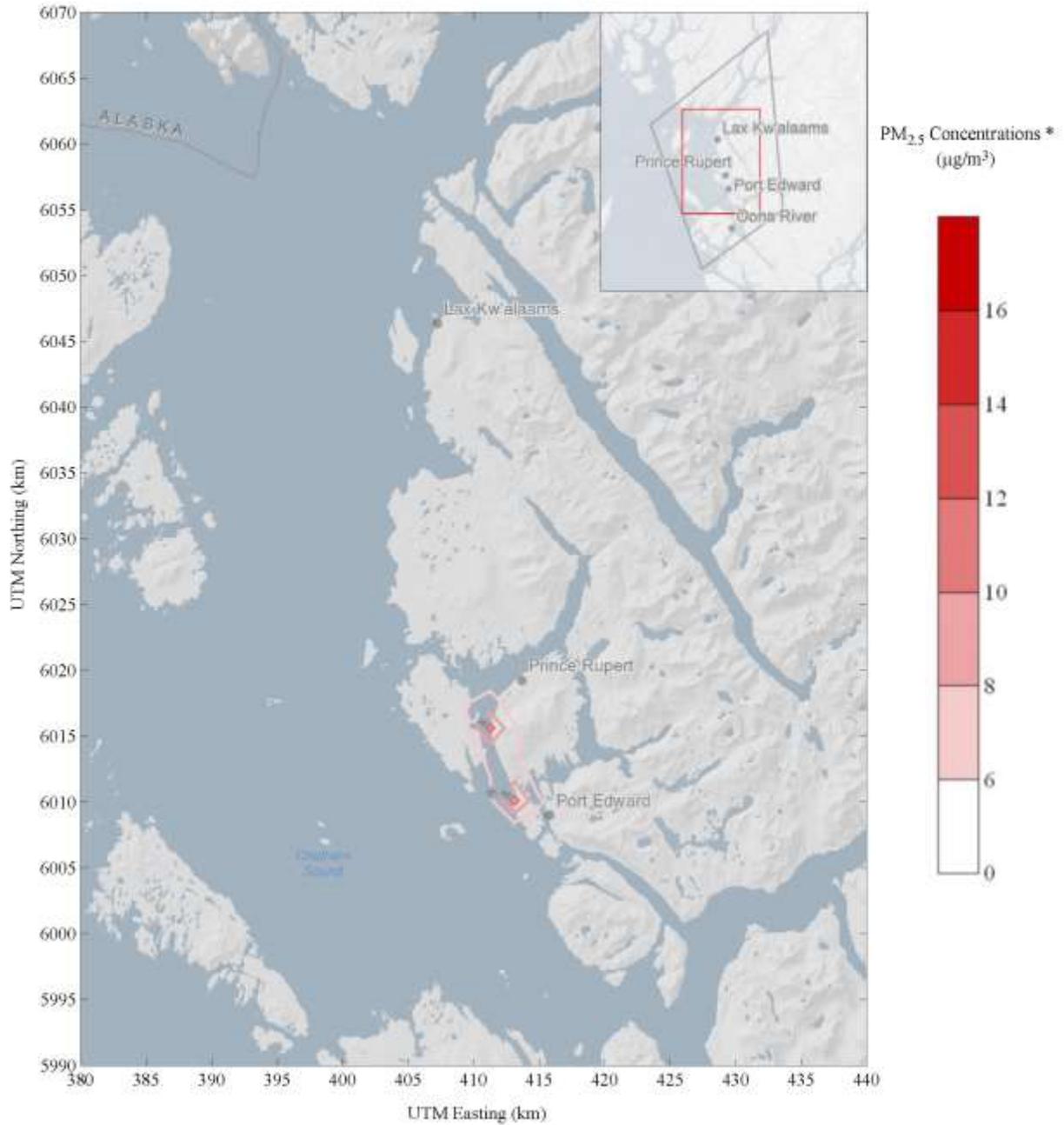
Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario E



* The modelled NO₂ concentrations include a background concentration of 3.0 ppb (5.64 µg/m³).



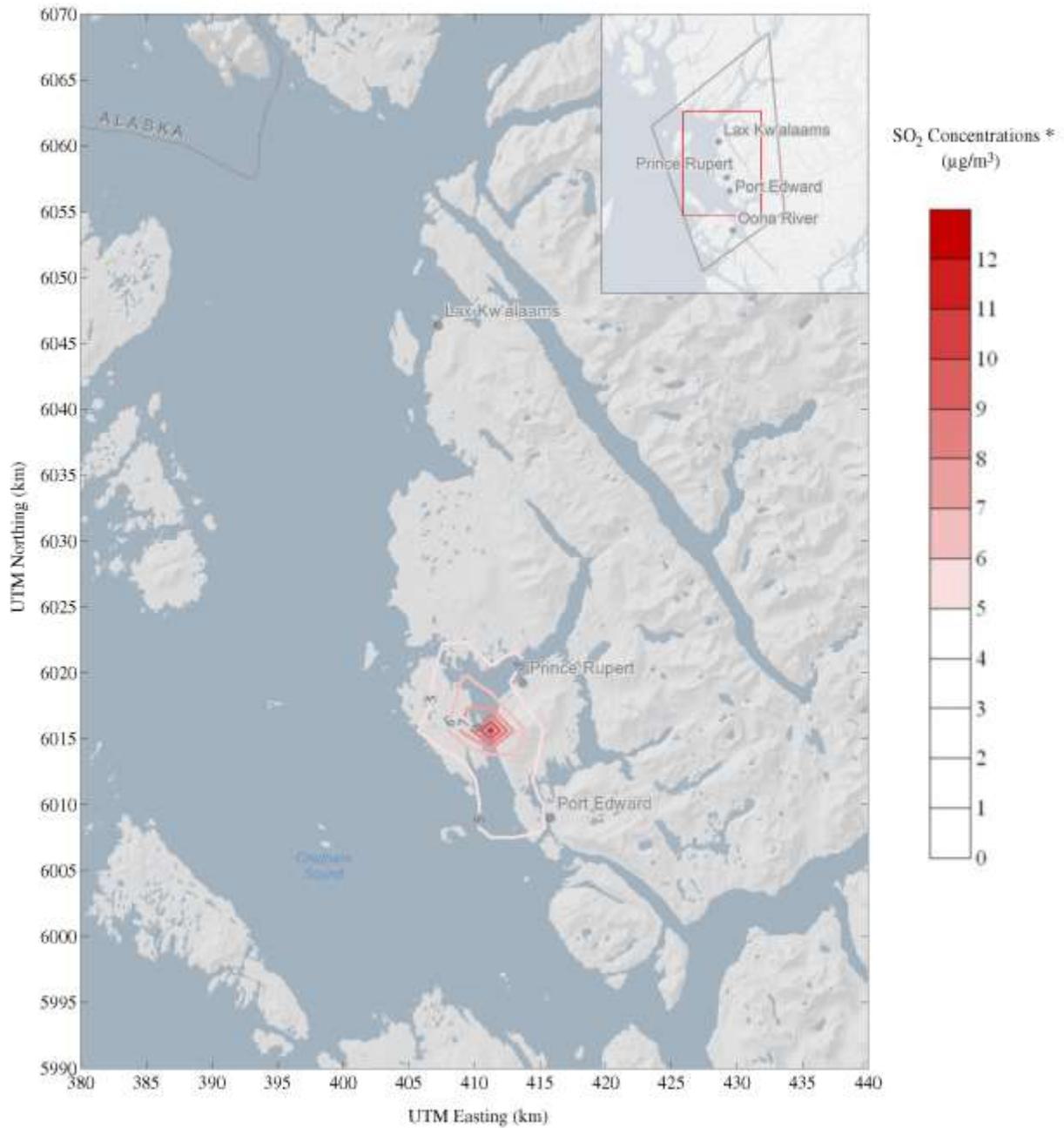
**Prince Rupert Airshed Study
PM_{2.5} Concentrations, Annual Average
2012 Meteorological Year
Scenario E**



* The modelled PM_{2.5} concentrations include a background concentration of 3.5 µg/m³.
Contour levels below the levels of 4 µg/m³ are not shown because they are very close to or below the background concentration.



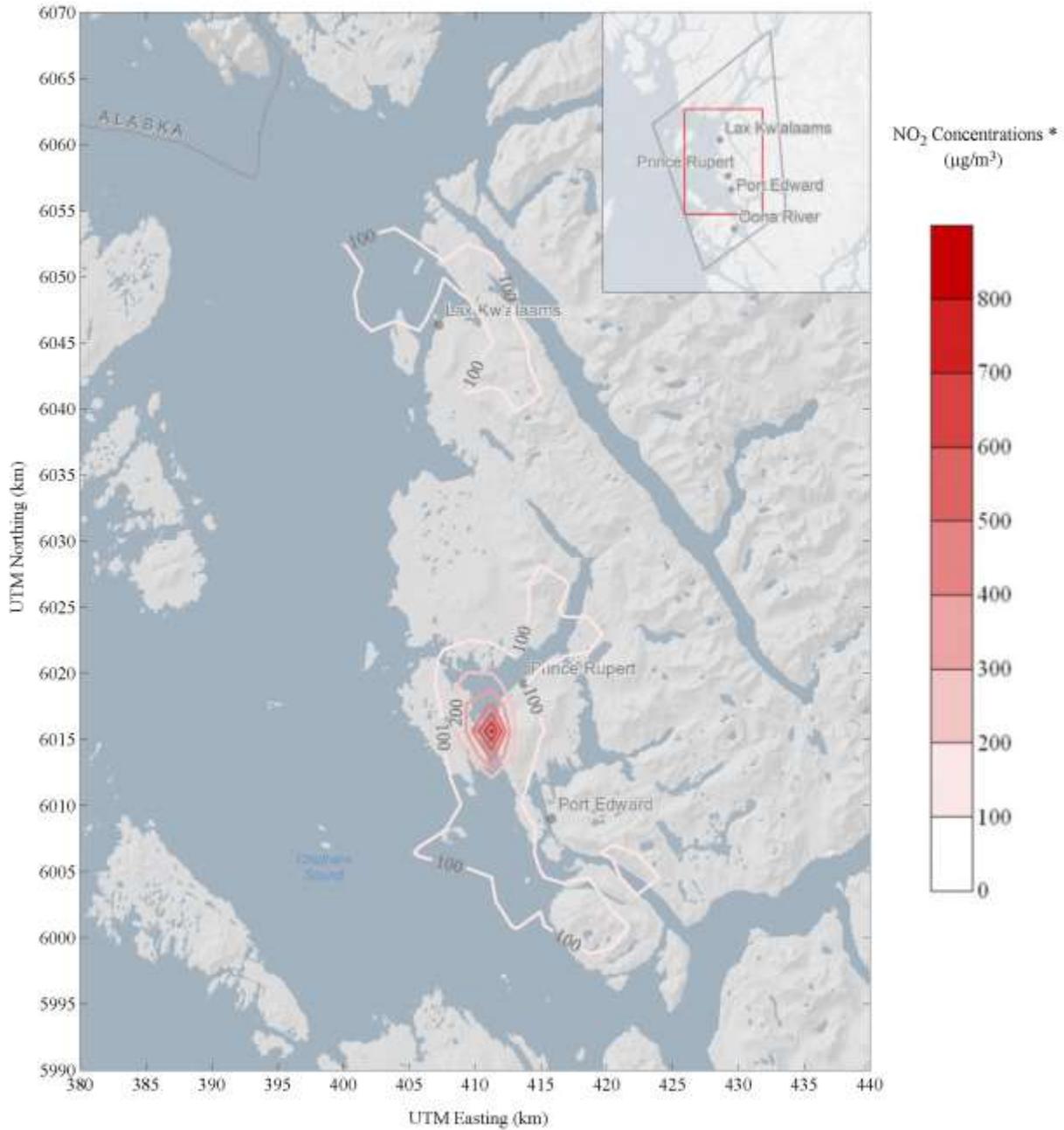
Prince Rupert Airshed Study
SO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario E



* The modelled SO₂ concentrations include a background concentration of 1.5 ppb (4.00 µg/m³).
Contour levels below the background concentration are shown as white.



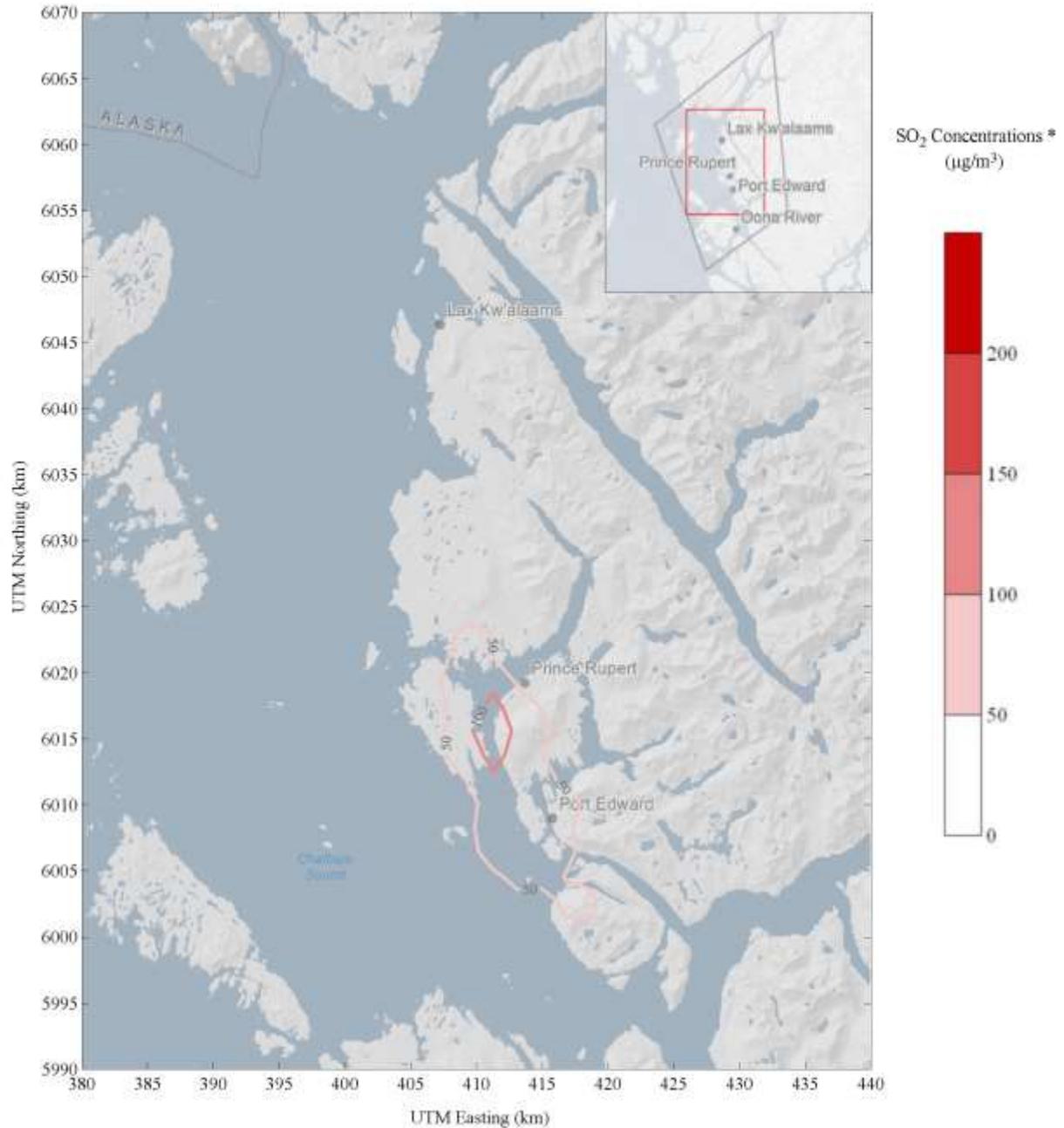
Prince Rupert Airshed Study
98th Percentile Daily Peak NO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario F_M



* The modelled NO_x concentrations are scaled to assume 80% of NO_x is NO₂, based on US EPA guidance (June 28, 2010 and March 1, 2011). Additionally, a background concentration of 13.0 ppb (24.4 µg/m³) is added.

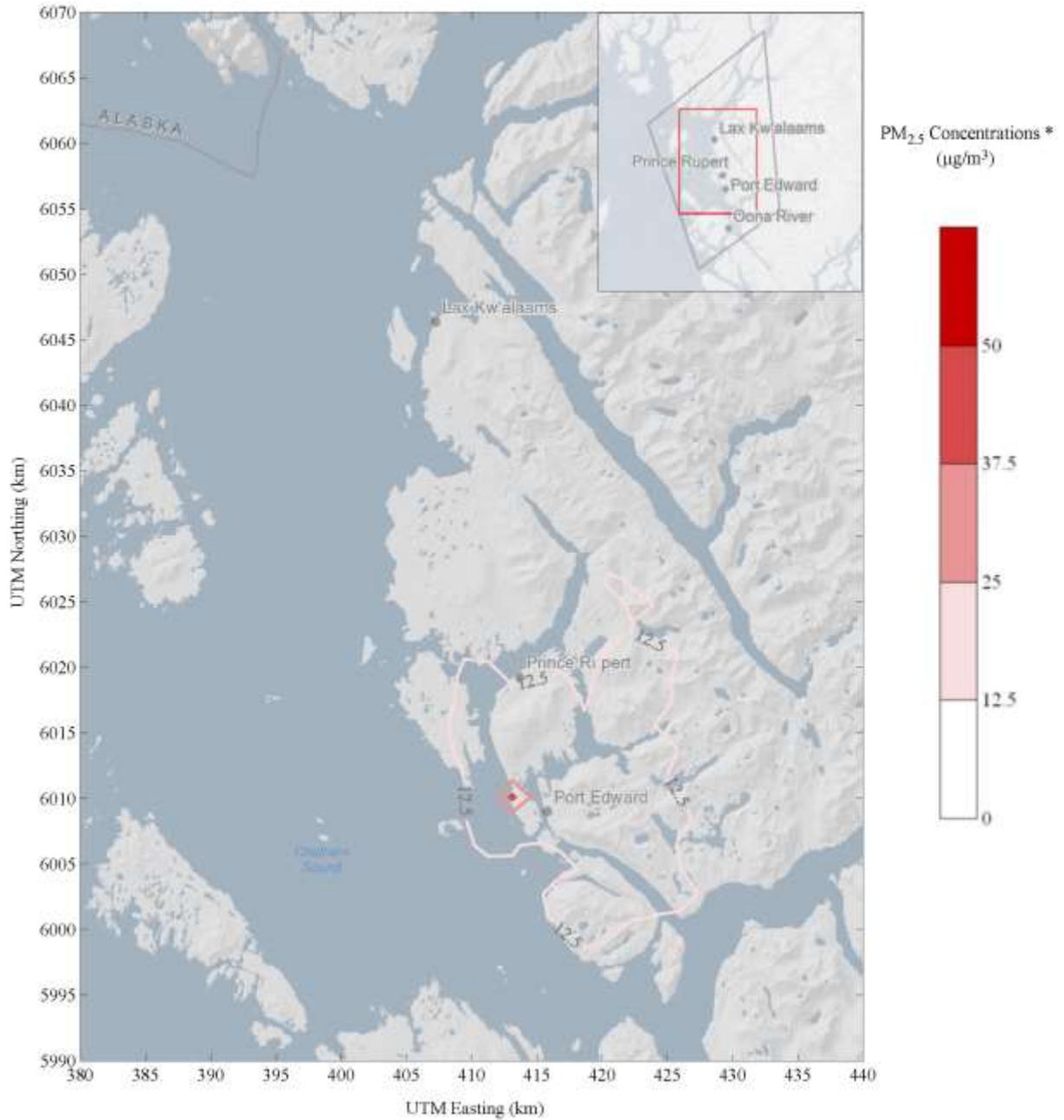


Prince Rupert Airshed Study
99th Percentile Daily Peak SO₂ Concentrations, 1 hour Average
2012 Meteorological Year
Scenario F_M



* The modelled SO₂ concentrations include a background concentration of 4.0 ppb (10.67 µg/m³).

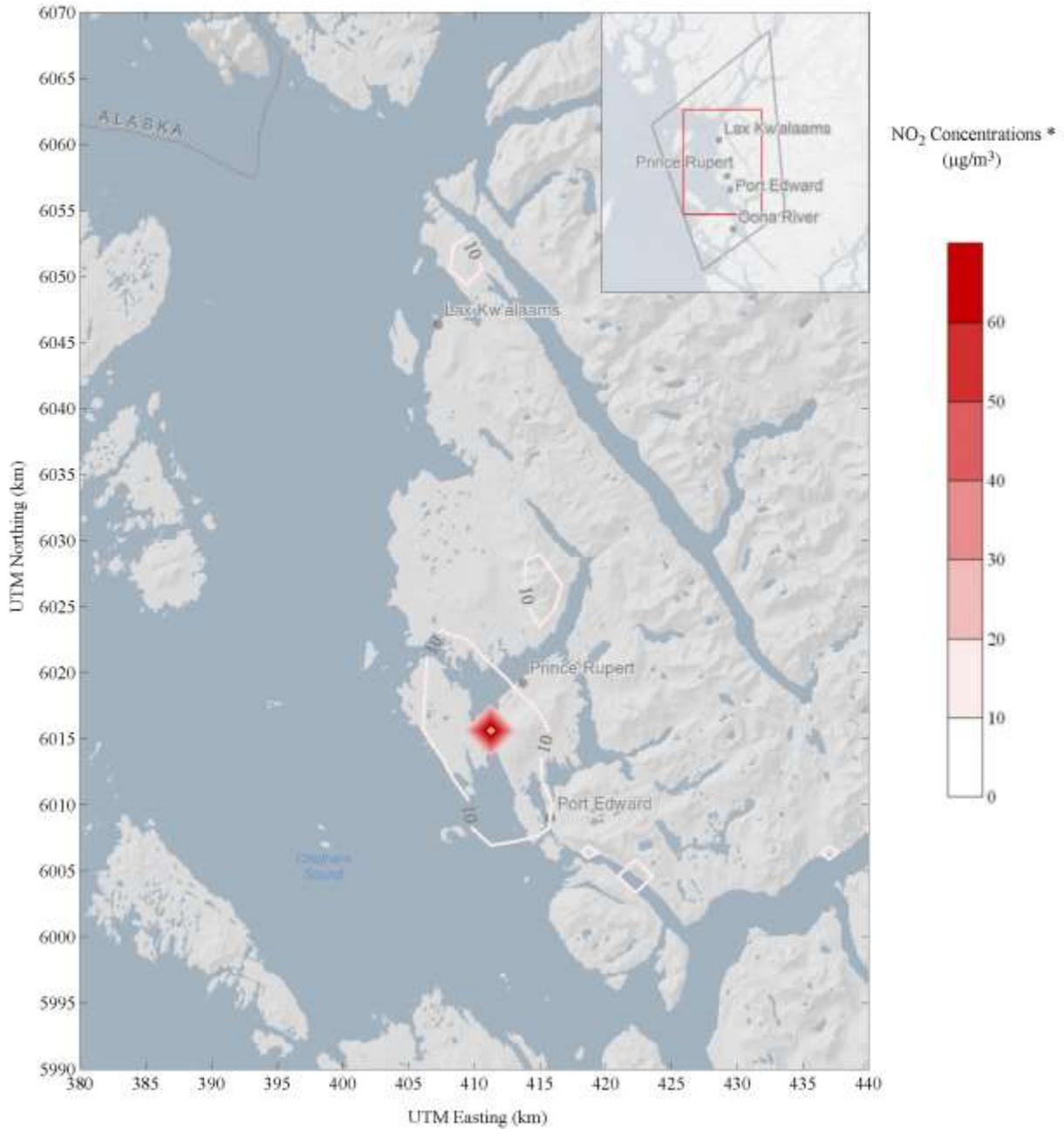
Prince Rupert Airshed Study
98th Percentile PM_{2.5} Concentrations, 24 hour Average
2012 Meteorological Year
Scenario F_M



* The modelled PM_{2.5} concentrations include a background concentration of 7.0 µg/m³.



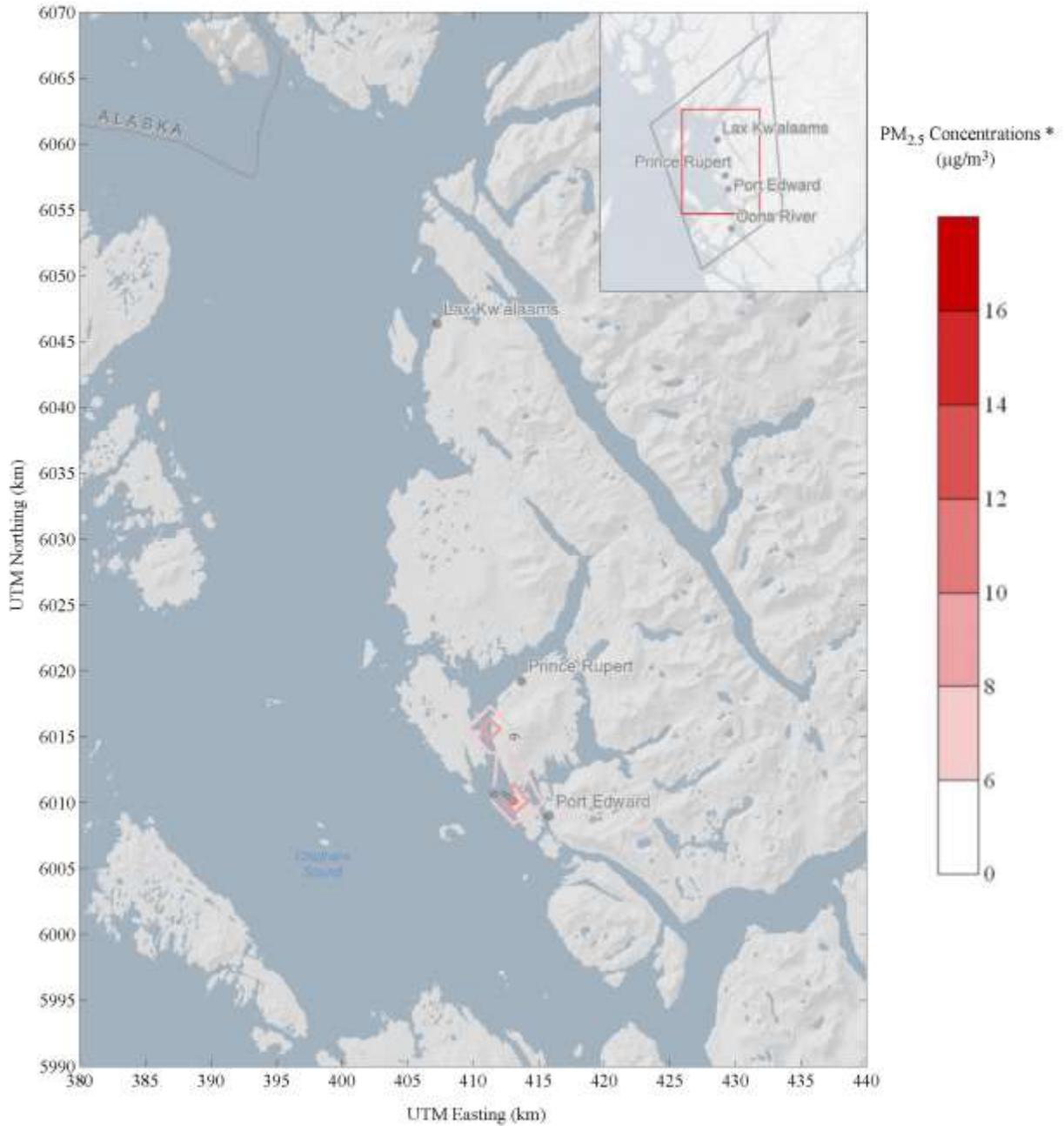
Prince Rupert Airshed Study
NO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario F_M



* The modelled NO_x concentrations are scaled to assume 75% of NO_x is NO₂, based on US EPA guidance (June 28, 2010 and March 1, 2011). Additionally, a background concentration of 3.0 ppb (5.64 µg/m³) is added.

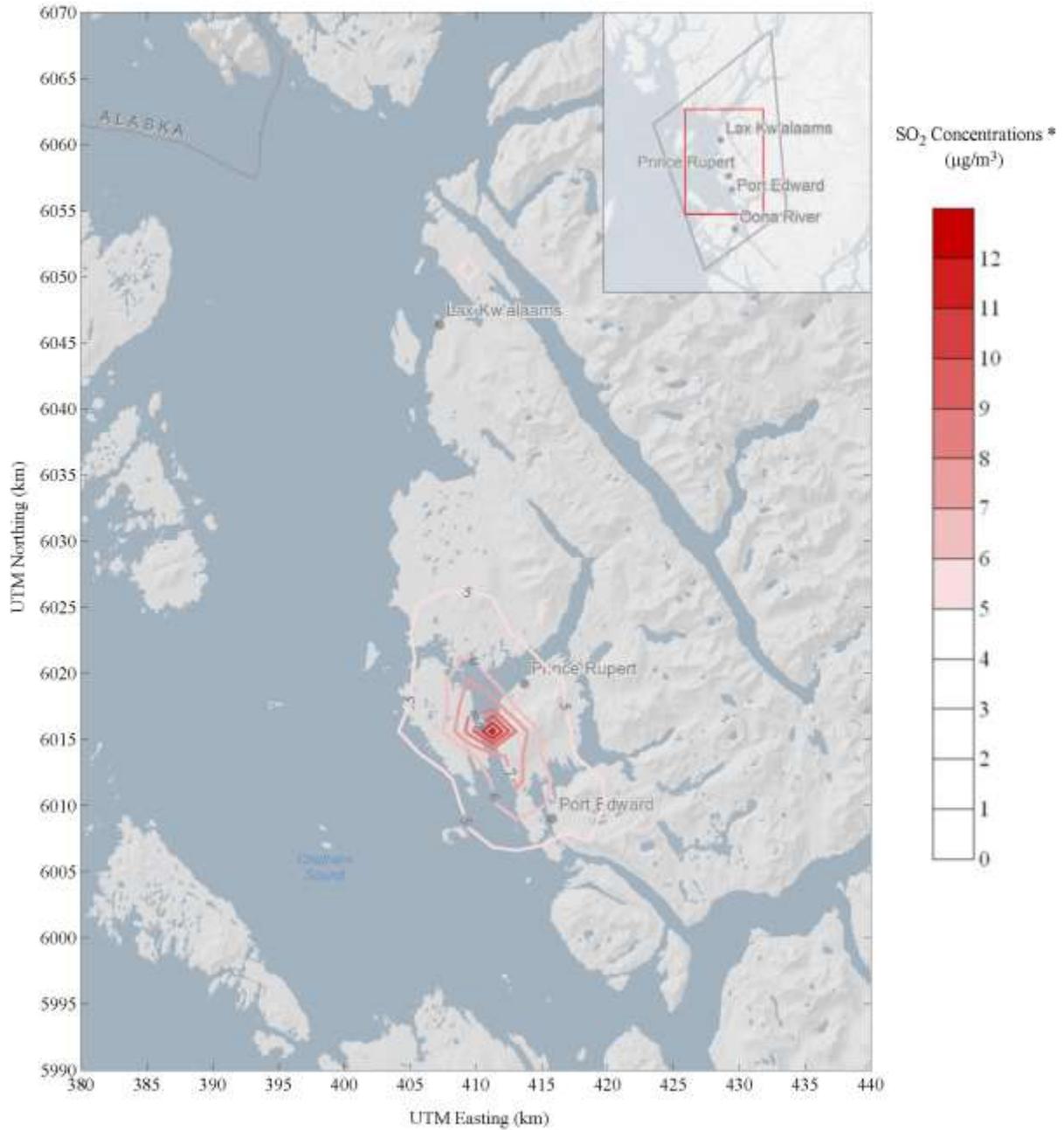


**Prince Rupert Airshed Study
PM_{2.5} Concentrations, Annual Average
2012 Meteorological Year
Scenario F_M**



* The modelled PM_{2.5} concentrations include a background concentration of 3.5 µg/m³.
Contour levels below the levels of 4 µg/m³ are not shown because they are very close to or below the background concentration.

Prince Rupert Airshed Study
SO₂ Concentrations, Annual Average
2012 Meteorological Year
Scenario F_M



* The modelled SO₂ concentrations include a background concentration of 1.5 ppb (4.00 µg/m³).
Contour levels below the background concentration are shown as white.



3 Appendices for Soils and Terrestrial Ecosystems

3.1 Soils: Skokloster Classification

The Skokloster classification divides soils into five acid sensitivity classes based on the mineralogy of the soil parent material. Critical load ranges have been assigned to these classes according to the amount of acid buffering produced by weathering of the soil minerals (i.e., the critical load of acidity is set to the base cation weathering rate; Table A3.1-1). The ranges are assumed to apply to the upper 50 cm of the soil (Nilsson and Grennfelt 1988). The Skokloster classification and the critical load ranges provide a simple method of assigning a critical load and weathering rate to a soil if mineralogy or parent material is known.

There are limited soils data for the Prince Rupert region. As such, it was assumed that bedrock geology reflected the dominant parent material mineralogy of the overlying soils. Each rock type (Figure A3.1-1; Bedrock Geology, Version: 2.2, October 2013) was assigned to one of the five Skokloster classes (Table A3.1-2), and the mid-point of the critical load range was chosen to represent the average base cation weathering rate. Further, the temperature-dependence of weathering was modelled using an Arrhenius-factor:

$$BC_w = \text{Skokloster}(\text{meq/m}^2/\text{yr}) \cdot \exp\left(\frac{A}{281} + \frac{A}{273+T}\right)$$

where T (°C) is the average annual (soil) temperature, and A = 3600 K (Sverdrup 1990).

Table A3.1-1: Skokloster classification: mineralogical and petrological classification of soil parent material. The critical load is set to the base cation weathering rate under the Skokloster classification. Source: after Nilsson and Grennfelt (1988).

Class	Minerals controlling weathering	Usual parent material	Critical load (meq/m ² /yr)
1	Quartz, K-feldspar	Granite, quartzite	< 20
2	Muscovite, plagioclase, biotite (<5%)	Granite, gneiss	20–50
3	Biotite, amphibole (<5%)	Granodiorite, greywacke, shale, schist, gabbro	50–100
4	Pyroxene, epidote, olivine (<5%)	Gabbro, basalt	100–200
5	Calcite, dolomite	Limestones, marlstones	> 200



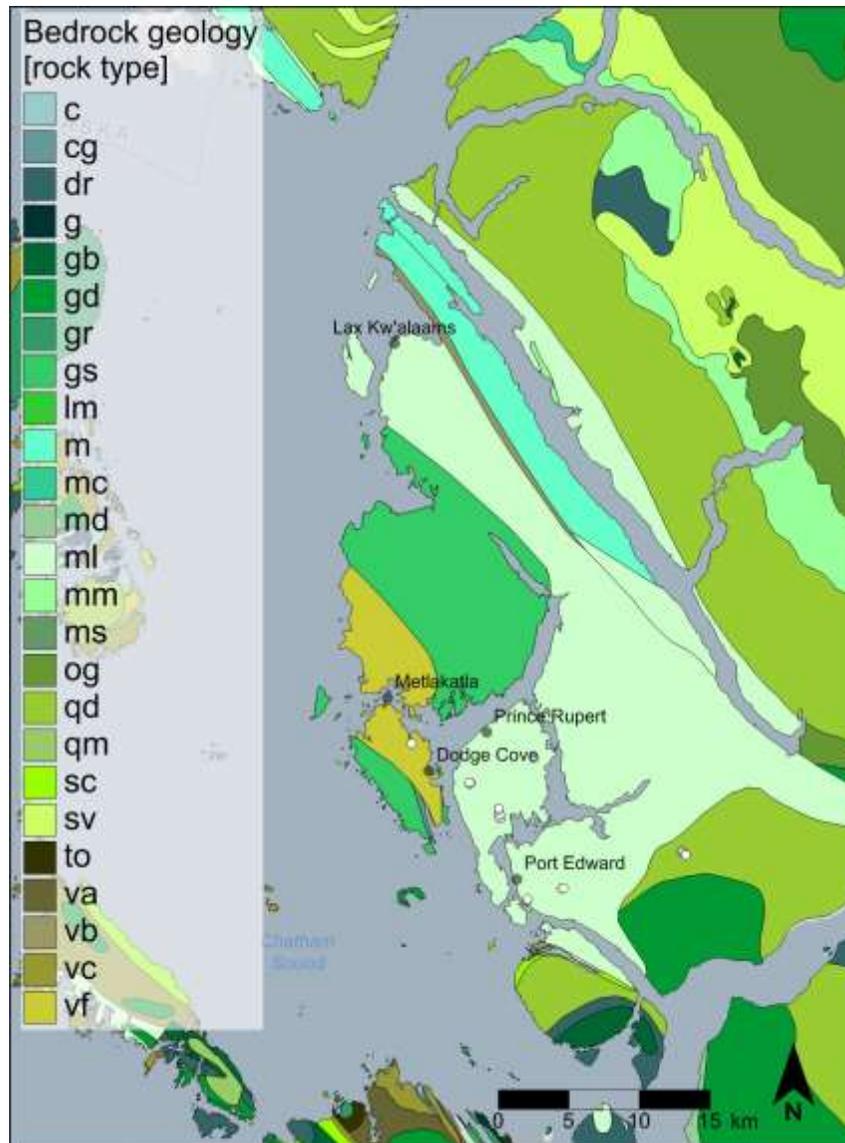


Figure A3.1-1: Bedrock geology for the Prince Rupert Airshed Study area showing rock type (Bedrock Geology, Version: 2.2, October 2013, BC Ministry of Energy and Mines, scale 1:250 000). See Table A3.1-2 for a description of rock type code. The location of soil sampling sites (white-filled circles) is also shown (see Table A3.2-1 for weathering estimates at these sites).

Table A3.1-2: Skokloster classification of bedrock geology in the Prince Rupert Airshed Study area based on rock type (Bedrock Geology, Version: 2.2, October 2013, BC Ministry of Energy and Mines, scale 1:250 000).

Rock Class	Code ^a	Skokloster class	Rock type
Intrusive rocks	dr	4	diorite
	gb	4	gabbro
	gd	3	granodiorite
	gr	2	granite, alkali feldspar granite intrusive rocks
	qd	3	intrusive rocks
	qm	3	quartz monzonitic intrusive rocks
	to	3	tonalite
Metamorphic rocks	cg	1	conglomerate
	dr	4	meta-diorite, meta-gabbro
	g	2	meta-felsic rocks
	gs	3	greenstone, greenschist metamorphic rocks
	lm	5	limestone
	m	2	metaplutonic rocks
	m	3	metavolcanic rocks
	mc	5	calcsilicate metamorphic rocks
	md	3	pelitic schist
	ml	3	amphibolite
	mm	3	metaplutonic rocks
	ms	3	metasediments
	og	3	orthogneiss metamorphic rocks
	sc	4	metaclastic, metacarbonate
	sc	3	tuff
	va	4	andesite
	vb	4	metabasalt
vc	2	volcanic sandstone	
Sedimentary rocks	lm	5	limestone
	sc	3	coarse clastic sedimentary rocks
	sv	3	marine sedimentary and volcanic rocks
Volcanic rocks	c	4	basalt, minor rhyolite
	gb	4	volcanic, volcanoclastic rocks; greenschist to amphibolite grade
	gs	4	basalt, rhyolite
	gs	3	volcanic, volcanoclastic rocks; greenschist to amphibolite grade
	v	4	undivided volcanic rocks
	vb	4	basalt, rhyolite
	vc	4	basalt, minor rhyolite
	vc	2	rhyolite
	vc	4	volcanic, volcanoclastic rocks; greenschist to amphibolite grade
	vc	3	volcanoclastic rocks
	vf	2	rhyolite

^a Rock codes can have several rock type descriptions

3.2 Base Cation Weathering: Soil Sampling Sites

Soil physicochemical properties including soil mineralogical data were available for 18 sampling sites grouped (or clustered) around seven locations (see Figure A3.1-1 and Figure A3.2-1). These data allow for the determination of site-specific weathering rates using the PROFILE



model (Warfvinge and Sverdrup 1992) for comparison against the Skokloster estimates (Table A3.1-1 and Table A3.1-2); however, the data coverage was not adequate to support regional mapping. Soil base cation weathering rates were estimated for these seven locations using soil data averaged across each cluster (Table A3.2-1).



Figure A3.2-1: Location of sites (n = 18; white-filled circles) with soil mineralogical data within the Prince Rupert Airshed Study area (see Figure A3.1-1 for location of ST5). Base cation weathering rates were estimated using the PROFILE model (Warfvinge and Sverdrup 1992) for each soil sample cluster, i.e., six locations (see Table A3.2-1 for average base cation weathering estimates for each site cluster).

Base cation weathering rates estimated using PROFILE ranged from 72.3 meq/m²/yr to 145.0 meq/m²/yr for the seven locations (Table A3.2-1). There was little variation between sites; average weathering was estimated at 122.8 meq/m²/yr with a coefficient of variation <20% across sites. The PROFILE weathering rate estimates were greater than the high end of the Skokloster range for all locations except ST2 (which approximately equalled the mid-point of the Skokloster range). In general, PROFILE weathering rates were double the regional estimates derived from the Skokloster classification. The high PROFILE weathering rates were driven by the high calcite content in the mineralogical analysis (estimated as the sum of calcite, magnesian and anhydrite) across the seven locations; average calcite was 3.4% with a coefficient of variation of 12.8%. In contrast, calcite was predicted to occur at <15% of the 80 soil sampling sites under the KAA (ESSA et al. 2014), with an average content of 0.8%. The higher content in the Prince Rupert study were driven by the high content of anhydrite (calcium sulphate), which was grouped with calcite under PROFILE. The high content of anhydrite (and

subsequently calcite) across all sites is unlikely, suggesting perhaps uncertainty in the quantitative mineralogical data.

Table A3.2-1: Average soil properties^a (per soil cluster, see Figure A3.2-1) and estimated base cation weathering rates for soil sampling sites with mineralogical data.

Soil property	Units	ST1	ST1-6	ST2	ST3-1	ST4	ST5	ST10
Soil depth	m	0.47	0.47	0.36	0.44	0.46	0.36	0.44
Soil organic matter	%	11.87	7.72	10.03	8.32	9.93	5.62	8.84
Soil bulk density	kg/m ³	693.6	405.9	631.2	784.9	651.5	851.8	792.3
K-Feldspar	% of total	2.01	1.90	1.93	3.30	1.74	4.79	2.86
Albite	% of total	22.46	21.40	11.68	16.10	25.04	40.69	18.96
Hornblende ^b	% of total	2.03	1.30	1.77	1.30	2.10	1.68	1.30
Muscovite ^b	% of total	4.36	15.30	1.50	5.30	10.70	1.10	2.08
Chlorite	% of total	5.48	5.20	1.56	3.50	2.48	0.33	2.57
Vermiculite	% of total	5.81	8.50	0.89	1.20	4.09	0.26	2.05
Kaolinite	% of total	0.82	1.60	0.35	0.90	0.72	0.15	0.49
Calcite ^b	% of total	3.61	3.70	2.47	3.70	3.37	3.62	3.34
Quartz	% of total	48.71	36.00	74.87	63.30	45.29	42.00	62.80
Base cation weathering		145.0	131.2	72.3	133.5	129.5	125.9	122.3
Skokloster range		50–100	50–100	50–100	20–50	50–100	50–100	50–100

^a Average soil properties were weighted by depth and bulk density

^b Hornblende = Actinolite + Montmorillonite, Muscovite = Muscovite + Illite, and Calcite = Calcite + Magnesite + Anhydrite

3.3 Base Cation Weathering: Prince Rupert and Kitimat

The estimated base cation weathering rates under the Prince Rupert Airshed Study (derived using the Skokloster classification) were generally similar to the range in values estimated under the Kitimat Airshed Emissions Effects Assessment (KAA) (ESSA et al. 2014), which was based on regression-kriging of site-specific PROFILE weathering rate estimates at 80 sampling sites. However, the alpine regions under the KAA have notably lower weathering rates compared with high elevation regions in the Prince Rupert study area (Figure A3.3-1).



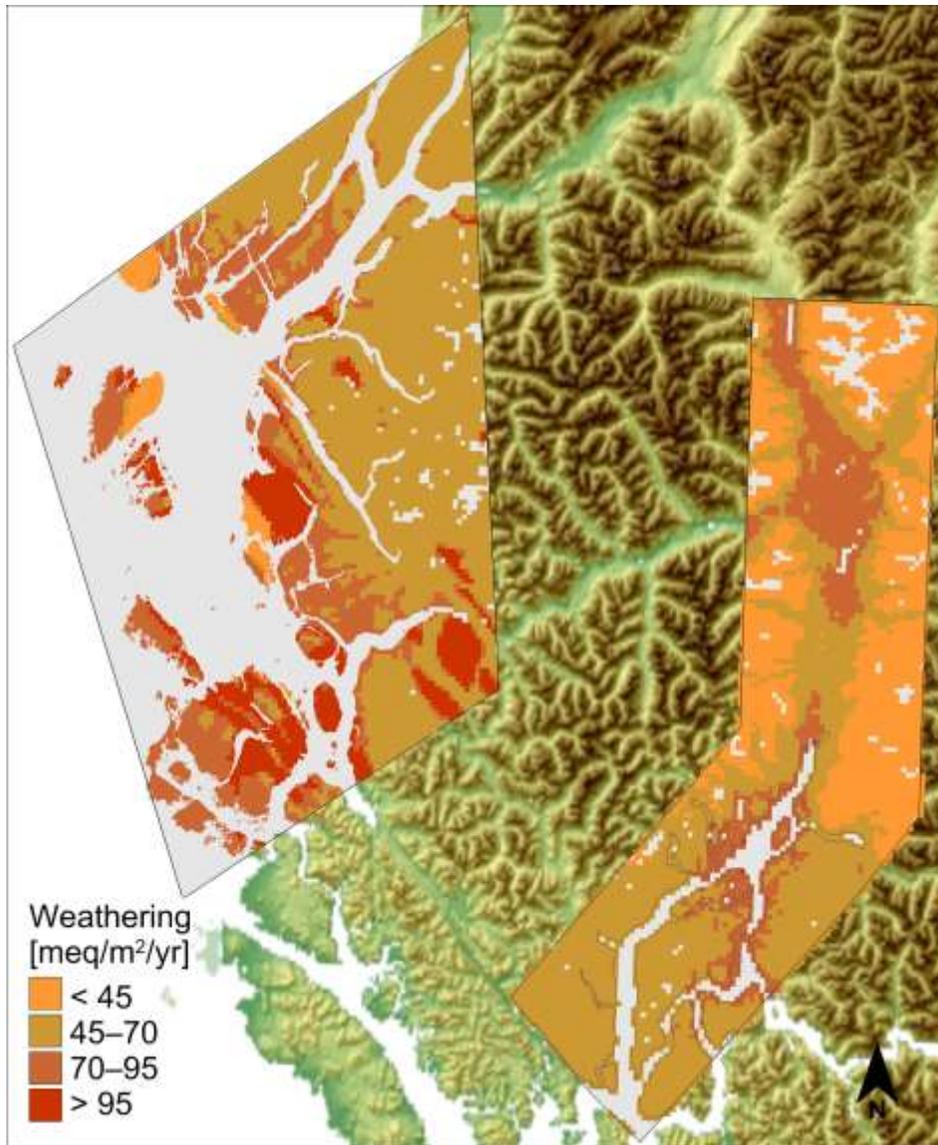


Figure A3.3-1: Soil base cation weathering rates (meq/m²/yr) estimated under the Prince Rupert Airshed Study (Appendix 3.1) compared with weathering rates estimated under the Kitimat Airshed Emissions Effects Assessment (ESSA et al. 2014). The background image shows elevation.

3.4 Background Deposition

Modelled sulphur and nitrogen deposition estimates (see Section 2, Volume 1 of this report) for this scoping study did not include background deposition estimates. Therefore, the modelled deposition for all scenarios represents the contribution of the stationary and mobile emissions sources (listed in Section 1, Volume 1) to total deposition, rather than total anthropogenic deposition to the study domain. Transboundary atmospheric sources contribute a significant amount of anthropogenic sulphur and nitrogen deposition, as observed by monitoring stations in

background regions (see CAPMoN [URL: www.on.ec.gc.ca/natchem], and NADP [URL: nadp.sws.uiuc.edu]).

Global anthropogenic sulphur emissions during 2010 were approximately $100 \text{ Tg}^{14} \text{ SO}_2$, with China responsible for approximately one third of all global emissions (Klimont et al. 2013). Mean multi-model global predictions of sulphur and nitrogen deposition indicate that shipping and emissions from China are significant sources of transboundary anthropogenic deposition to northern British Columbia (Lamarque et al. 2013). Global model estimates of wet anthropogenic sulphur deposition to north coastal British Columbia during 2000 ranged from $100\text{-}200 \text{ mg S/m}^2\text{/yr}$ ($6.3\text{-}12.5 \text{ meq/m}^2\text{/yr}$); notably global sulphur emissions during 2000 were similar to 2010 (Klimont et al. 2013), although China's contribution to this total was about 20% higher in 2000 than 2010. Global model estimates of wet oxidized nitrogen during 2000 ranged from $50\text{-}100 \text{ mg N/m}^2\text{/yr}$ ($3.6\text{-}7.1 \text{ meq/m}^2\text{/yr}$).

Observations of wet deposition from monitoring stations within the Canadian Air and Precipitation Monitoring Network (CAPMON), National Atmospheric Deposition Program (NADP), and European Monitoring and Evaluation Programme (EMEP) networks show similar ranges in background regions, e.g., average non-marine sulphur deposition to three NADP stations in Washington state and two stations in Alaska during the last decade was approximately $5 \text{ meq/m}^2\text{/yr}$. Average wet nitrate deposition at the same sites was approximately $3.5 \text{ meq/m}^2\text{/yr}$. This suggests that background deposition of sulphur (owing to transboundary sources) in the Prince Rupert Airshed ranges from $5\text{-}10 \text{ meq/m}^2\text{/yr}$, and background nitrogen deposition ranges from $3\text{-}5 \text{ meq/m}^2\text{/yr}$.

There are two wet deposition monitoring stations in (or close to) the study area, i.e., Port Edward and Lakelse Lake (BC24 and BC23, respectively operated by NADP). During 2014, average wet non-marine sulphur deposition at these stations ranged from $6.5\text{-}7.8 \text{ meq/m}^2\text{/yr}$ (BC23-BC24), and average wet nitrogen deposition ranged from $5.3\text{-}7.5 \text{ meq/m}^2\text{/yr}$ (BC23-BC24). While both stations may not truly reflect background atmospheric deposition, owing to nearby industrial activity, wet deposition in general represents only about 50% of total deposition.

Based on wider monitoring networks and global modelling studies, we chose a constant sulphur deposition of $10 \text{ meq/m}^2\text{/yr}$ and nitrogen deposition of $5 \text{ meq/m}^2\text{/yr}$ to represent background deposition. It is recognised that actual background deposition will vary across the region, and that the selected values represent precautionary estimates of background deposition.

¹⁴ Teragram, which equals 1 million metric tons.



4 Appendices for Aquatic Ecosystems

4.1 Application of the Steady State Water Chemistry (SSWC) Model to Estimate Critical Loads

We have closely followed the implementation of the SSWC model as described by Henriksen et al. (2002), UNECE (2004), and is summarized in ESSA et al. 2013 (pg. 240-241). We provide further discussion below only for components where we have adapted the methodology for the current analysis or for issues where additional clarification within this document is beneficial. Table A4.1-1 presents the modifications to the SSWC model (relative to Henriksen et al. 2002) that were included for PRAS application.

Table A4.1-1: Core components of the SSWC model.

Component	Equation applied	Modifications relative to Henriksen et al. (2002), if applied in this study
Critical load of acidity	$CL(A) = BC^*_0 - ANC_{limit}$	ANC_{limit} is lake-specific and varies with DOC
Original non-marine base cations	$BC^*_0 = BC^*_t - F \times (SO_4^*_t - SO_4^*_0)$	Does not include ΔNO_3 since current $[NO_3]$ were extremely low in all lakes (generally not detectable).
F-factor	$F = \sin\left(\frac{\pi \cdot Q \cdot [BC^*]_t}{S}\right)$	As in Henriksen et al. (2002)
Original non-marine sulphate	$[SO_4^*]_0 = [SO_4^*]_t - [SO_4^*]_{exp}$	Alternate calculation (see text)
Exceedance of acidity	$Ex(A) = S^*_{dep} + N_{leach} - CL(A)$	As in Henriksen et al. (2002)

Negative critical loads (CL <0)

As in the KAA, we constrained the estimates of critical loads to be a minimum of zero (i.e., cannot be negative), and implemented this constraint by adjusting the critical ANC limit for such lakes to equal the original, non-marine contribution of base cations from weathering (i.e., $ANC_{limit} = BC^*_0$). Several lakes in the study area have high concentrations of dissolved organic carbon, and as a result have low ANC values; some are naturally acidic ($ANC < 0$). If a naturally low ANC or acidic lake or stream is estimated to have a negative critical load (i.e., original base cations less than the ANC limit), it would have exceedance even with zero acidic deposition, and this exceedance could only be eliminated through mitigative actions to bring the ANC up to the ANC limit. Setting the critical load to zero (which yields zero exceedance when there is no acidic deposition) provides greater clarity on the impacts of emission sources under analysis, and is also consistent with methods applied in Europe (J. Aherne, Trent University, October 2012, pers. comm.).



ANC limit

The SSWC employs an alkalinity threshold called ANC_{limit} to define the onset of significant harmful effects, most commonly loss of fish populations. For the PRAS study, we used a lake-specific ANC_{limit} which varies with the concentration of dissolved organic carbon (DOC) present in the lake, as described in Section 6.1.1 (Volume 1 of this report), Equation 6.1.

F-factor

The F-factor is defined as the ratio of changes in non-marine base cation concentrations (i.e., Ca, Mg, Na, K) to changes in strong acid anion concentrations (i.e., SO_4 , NO_3). If $F = 1$, all incoming protons are neutralized in the catchment; at $F = 0$, none of the incoming protons are neutralized in the catchment. As described in Henriksen et al. (2002), we estimated the F-factor based on current base cation concentrations and the runoff of the lake's watershed, as indicated in Table A4.1-1. The factor S in the equation is the base cation flux at which $F = 1$. We used $S = 400$, as adopted by Henriksen and Posch (2001).

Original SO_4

We investigated several methods of estimating $[SO_4^*]_0$. We applied the regression equations cited in Henriksen et al. (2002) and Wilander (1994) that estimate $[SO_4^*]_0$ based on current non-marine base cation levels ($[BC^*]_t$). However, the concern with all of those methods is that they frequently estimate an original sulphate concentration that is greater than the current sulphate concentration (i.e., $[SO_4^*]_0 > [SO_4^*]_t$). As per Henriksen et al. (2002), it is commonly assumed that original sulphate levels cannot be greater than current levels and therefore the convention is to constrain estimates of original sulphate to no greater than current sulphate.

For PRAS, we estimated original SO_4 by subtracting the change in sulphate from the current observed sulphate:

$$[SO_4^*]_0 = [SO_4^*]_t - \Delta SO_4 \quad \text{Equation 4.1.1}$$

We assume that the current sulphate concentration in a lake is equal to its original, pre-industrial sulphate concentration plus the increase in sulphate attributable to deposition from existing background sources. For the PRAS area, the background level of SO_4 deposition, including current emission sources, was set at $10 \text{ meq/m}^2/\text{yr}$. The concentration of background sulphate in lakewater depends on the catchment's runoff. By applying this value in Equation 4.1.2, we obtained the following expression:

$$[SO_4^*]_0 = [SO_4^*]_t - S_{\text{DEPBACK}} / Q \quad \text{Equation 4.1.2}$$

Where Q = runoff in m/yr and $S_{\text{DEPBACK}} = 10 \text{ meq/m}^2/\text{yr}$.



Deposition

Total deposition of SO₄ was obtained from the emissions and deposition modelling performed by Trinity Consultants (see Section 2.2, Volume 1 of this report). Deposition of NO₃ was not included in the SSWC model but current NO₃ deposition is accounted for through the NO₃ leaching component of the SSWC model.

Runoff

As we did for the KMP SO₂ Technical Assessment (STAR) (ESSA et al. 2013) and the KAA (ESSA et al. 2014), average annual runoff values for the 1960-1999 period were estimated by Joel Trubilowicz (Ph.D. candidate at UBC) for the entire study area on a 0.4 km x 0.4 km grid. These estimates were calculated via application of the Distributed Climate Water Balance Model described in Moore et al. (2012). We then used them to calculate area-weighted estimates of runoff within the upstream watershed area or catchment of each lake.

Exceedance

We calculated the level of exceedance (if any) of the critical loads of each lake under the scenarios of modelled levels of deposition, and classified exceedance levels into the categories used by Dupont et al. (2005). We also conducted a sensitivity analysis wherein we varied the ANC_{limit} parameter, as described in Appendix 4.4.

4.2 Application of First-order Acidity Balance (FAB) model

The First-order Acidity Balance (FAB) model allows the simultaneous calculation of critical loads of acidifying S and N deposition and their exceedances. The acidity critical load CL(A), as calculated by the SSWC model, is used as input to the FAB model. Additionally, the FAB model takes into account catchment processes in terrestrial soils, such as uptake, immobilisation, and denitrification, and the in-lake retention of S and N.

In order to estimate the critical loads and exceedances using the FAB model, we have followed the approach described in Aherne et al. (2002). For FAB purposes there is no unique critical load, but every pair of N and S deposition, (N_{dep}, S_{dep}), satisfying the following equation is called a critical load (Aherne et al. 2002):

$$(1 - \rho_S) \cdot S_{dep} + (1 - \rho_N) \cdot b_N \cdot N_{dep} = (1 - \rho_N) \cdot Mn + CL(A)$$

Equation 4.2.1

Equation 4.2.1 defines the so-called Critical Load Function (CLF) of a lake (Figure A4.2-1). The intercepts of the CLF on the S_{dep} and N_{dep} axes define the “maximum” critical loads of S and N, i.e., the critical load for either S or N alone. All combinations of S_{dep} and N_{dep} lying below the CLF (grey-shaded area) do not exceed critical loads.



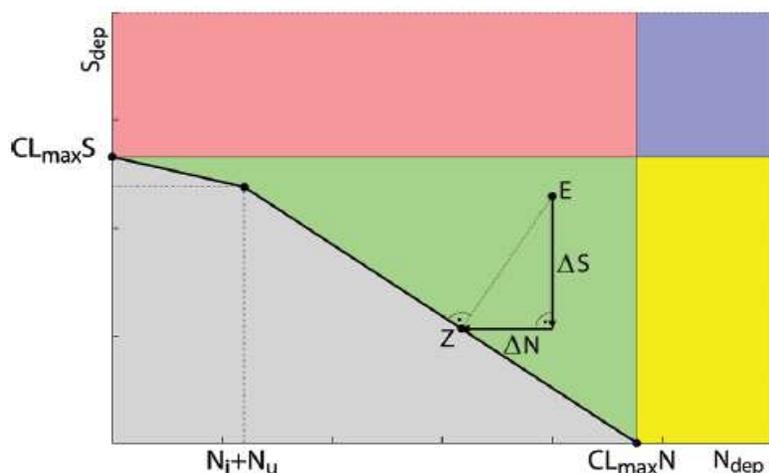


Figure A4.2-1. Piece wise critical load function (CLF) for S and acidifying N as defined by soil or catchment properties (thick black line), for a terrestrial system or for one lake and its catchment. The gray-shaded area below the critical load function defines deposition pairs (N_{dep} , S_{dep}) for which there is no exceedance, and the terrestrial system or lake's ANC is kept above the critical level. For a given deposition pair (N_{dep} , S_{dep}) the critical load exceedance is calculated by adding the N and S deposition reductions needed to reach the CLF via the shortest path (E→Z): $Ex = \Delta S + \Delta N$. The gray area below the CLF denotes deposition pairs resulting in non-exceedance of critical loads. If a deposition pair is located in the green area (such as E), non-exceedance can be achieved by reducing N or S deposition (or both); in the red (yellow) area S_{dep} (N_{dep}) has to be reduced to achieve non-exceedance; and in the blue area both N_{dep} and S_{dep} have to be reduced. Source: Posch et al. (2012), Figure 5.7 in UNECE (2004) and associated text.

In addition to water chemistry data, the FAB model requires the following data inputs for the estimation of the critical load of S and N:

- SSWC critical load of acidity (lake chemistry and annual average catchment runoff)
- Catchment and lake sizes as well as the fraction of forest, wetland and open land
- Net mass transfer coefficients for S and N
- Denitrification rates within the catchment soils
- Net N immobilization rates within the catchment soils
- Net N uptake rates by forests within the catchment measured or estimated runoff within each catchment.

SSWC critical load

As described in Appendix 4.1 and discussed in Sections 6.1.2 and 6.2.3 (Volume 1 of this report), critical loads of acidity were estimated for the 35 lakes using the Steady-State Water Chemistry (SSWC) model.

Catchment and lake sizes

We defined watershed area using the approach applied in the KAA. Upstream watersheds for each sampled lake were defined primarily using the 1:20K Freshwater Atlas Fundamental Watersheds. However, because the Freshwater Atlas watersheds do not use lake outflows as



natural pour points to define the watershed boundaries, watershed polygons often encompass lakes and result in an area of watershed downstream of the lake. We therefore used flow direction calculated from the Canadian Digital Elevation Data 1:50K digital elevation model (DEM) to identify areas downstream of the lake, and removed them from the Freshwater Atlas watershed polygons. We used the 1:20K Freshwater Atlas stream network to enforce drainage within the DEM, and ESRI's hydrology toolset within ArcMap to define the upstream/downstream areas around the lake outflow.

Land cover classes

The FAB model requires estimates of the areas of grass/heath-land, forested land, peat land (considered equivalent to wetlands) and bare rock within each lake catchment. The fraction of peat land/wetland can be used to estimate the rate of de-nitrification (Posch et al. 1997, as explained in Henriksen and Posch (2001) and UNECE (2004)). Land use and land cover classifications were produced using a combination of provincial and national data sets available from GeoBC and GeoBase (Table A4.2-1).

Table A4.2-1: Land cover classes generated from land cover data sources and their equivalent FAB class.

Land cover class	Cover type	FAB Land Class
Coniferous forest dense	211	1
Coniferous forest open	212	1
Coniferous forest sparse	213	1
Cut blocks	200	1
Deciduous forest dense	221	1
Deciduous forest open	222	1
Deciduous forest sparse	223	1
Mixed forest dense	231	1
Mixed forest open	232	1
Mixed forest sparse	233	1
Wetland treed	81	1 (5) ^a
Grassland	110	2
Herb	100	2
Herb dense	101	2
Herb sparse	103	2
Shrub low	52	2
Shrub low open	522	2
Shrub low sparse	523	2
Shrub tall dense	511	2
Wetland	80	2 (5)*
Wetland herb	83	2 (5)*



Land cover class	Cover type	FAB Land Class
Wetland shrub	82	2 (5)*
Water	20	3
Developed land	34	4
Exposed land	30	4
Rock/Rubble	32	4
Snow/Ice	31	4
Unclassified	10	4

^a These land cover types, representing different types of wetland, were classified as peat for the purpose of de-nitrification estimation.

Net mass transfer coefficients for S and N

The lake/watershed area ratio, runoff and mass transfer coefficients are used in FAB to estimate in-lake retention of nitrogen (Equation 5.87 in UNECE 2004), and an example application is provided in Aherne et al. (2004). We used the default parameters of $S_N=6.5$ m/yr and $S_S=0.5$ m/yr, as per Posch et al. (2012).

Denitrification rates within the catchment soils

Denitrification is the process in which N is lost to the atmosphere under anaerobic soil conditions. The denitrification fraction depends on soil type and its moisture status; Posch et al. (1997) suggested a model based on the fraction of peat soils in a catchment, which has been used in the current study:

$$f_{de} = 0.1 + 0.7 \cdot f_{peat}$$

Equation 4.2.2

Where f_{peat} is the proportion of peat soils within the catchment. As indicated in Table A4.2-1, and in the absence of more detailed information on the soil of the study area, areas of wetland were identified as peat land for the purpose of this study.

Net N immobilization rates in the catchment soils

N immobilisation, N_i , refers to the long-term storage of N in soil organic matter. Hornung et al. (1995, as cited in Aherne et al. 2002) suggest a range of 7.1-21.4 meq/m²/yr depending on warm-cold climate for coniferous and deciduous forests. Based on this range, a default value of 14.29 meq/m²/yr, as in Aherne et al. 2002, has been used in the current study.



Net N uptake rates and Removal of Base Cations

Nitrogen uptake, N_u , refers to the net removal of N in biomass from catchments through harvesting of forests. Forest harvesting also involves the removal of base cations which have been absorbed by the forest biomass.

Long-term, steady-state removals were estimated using a two-step process, and the same general approach as described in the STAR (ESSA et al. 2013, pg. 208-209):

1. Estimate the long-term, steady state rate of biomass removal due to harvest. The PRAS study area is almost completely within a single Timber Supply Area (North Coast TSA), with a minor amount of area in the Nass and Kalum TSA and in TFL 1. Data were gathered from the publicly available layers of base data (e.g., acquired through GeoBC) and estimates of harvest rates (e.g., from the Timber Supply Reviews (TSR) for each TSA). As for the KAA, we allocated predicted harvest within the TSAs and TFL to the study area based on its proportional overlap with the TSAs' and TFL's spatial extent. Harvest estimates were not available either by species or in a spatially explicit manner. We therefore approximated the spatial distribution of harvesting within each polygon by removing areas in which forestry operations would not occur (non-THLB, alpine and other non-forested regions, parks, reserves, agricultural and developed areas, as determined by land-use data from GeoBC). When this still resulted in a total harvested area that was too large (i.e., exceeded the predicted extent of harvesting based on estimates of rates in the TSAs), we limited allocations to areas with recent cutblocks or with dense coniferous forest. After this overall net-down of forest, we had no harvestable area in the Nass TSA; 86% of the harvestable area was in the North Coast TSA. As we did for the STAR and KAA, we made the precautionary assumption of the maximum rate of removal of base cations from forest harvesting, based on the annual allowable cut (AAC). Also like the STAR and KAA, we assumed that the main harvested species was hemlock and used the same conversion factors for converting volume to biomass.
2. Convert the estimates of exported biomass (i.e., removals) to estimates of exported base cations and nitrogen by applying estimates of nutrient concentration (i.e., per unit of biomass). We used the same nutrient concentration estimates as for the STAR and KAA to maximize efficiency and enable comparability among assessments. After extensive searching and outreach to experts during the STAR and KAA, we are confident that these data represent the best available information on nutrient concentration that is applicable to BC coastal conifer forests.

Nutrient concentration data are used to calculate estimates of cation (K, Ca, Mg) and nitrogen (N) export from estimates of biomass export (due to harvesting). Estimates of biomass export are based on long-term, steady-state harvest rates.

Table A4.2-2: Coefficients of N uptake and base cation removal.

Uptake coefficients	N	K	Ca	Mg
Bark coeff (%)	0.35	0.157	1.231	0.112
Wood coeff (%)	0.155	0.032	0.113	0.023



4.3 Application of Modified ESSA-DFO Model to Estimate Original, Pre-industrial pH_o and future steady-state pH_∞

The modified ESSA-DFO model is explained in ESSA et al. 2013 (Section 8.6.3.4), and was applied in both the KMP SO₂ Technical Assessment and the KAA (see Appendix 16 in ESSA et al. 2014) to estimate pH_o and pH_∞. This approach builds on the model described in Marmorek et al. (1990). For the PRAS, we adjusted this model as follows:

The pre-industrial, original pH is calculated to help determine if there are naturally acidified lakes that have always had a pH <6.

➤ **Original [SO₄]_o** was estimated as follows:

$$[\text{SO}_4]_o = [\text{SO}_4]_t - [\text{S}_{\text{DEPBACK}}/\text{Q}]$$

Equation 4.3.1

Where:

- Q = runoff (m/yr).
- S_{DEPBACK} = background levels of SO₄ deposition (assumed to be 10 meq/m²/yr).

This approach gave positive estimates of [SO₄]_o for 16 of the 35 lakes. However, in 19 of the 35 lakes, Equation 4.3.1 generated a negative estimate of [SO₄]_o, which was reset to 0. Lower values of [SO₄]_o will generate lower CL estimates, so this approach was precautionary. Lakes in the PRAS area generally have quite low [SO₄] currently so the background estimate of sulphate deposition of (S_{DEPBACK}) may be an overestimate.

➤ **Future acid neutralizing capacity, ANC_∞**, was estimated as follows:

$$\text{ANC}_\infty = \text{ANC}_t + \Delta\text{ANC}_{\text{FUTURE}}$$

Equation 4.3.2

$$\Delta\text{ANC}_{\text{FUTURE}} = (= 1) * [(1-F) * (\text{S}_{\text{DEPSCEN}} - \text{S}_{\text{DEPBACK}}) + (1-F_N) * (\text{N}_{\text{DEPSCEN}} - \text{N}_{\text{DEPBACK}})] / \text{Q}$$

Equation 4.3.3

Where:

- S_{DEPSCEN} = the sulphate deposition level (meq/m²/yr) for a given emissions scenario and S_{DEPBACK} = the background levels of S deposition (10 meq/m²/yr), respectively.
- N_{DEPSCEN} = the nitrogen deposition level (meq/m²/yr) for a given emissions scenario and N_{DEPBACK} = the background levels of N deposition (5 meq/m²/yr), respectively.
- F (F-factor) = proportion of incoming acidity neutralized by cation exchange (proportional to base cations)



- F_N = the fraction of N deposition neutralized in the watershed. To reflect the fact that catchments retain more N than S (as shown by the CL functions in Figure 6-5 (Volume 1 of this report)), we set $F_N = F * [CL_{max}(N)/CL_{max}(S)]$, while ensuring that F_N remained bounded between 0 and 1.

We estimated each lake’s original, pre-industrial pH (pH_o) in the absence of any deposition by setting $S_{DEPSCEN}$ and $N_{DEPSCEN}$ to zero in Equation 4.3.3.

We used the titration curve described in Section 6.1 (Volume 1 of this report) (newly developed for KAA and PRAS lakes) to estimate the future steady state pH (pH_∞) associated with ANC_∞ , correcting for the residual in the fit of the curve to measured lab pH values (i.e., if a measured lab pH value was originally below the pH-ANC titration curve, it stayed below the curve). The adapted equation of the titration curve to estimate pH value at a given time, considering the changes in ANC, is as follows:

$$pH(t) = a + \frac{1}{\ln 10} \operatorname{arcsinh} \left[\frac{(Gran\ ANC + \Delta ANC) - d}{c} \right] - e * DOC$$

Equation 4.3.4

According to these calculations, all of the 14 currently acidic ($pH_t < 6$) lakes (out of the 35 sampled lakes in the PRAS area) had an original pH (pH_o) slightly higher than the current pH (i.e., median $\Delta pH = -0.07$). Only two of these lakes (NC314, $pH_o = 6.0$, and NC338, $pH_o = 6.01$) had an original pH equal to or greater than the biological threshold of 6.0.

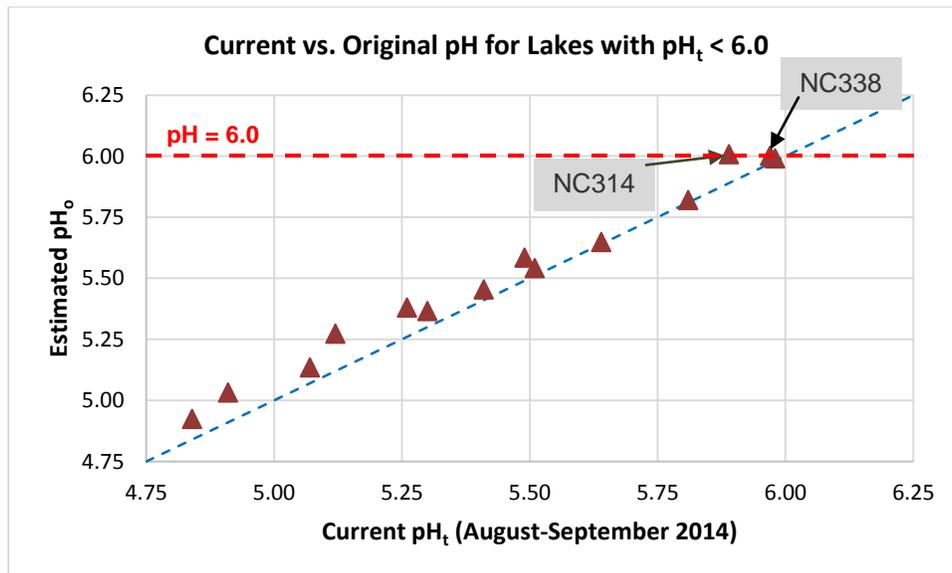


Figure A4.3-1: Comparison of current pH (as measured in the laboratory in August-September 2014).

To estimate future steady state pH under each emission scenario, the values of S and N deposition specific to each scenario were applied to Equation 4.3.3. Because the emissions



simulation for PRAS did not include background values of S and N deposition, and because the current ANC reflects background deposition, we estimated the change in ANC due to the net increase (i.e., scenario deposition value) in S and N deposition as follows:

$$\Delta \text{ANC}_{\text{FUTURE}} = (= 1) * [(1-F) * (\Delta S_{\text{DEP}}) + (1-F_N) * (\Delta N_{\text{DEP}})] / Q$$

Equation 4.3.5

Where:

- ΔS_{DEP} and ΔN_{DEP} are the modelled deposition values (meq/m²/yr) for S and N, respectively, for the various scenarios.

4.4 Sensitivity Analysis of Lakes Acidification based on $\text{ANC}_{\text{limit}}$

We explored the influence of critical ANC ($[\text{ANC}]_{\text{limit}}$) on the calculation of critical loads and exceedance using both SSWC and FAB models. Jeffries et al. (2010) pointed out that the SSWC model was not originally developed to explicitly address the influence of naturally occurring organic acids on the calculation of critical loads. Given the high content of dissolved organic carbon (DOC) in the sampled lakes, and the potential effect of DOC on critical ANC, we decided to analyze the sensitivity of the acidification models by assessing the influence of $[\text{ANC}]_{\text{limit}}$ estimated using three different approaches:

- **$[\text{ANC}]_{\text{limit}}$ 1:** Critical ANC calculated, as explained in Section 6.2.1.3 (Volume 1 of this report), based on the new titration curve developed for the combined PRAS and KAA datasets, and estimated using Equation 6.6 (Volume 1 of this report) for a pH of 6. Since this approach is based on data collected for the Prince Rupert and Kitimat airshed studies, and reflects the charge balance associated with organic acids in this region, it is the most scientifically defensible approach.
- **$[\text{ANC}]_{\text{limit}}$ 2:** Critical ANC estimated using the following equation as proposed in Jeffries et al. (2010), and based on the relationship that Lydersen et al. (2004) used to estimate $\text{ANC}_{\text{limit}}$ on a lake-by-lake basis in waters with higher DOC levels:

$$\text{ANC}_{\text{limit}} = 10 + \left(\frac{10.2}{3}\right) * \text{DOC}$$

Equation 4.4.1

Where DOC is the dissolved organic carbon in mg/l.

- **$[\text{ANC}]_{\text{limit}}$ 3:** Fixed value of critical ANC of 26 µeq/L as used for all lakes in the STAR and KAA studies.

Applying these three ANC scenarios to the SSWC and FAB models, we obtained the following results (shown in the figures and tables presented in this section):

- As in the case of the primary scenario (i.e., critical ANC estimated based on the adapted titration curve), no biologically significant changes in pH (i.e., $\text{IpHl} > 0.3$), under the worst case emissions scenario (Scenario F_R), were predicted for either $[\text{ANC}]_{\text{limit}}$ 2 or 3.



Therefore, the overall risk category of lakes acidification for PRAS remains **low**, according to the risk classification scheme described in Section 6.1.3 (Volume 1).

- In terms of critical load exceedance, both alternate critical ANC scenarios resulted in a few cases of exceedance, compared to the primary scenario for which no exceedance was predicted under SSWC or FAB (see Section 6.2.3, Volume 1 of this report). Table A4.4-1 summarizes the statistics of these exceedance cases for the worst case emission scenario (F_R).

Table A4.4-1: Exceedances (meq/m²/yr) of critical loads under scenarios SSWC and FAB for the alternate critical ANC values.

Statistics	Exceedance SSWC		Exceedance FAB	
	ANC _{limit 2}	ANC _{limit 3}	ANC _{limit 2}	ANC _{limit 3}
#Lakes	5	2	4	2
%Lakes ^a	14%	6%	11%	6%
Median Exc.	15.26	14.70	11.02	16.22
Max Exc.	23.21	15.26	22.91	16.42
Min Exc.	2.81	14.13	3.37	16.01

^a Percentage of lakes relative to the 35 sampled lakes

The lakes showing exceedance under at least one of the two alternative critical ANC assumptions are the following: NC309, NC327, NC338, NC360, and AD-SW9. Figure A4.4-1 shows the location of these five lakes; they are all situated in the middle to northern part of the PRAS region.



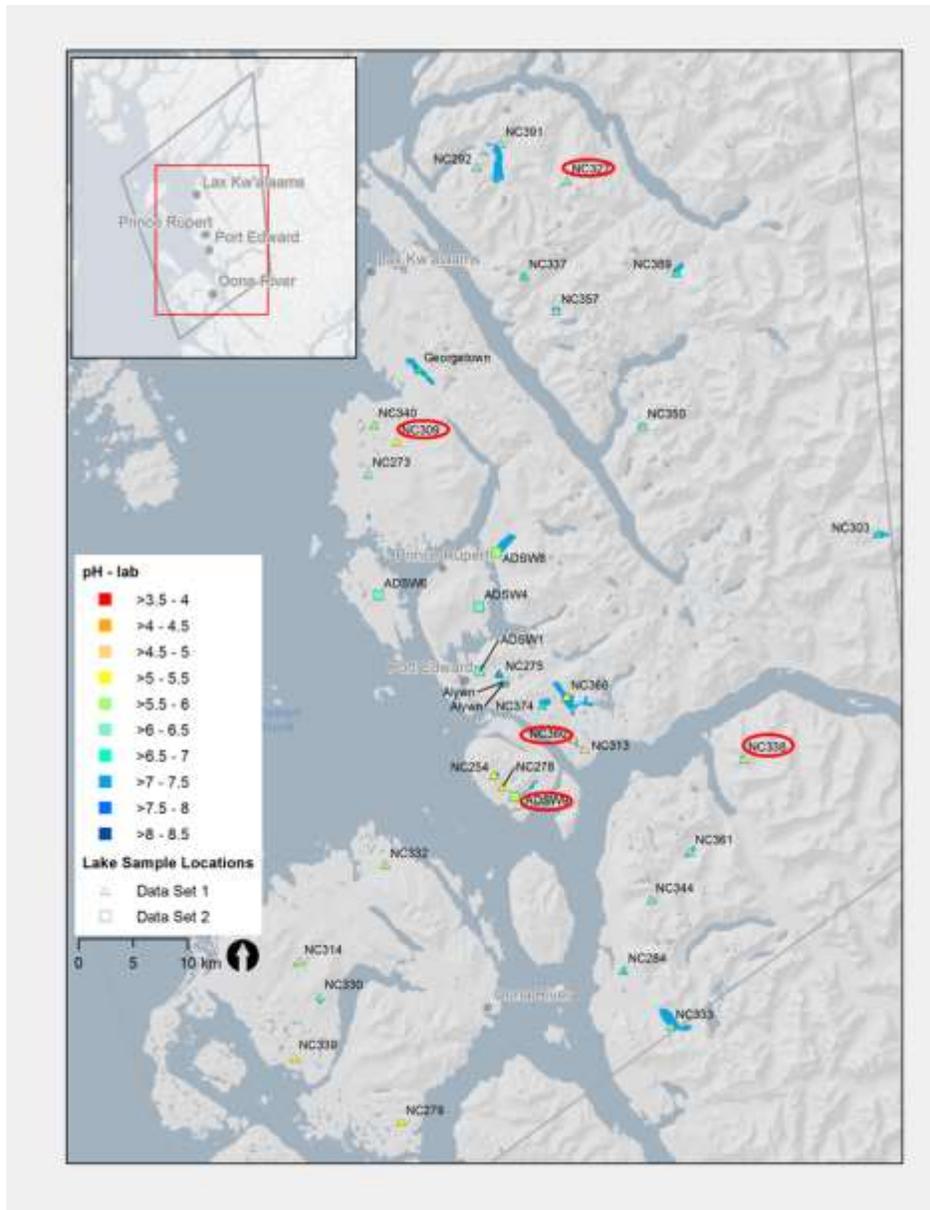


Figure A4.4-1: Location of lakes with critical load exceedance for the two alternative critical ANC scenarios.

We followed the same Sample process for the sensitivity analysis as for the primary analysis presented in Volume 1:

1. We applied the SSWC model to determine the critical loads for acidification (see Figure A4.4-2) and exceedances (Table A4.2-1);
2. We input the SSWC critical loads into the FAB model and determined the critical loads for S and N (see Figure A4.4-3) and exceedances under this model (see Figure A4.4-4); and
3. We assessed potential changes in the pH of the lakes under the different assumptions for ANC_{limit} , using the ESSA-DFO model.

Figure A4.4-2 shows the critical ANC values for each lake according to the three methods used to estimate $[\text{ANC}]_{\text{limit}}$. For most lakes, the estimation of critical ANC based on Equation 4.4.1, as proposed in Jeffries et al. (2010), resulted in higher $[\text{ANC}]_{\text{limit}}$ values compared to the other two approaches, especially in the case of the lakes with a higher concentration of dissolved organic carbon (DOC).

Table A4.4-2 summarizes the results of the sensitivity analysis, in terms of predicted exceedances and changes in pH, for Scenario F_R (i.e., worst case for emissions) and under models SSWC and FAB. For most lakes the exceedance values are below $-20 \text{ meq/m}^2/\text{yr}$, or well below the critical load. The “[ANC]_{limit 2}” approach results in the most unfavourable condition with positive exceedances for five lakes (14% of the 35 sampled lakes) under SSWC and for four lakes (11% of the 35 sampled lakes) under FAB. All these cases of exceedance would be classified as low concern (see Table 6-3 in Section 6.1.3) because they imply exceedance of the critical load, but the change in pH in the lake is not biologically significant (pH change <0.3).



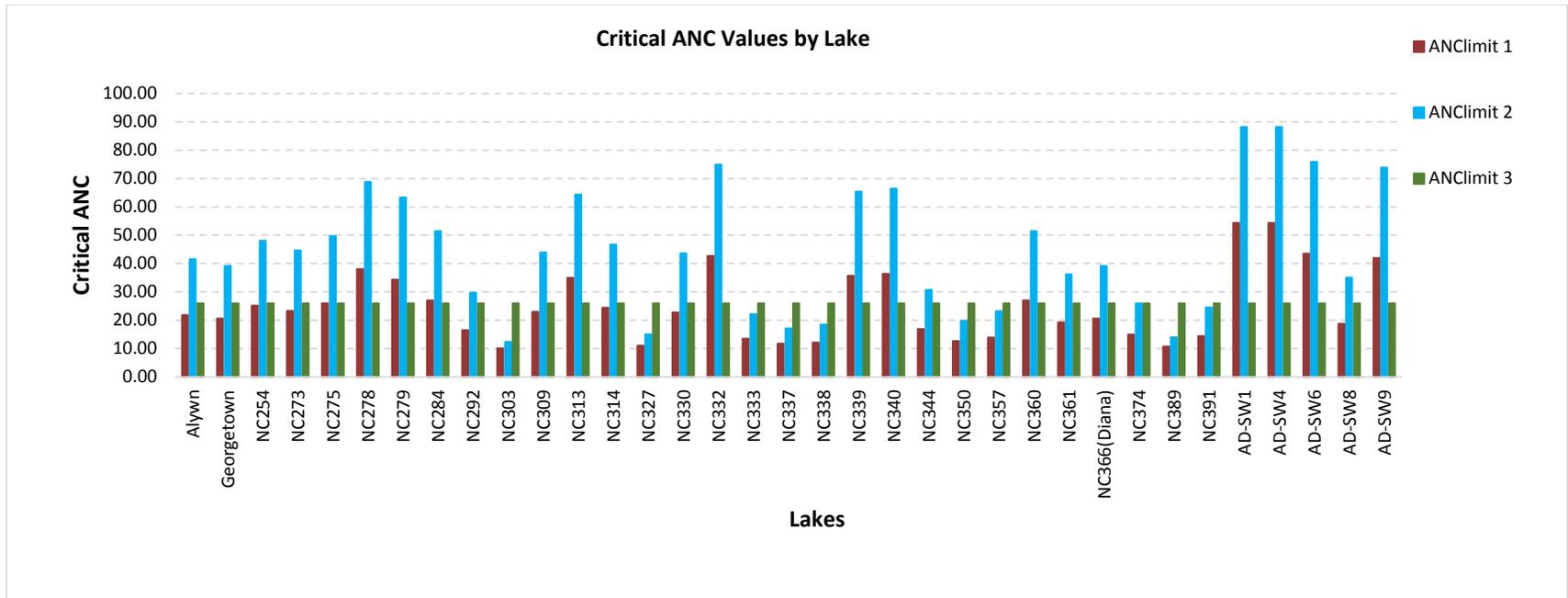


Figure A4.4-2: Critical ANC in the sampled lakes, estimated according to the three approaches used for the sensitivity analysis.



Table A4.4-2: Results of exceedances, pH changes for and risk categories of biological concern for the 35 sampled lakes across the three critical ANC assumptions, for bookend emission Scenarios A and F_R. Results are provided for the worst case emission scenario (F_R). Exceedance values (meq/m²/yr) are highlighted according to the following key: light green for well below the critical load (CL) ≤ -20 meq/m²/yr, dark green for below CL = -20 to -10 meq/m²/yr, yellow for near CL = -10 to 0 meq/m²/yr, light orange for CL exceeded in 0 to 10 meq/m²/yr, dark orange for CL exceeded in 10 to 20 meq/m²/yr, and red for CL exceeded in more than 20 meq/m²/yr. Predicted ΔpH is based on the modified ESSA-DFO model; yellow = |ΔpH|>0.1.

Lake	Exceedance SSWC Scenario A			Exceedance SSWC Scenario F_R			ΔpH			Risk category
	ANC _{limit 1}	ANC _{limit 2}	ANC _{limit 3}	ANC _{limit 1}	ANC _{limit 2}	ANC _{limit 3}	ANC _{limit 1}	ANC _{limit 2}	ANC _{limit 3}	CL exceedance?/ ΔpH ≤ -0.3
Alywn	-193.36	-137.79	-181.67	-204.09	-143.45	-191.34	-0.002	-0.002	-0.002	No/No
Georgetown	-354.22	-303.95	-339.84	-383.13	-328.61	-367.54	0.000	0.000	0.000	No/No
NC254	-63.80	-10.01	-61.79	-70.11	-8.03	-67.79	-0.098	-0.098	-0.098	No/No
NC273	-59.84	-12.82	-54.03	-65.20	-6.96	-58.01	-0.067	-0.067	-0.067	No/No
NC275	-781.71	-718.17	-781.88	-844.83	-775.72	-845.02	0.000	0.000	0.000	No/No
NC278	-105.90	-35.87	-133.57	-114.45	-38.64	-144.41	-0.032	-0.032	-0.036	No/No
NC279	-116.36	-54.38	-134.14	-148.11	-72.75	-169.72	-0.002	-0.002	-0.002	No/No
NC284	-325.49	-256.13	-328.36	-379.94	-303.48	-383.10	0.000	0.000	0.000	No/No
NC292	-53.70	-12.03	-23.76	-57.20	-10.77	-23.84	-0.027	-0.027	-0.025	No/No
NC303	-141.09	-127.09	-40.32	-156.99	-141.55	-45.88	-0.001	-0.001	-0.001	No/No
NC309	-17.92	23.21	-10.77	-16.51	43.59	-7.94	-0.292	-0.292	-0.284	Yes/No
NC313	-71.51	-4.36	-92.12	-87.58	-6.22	-112.56	-0.021	-0.021	-0.021	No/No
NC314	-107.84	-57.93	-104.31	-129.63	-73.61	-125.67	-0.002	-0.002	-0.002	No/No
NC327	-14.26	4.22	14.13	-9.13	10.77	21.48	-0.019	-0.019	-0.020	Yes/No
NC330	-106.08	-59.35	-99.00	-130.87	-76.54	-122.64	-0.001	-0.001	-0.001	No/No
NC332	-163.62	-94.59	-199.63	-196.26	-120.84	-235.61	-0.001	-0.001	-0.001	No/No
NC333	-97.45	-62.05	-46.68	-117.92	-77.60	-60.09	-0.001	-0.001	-0.001	No/No
NC337	-64.46	-45.55	-14.37	-69.30	-47.99	-12.86	-0.012	-0.012	-0.011	No/No
NC338	-9.48	15.26	15.26	-10.34	19.82	19.82	-0.038	-0.038	-0.044	Yes/No
NC339	-125.70	-65.62	-145.36	-147.43	-81.30	-169.07	-0.001	-0.001	-0.002	No/No
NC340	-147.64	-83.36	-169.98	-165.03	-91.36	-190.64	-0.011	-0.011	-0.011	No/No
NC344	-109.99	-51.02	-71.25	-126.66	-61.17	-83.64	-0.001	-0.001	-0.001	No/No
NC350	-81.21	-53.81	-30.26	-83.84	-54.23	-28.76	-0.015	-0.015	-0.014	No/No
NC357	-69.56	-36.04	-26.16	-74.55	-38.00	-27.23	-0.013	-0.013	-0.012	No/No
NC360	-55.02	2.81	-57.41	-64.38	26.21	-67.16	-0.076	-0.076	-0.077	Yes/No
NC361	-111.26	-47.80	-86.04	-121.20	-54.54	-94.71	-0.003	-0.003	-0.003	No/No



NC366	-74.87	-25.44	-60.74	-87.92	-30.37	-71.46	-0.044	-0.044	-0.042	No/No
NC374	-186.27	-158.32	-158.27	-218.08	-184.68	-184.62	-0.002	-0.002	-0.002	No/No
NC389	-427.24	-415.21	-372.32	-469.44	-456.52	-410.48	0.000	0.000	0.000	No/No
NC391	-106.01	-69.95	-65.04	-114.86	-75.88	-70.57	-0.006	-0.006	-0.006	No/No
AD-SW1	-478.86	-398.23	-546.68	-534.49	-442.79	-611.62	0.000	0.000	0.000	No/No
AD-SW4	-550.47	-468.81	-619.15	-588.06	-499.70	-662.37	0.000	0.000	0.000	No/No
AD-SW6	-315.78	-251.47	-350.75	-337.59	-263.40	-377.92	0.000	0.000	0.000	No/No
AD-SW8	-135.73	-84.80	-113.29	-158.18	-101.46	-133.20	-0.006	-0.006	-0.006	No/No
AD-SW9	-54.53	17.27	-90.43	-78.88	5.02	-119.88	-0.009	-0.009	-0.012	Yes/No



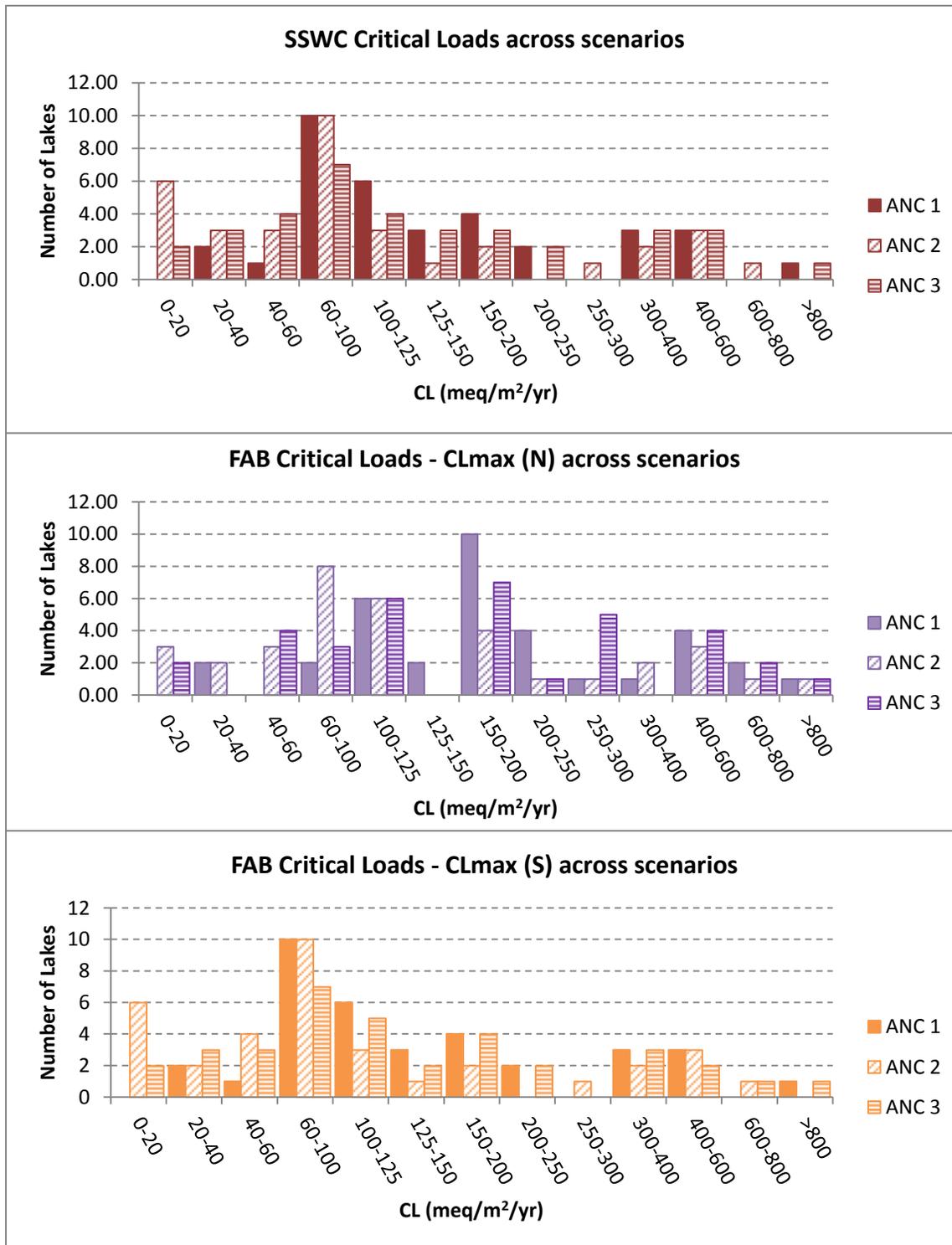


Figure A4.4-3: Frequency of critical loads (CLs) for the 35 sampled lakes and across the three critical ANC scenarios. Upper panel: CLs as calculated by the SSWC model; middle panel: maximum CLs for nitrogen as calculated by the FAB model; lower panel: maximum CLs for sulphur as calculated by the FAB model.



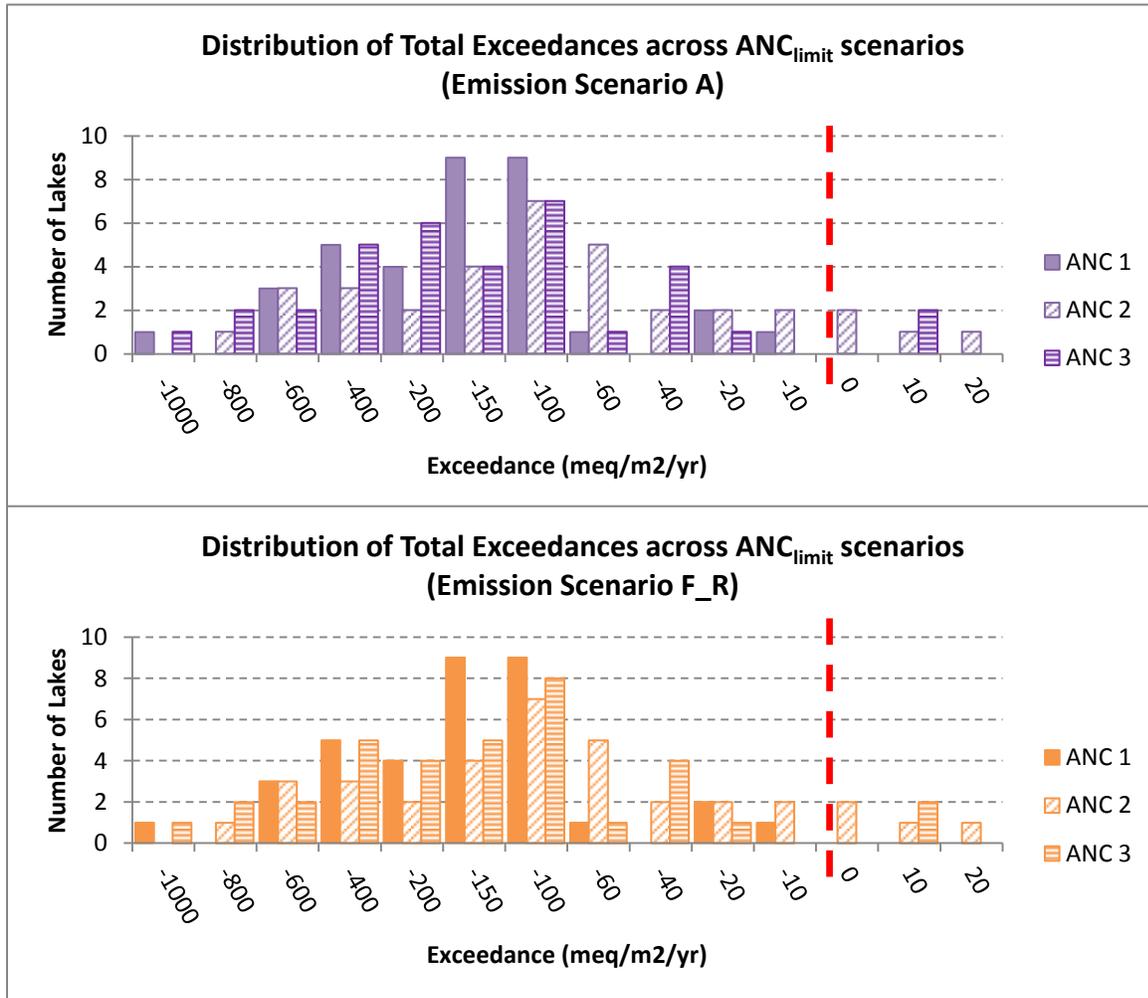


Figure A4.4-4: Distribution of exceedance values, for FAB mode, under Scenario A (upper panel) and Scenario F_R (lower panel). Exceedance values under the three critical ANC scenarios are shown.



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Appendices



ESSA

35
YEARS



Environmental & Cumulative
Effects Assessment



Climate Change Adaptation &
Risk Reduction



Aquatic Species at Risk &
Water Resource Management



Terrestrial Ecology &
Forest Resource Management