Sulphur Dioxide Technical Assessment Report in Support of the 2013 Application to Amend the P2-00001 Multimedia Permit

Kitimat Modernization Project

Volume 2: Technical Report

Final

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Appendices

See Volume 3.

List of Symbols and Abbreviations

Δ	delta, meaning quantitative change (e.g. ΔANC or ΔSO_2)
<	is less than what follows
≤	is less than or equal to what follows
>	is greater than what follows
≥	is greater than or equal to what follows
[ ]	the concentration of something, e.g., $[SO_2]$ means the concentration of sulphur dioxide
AAC	annual allowable cut
Al	aluminum
Al_2O_3	aluminum oxide trihydrate (alumina)
AM	adaptive management
ANC	acid neutralizing capacity
ASC	acid sensitivity class
BC, B_C	base cations
B.C.	British Columbia
BLIERS	Base Level Industrial Emission Requirements
CAAQS	Canadian Air Quality Management System
CABIN	Canadian Aquatic Biomonitoring Network (http://www.ec.gc.ca/rcba-cabin/)
CAMS	Comprehensive Air Management System
CCME	Canadian Council of the Ministers of Environment
CL	critical load
CO	carbon monoxide
CO_2	carbon dioxide
COPD	chronic obstructive pulmonary disease
CRP	C-reactive protein
DEM	digital elevation model
DFO	Fisheries and Oceans Canada
DL	analytical detection limit

DOC	dissolved organic carbon
ESSA	ESSA Technologies Ltd.
EX	exceedance
FEV1	forced expiratory volume in 1 second
FTC	Fume Treatment Centre
GHG	greenhouse gas
GIS	geographic information system
GranANC	the capacity of a solution to neutralize strong acids, determined by titration to the inflection point of the pH-alkalinity titration curve
GTC	Gas Treatment Centre
H_2SO_4	sulphuric acid
HF	hydrogen fluoride
HSS	horizontal stud Söderberg
HRV	a mesure of cardiovascular autonomic control
IVF	in vitro fertilization
KMP	Kitimat Modernization Project
LFH	litter-fibric-humic soil layer
LOI	loss-on-ignition
MAML	Mobile Air Monitoring Laboratory
MDISP	dispersion coefficients switch setting
MM5	5^{th} generation mesoscale model (data from this model used in sensitivity analyses of CALPUFF model output)
MOE	British Columbia Ministry of Environment
MoU	Memorandum of Understanding
Mt	Million tonnes
MW	megawatt
n	number (sample size, e.g. “n=6”)
N	nitrogen
Na_3AlF_6	cryolite
NADP	National Atmospheric Deposition Program
NEG/ECP	New England Governors/Eastern Canadian Premiers region

NO_2	nitrogen dioxide
NO_3	nitrate
NO_x	nitrogen oxides
NSWS	National Surface Water Survey
O_2	oxygen
O_3	ozone
P2	Pollution Prevention
PAH	polycyclic aromatic hydrocarbon
PB	pre-baked anode cell
Pb	lead
PCO	Pollution Control Objectives (of B.C.)
PDS	Passive Diffusive Samplers
PFPB	Point Feeder Prebake
PM	particulate matter
$PM_{2.5}$	particulate matter up to 2.5 micrometers in diameter
PM_{10}	particulate matter up to 10 micrometers in diameter
POP	persistent organic pollutants
QA/QC	quality assurance/quality control
RED	Regional Economic Development
RTA	Rio Tinto Alcan
S	sulphur
SDI	social deprivation index
SO_2	sulphur dioxide
SO_4	sulphate, a salt of sulphuric acid
sRAW	specific airway resistance
SRMZ	Special Resource Management Zone
SMB	Simple Mass Balance model
SSWC	steady state water chemistry (model)
TFL	tree farm license
TRS	total reduced sulphur

TSA	timber supply area
U.S.	United States (of America)
U.S. EPA	United States Environmental Protection Agency
UTM	Universal Transverse Mercator
UV	ultraviolet
VSS	vertical stud Söderburg
YSI	Yellow Springs Instrument

List of Measurement Units

$eq/m^3/a$	equivalents per cubic metre per annum (year)
g/s	grams per second
g/m^3	grams per cubic metre
ha	hectares
km	kilometre
kg/h	kilograms per hectare
keq/ha/yr	kiloequivalents per hectare per year
kg/ha/yr	kilograms per hectare per year (units of deposition flux)
L/min	litres per minute
m	metres
m/s	metres per second
m^3/s	cubic metres per second
m^4/s^3	metres to the fourth power per seconds cubed (units for buoyancy)
mg/L	milligrams per litre
Mg/d	mega grammes per day, equivalent to metric tonnes per day
mg/m^3	milligrams per cubic metre
$meq/m^2/yr$	milliequivalents per square metre per year
ng/g	nanograms per gram
ng/m^3	nanograms per cubic metre
ppb	parts per billion
ppm	parts per million

t/d	tonnes per day
t/month	tonnes per month
t/yr	tonnes per year
$t/km^2/yr$	tonnes per square kilometer per year
wt%	percent by weight
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)
µm	micrometres (µ can also be shown as u)

Conversion Factors

SO_2 concentration in air

1 ppb SO_2 = 2.62 $µg/m^3$ at 25°C and 1 atm pressure

1 ppm SO_2 = 2,620 $µg/m^3$ at 25°C and 1 atm pressure

1 ppb SO_2 = 2.66 $µg/m^3$ at 20°C and 1 atm pressure

1 ppm SO_2 = 2,660 $µg/m^3$ at 20°C and 1 atm pressure

The equation used for the above conversion is:

$µg/m^3 = (ppb)(12.187)(MW)/(273.15 + {}^oC)$

or

$mg/m^3 = (ppm)(12.187)(MW)/(273.15 + {}^oC)$

where:

$µg/m^3$	=	micrograms of gaseous pollutant per cubic metre of ambient air
mg/m^3	=	milligrams of gaseous pollutant per cubic metre of ambient air
ppb	=	parts per billion by volume
ppm	=	parts per million by volume
12.187	=	inverse of the Universal Gas Law constant
MW	=	molecular weight of the gaseous pollutant (for SO_2, this value is 64.06 g/mol)
°C	=	ambient air temperature in degree Centigrade

Measures of acidic deposition

1 $meq/m^2/yr$ = 0.48 kg SO_4 deposition/ha/yr

2.08 $meq/m^2/yr$ = 1 kg SO_4 deposition/ha/yr

20.8 $meq/m^2/yr$ = 10 kg SO_4 deposition/ha/yr

Glossary

A2M	Analysis to Mineralogy; a matrix-based model that estimates relative mineral content of soils
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
adaptive management	a systematic process for improving management policies and practices by learning from the outcomes of operational programs
afforestation	Establishment of a forest or stand of trees in an area where there was no forest
alkalinity	Measures the ability of a solution to neutralize acids; the terms acid neutralizing capacity and alkalinity are sometimes used interchangeably
alluvial fan	fan- or cone-shaped deposit of loose, unconsolidated sediment built up by streams or debris flows
ambient	Of the surrounding area or environment
anadromous	Migrating from salt water to spawn in fresh water, as salmon of the genera *Salmo* and *Oncorhynchus*
anion	An ion with more electrons than protons, giving it a negative charge, e.g., SO_4^{2-}
anode	An electrode through which electric current flows into a polarized electrical device.

anoxic	Lacking oxygen
anthropogenic	Of, relating to, derived from, or caused by humans or related to human activities or actions
arrhythmia	An irregular heartbeat
atherosclerosis	A condition in which an artery wall thickens as a result of the accumulation of fatty materials such as cholesterol
base cations	An alkali or alkaline earth metal (Ca2+, Mg2+, K+, Na+)
base cation buffering	The capacity of a watershed soil or a sediment to supply base cations (Ca2+, Mg2+, K+, Na+) to receiving waters in exchange for acid cations (H+, Al3+); may occur through cation exchange in soils or weathering of soil or bedrock minerals
base cation exchange	The replacement of hydrogen ions in the soil water by base cations from soil particles
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^{+})
benthic	Referring to bottom zones or bottom-dwelling organisms in water bodies
biomass	The total quantity of organic matter in units of weight or mass
biota	The total collection of organisms, both plant and animal
brackish	Having more salinity than fresh water, but not as much as seawater
buffer intensity	The change in pH per unit addition of strong acids or strong bases
calcination	The process of heating coke to drive off volatile hydrocarbons and moisture
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
carcinogenicity	The ability or tendency to produce cancer
catalysis	The change in rate of a chemical reaction due to the participation of a substance called a catalyst
catalyst	A substance that either speeds (positive catalyst) or slows (inhibitor) the rate of a chemical reaction; catalysts are not consumed by the reactions in which they participate
catchment	See “watershed”
cation	An ion with fewer electrons than protons, giving it a positive charge, e.g., Ca^{2+}
cathode	An electrode through which electric current flows out of a polarized electrical device
cerebral infarction, cerebral hemorrhage	stroke
climate	The average weather of a location over a long period of time
colluvium	Loose bodies of sediment that have been deposited or built up at the bottom of a low-grade slope or against a barrier on that slope, transported by gravity
conceptual model	Simplified or symbolic representation of prototype or system behaviour and responses
conductivity	A measure of a material's ability to conduct an electric current
congenital	Existing at birth and often before birth, or that develops during the first month of life
conjunctivitis	An inflammation of the conjunctiva (the outermost layer of the eye and the inner surface of the eyelids); also called pink eye or madras eye
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
critical uncertainties	Uncertainties emerging from the technical assessment which, when resolved, may result in a predicted impact shifting up or down one or more levels in either of the dimensions in the risk assessment framework, which could result in a different impact category (green, yellow, orange or red); resolving critical uncertainties could also result in a change in decisions about mitigative actions; other uncertainties emerging from the technical assessment, but if resolved are not expected to change either the impact category or appropriate mitigative actions, may be 'nice to know' but are not considered 'critical'
cryoboreal	Referring to species characteristic of the colder parts of the Boreal Zone
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)
drainage basin	See watershed
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
electrolysis	A method of using a direct electric current to drive an otherwise non-spontaneous chemical reaction
embolism	An event in which an embolus (a detached intravascular mass) clogs arterial capillary beds at a site far from its origin
empirical	Derived from or guided by experience or experiment
epidemiology	The study of the patterns, causes, and effects of health and disease conditions in defined populations
ephemeral	Transitory, existing only briefly, e.g., a stream that doesn't flow continuously throughout the year
escapement	The number of adult *salmon* that manage to return to their spawning streams

estuary	A partly enclosed coastal body of water with one or more rivers or streams flowing into it, and with a free connection to the open sea
etiology	The study of causation, or origination, i.e., why things occur, or whey they occur the way they do
fry	A very early free-swimming stage of fish development; tiny fish without yolk sacs still attached
genotoxicity	Pertaining to agents known to damage DNA, thereby causing mutations, which can result in cancer
glaciofluvial	Pertaining to streams fed by melting glaciers, or to the deposits
glaciomarine	A general term to describe inorganic and organic material deposited in a marine setting by a combination of glacier- and marine-related processes
hydrology / hydrologic	Pertaining to the movement, distribution, and quality of water
hydrolysis	Chemical process in which a water molecule is added to a substance resulting in the split of that substance into two parts
in vitro	Refers to isolation of the components of an organism from their usual biological surroundings in order to permit a more detailed or more convenient analysis than can be done using whole organisms, e.g., in a test tube
intertidal	Above water at low tide and under water at high tide (in other words, the area between tide marks)
interquartile range	A measure of statistical dispersion; also called the midspread or middle fifty
invertebrate	An animal without a backbone, e.g., insects
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

liming	The addition of any base materials to neutralize surface water or sediment or to increase acid neutralizing capacity
littoral zone	The shallow, near-shore region of a body of water; often defined as the band from the shoreline to the outer edge of the occurrence of rooted vegetation
methylmercury	The form of mercury that accumulates in the food chain
mineral acids	Inorganic acids, for example H_2SO_4, HNO_3, HCl, and H_2CO_3 (see strong acids and weak acids)
mineral weathering	Dissolution of rocks and minerals by chemical and physical processes
molluscs	A large group of invertebrate animals
morbidity	Refers to the disease state of an individual, or the incidence of illness in a population
morphologic	Pertaining to form and structure and to specific structural features
mortality	Refers to the state of being mortal, or the incidence of death (number of deaths) in a population
myocardial infarction	Heart attack
neonatal	Of, relating to, or affecting the newborn and especially the human infant during the first month after birth
ocular	Of or relating to the eye
oligotrophic	Having very little or no aquatic vegetation and being relatively clear
organic acids	Acids possessing a carboxyl (-COOH) group or phenolic (C-OH) group; includes fulvic and humic acids
oxidation	Chemical process in which a substance gets combined with oxygen
patent ductus arteriosus	A condition in which the ductus arteriosus (a blood vessel that allows blood to around the baby's lungs before birth) does not close
parent material	The underlying geological material (generally bedrock or a superficial or drift deposit) in which soil horizons form

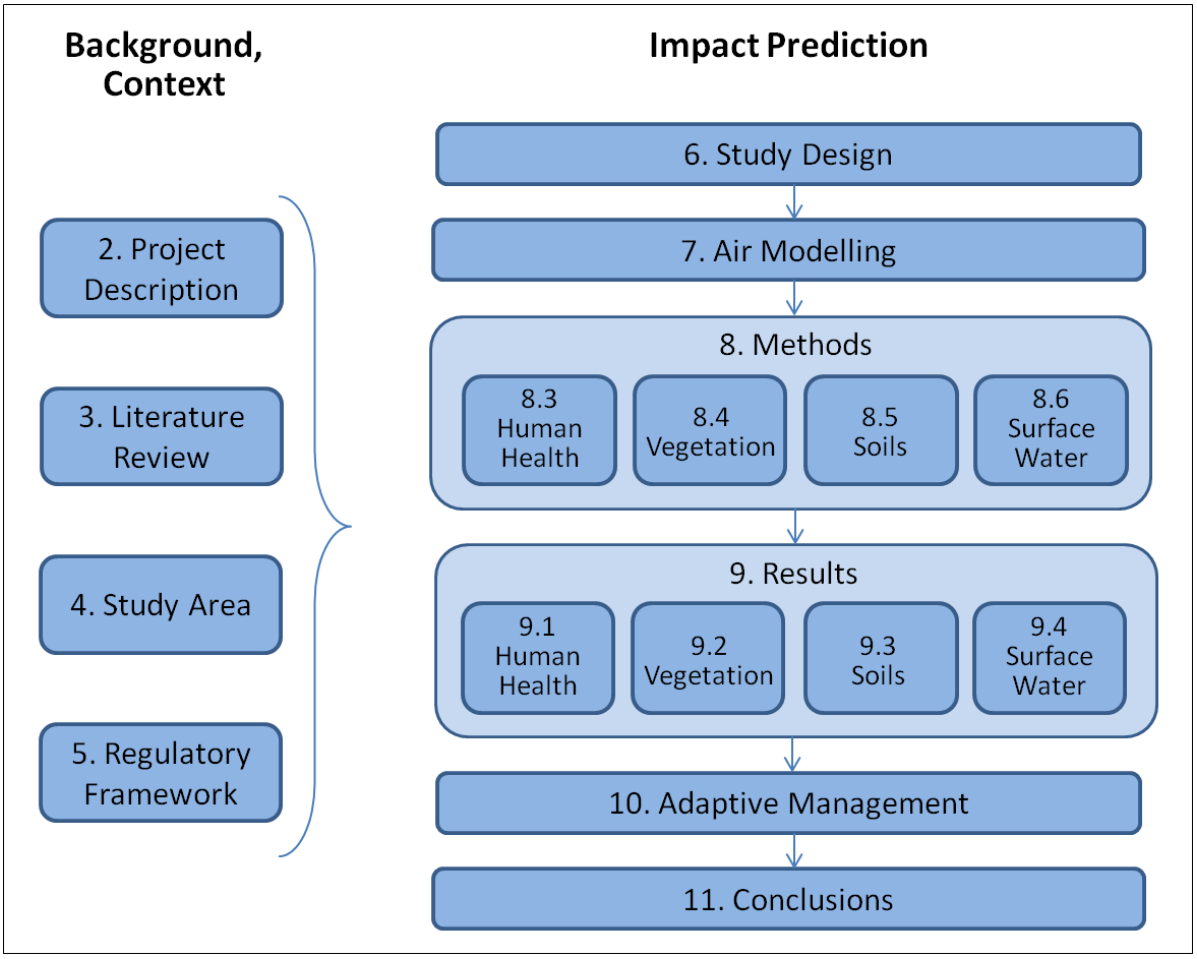
peak exposure	The highest average exposure over a short time period, generally in the range of 5 to 15 minutes, as compared to the average exposure over a longer period that contains the peak exposure (e.g., over the corresponding hour, or day)
pelagic zone	Referring to open-water areas not directly influenced by the shore or bottom
perhumid	The wettest climate, with humidity index values of +100 and above
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
photolysis	The process by which dissolved organic carbon is decomposed into smaller molecules (including CO_2) by natural light, especially ultraviolet light
physiology	The scientific study of function in living systems; includes how organisms, organ systems, organs, cells, and bio-molecules carry out the chemical or physical functions that exist in a living system
plankton	Plant or animal species that spend part or all of their lives carried passively by water currents; phytoplankton is plant plankton, and zooplankton is animal plankton
PROFILE	A steady-state soil chemistry model
QT interval	An electrocardiographic marker of ventricular repolarization
recruitment	The number of fish surviving to enter the population as mature individuals
reduction/oxidation reactions	Reactions in which substances gain or lose electrons (i.e., in which substances are converted from an oxidized to a reduced oxidation state and vice versa) – also called redox reactions
reforestation	The natural or intentional restocking of existing forests and woodlands that have been depleted, e.g., tree planting following a harvest
salmonids	A family of ray-finned fish, including salmon, trout, char, freshwater whitefish and grayling

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"
saturation	The point at which a solution of a substance can dissolve no more of that substance
source-pathway-receptor	A method for visually depicting the ways in which SO_2 and acidic deposition affect the environment, biota, and human health
species diversity	The effective number of different species that are represented in a collection of individuals; "species diversity" consists of two components - species richness (a simple count of the number of species) and species evenness (a measure of how equal abundances are among the species that are present)
species richness	The number of different species represented in a set or collection of individuals; a component of "species diversity"
stomata	Microscopic pores on the surface (epidermis) of land plants
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)
subsistence	Maintaining or supporting at a minimum level
thrombosis	Formation of a blood clot inside a blood vessel, obstructing the flow of blood through the circulatory system
trophic level	The position occupied in a food web
toxicology	The study of the adverse effects of chemicals on living organisms, of symptoms, mechanisms, treatments and detection of poisoning, especially the poisoning of people
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
weak acids	Acids having a low proton-donating tendency that tend to dissociate only partially in natural waters (e.g., H_2CO_3, H_4SiO_4, and most organic acids)

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

1.0 Introduction

This report contains a considerable amount of information. The following diagram represents the main sections of the report, and will help readers understand its structure and flow. A smaller version of the diagram is repeated at the beginning of each main section to help orient readers as they work their way through the document.



1.1 PURPOSE AND RATIONALE OF THE SO_2 PERMIT AMENDMENT

Rio Tinto Alcan (RTA) is modernizing the Kitimat Aluminum Smelter with state-of-the-art AP-4X pre-bake smelting technology through the replacement of the existing 60 year old vertical stud Söderburg (VSS) technology. The new aluminum smelting technology is more efficient, producing more aluminum per kilowatt hour of electricity than the smelting technology

currently in use. As a result, the Kitimat smelter will increase both the production of aluminum and the consumption of petroleum coke, the primary source of sulphur emissions. The purpose of this permit amendment application is to add the new SO_2 emission sources associated with a modern pre-bake aluminum smelting process to RTA's P2-00001 Multimedia Waste Discharge Permit, as well as to increase the permitted limit on SO_2 emissions to allow for increased aluminum production capacity.

1.2 BACKGROUND

The Rio Tinto Alcan aluminum smelter has been a mainstay to the Kitimat economy since the 1950s. The Kitimat Modernization Project (KMP) is a significant upgrade that is under construction to replace the existing VSS aluminum production technology with state-of-the-art AP-4X technology. This upgrade has resulted in the demolition of the existing # 7&8 VSS electrolytic reduction potlines as well as many of the supporting service buildings north of Moore Creek to make way for construction of the new smelter facility. KMP is designed to increase aluminum production capacity from the current name plate capacity of 282,000 tonnes per year (t/yr) to 420,600 t/yr, with significant decreased overall emissions and improved efficiencies.

Sulphur dioxide emissions from aluminum smelting are mostly the result of the consumption of petroleum-derived carbon that is used as an electric anode. Sulphur is a natural contaminant of petroleum-based coke, and is released as sulphur dioxide through the carbon process lifecycle in smelting aluminum (coke caclination, anode baking and anode consumption). RTA B.C. Operations has a current SO_2 P2 permit limit of 27 tonnes per day (t/d) for emissions resulting from carbon consumption. This limit needs to be increased to 42 t/d for KMP due to both the added consumption of coke on site to meet the new aluminum production capacity as well as to provide room for ongoing coke quality fluctuations within the market place.

The current 27 t/d limit was established in 1999 when the P2 Multimedia permit was issued. Prior to 1999, under the 1987 amended permit PA 02552, SO_2 emissions were regulated by controlling the concentration of SO_2 emanating from the coke calciner's pyroscrubber. However, due to coke market fluctuations (see Section 2.8.2), permit compliance based on an end-of-pipe concentration was difficult to consistently meet. In conjunction with a permit amendment for total particulate discharges from the pyroscrubber, a change of the permit metric to a daily mass load of 20.7 t/d was requested (but not formalized) (B.C. Ministry of Environment 1998). This limit was further increased to 27 t/d in the P2 permit due to concerns about declining petroleum coke quality (increasing sulphur concentration in the coke). This concern is still valid today as quantities of sweet petroleum crude oil, which is the source of low sulphur content coke, continue to decline.

Figure 1.2-1 shows the SO_2 emission history from the RTA Kitimat aluminum smelter between 1982 and 2011. As can be seen in the figure, annual emissions trended upwards from below 12

t/d to a peak of 23.25 t/d in 2000, but have since declined to below 16 t/d. The recent decline in SO_2 emissions has been related to coke quality management (structure and contaminants) as well as declining metal production in preparation for modernization. Future SO_2 emissions with KMP will increase to a projected 42 t/d under steady state operations.

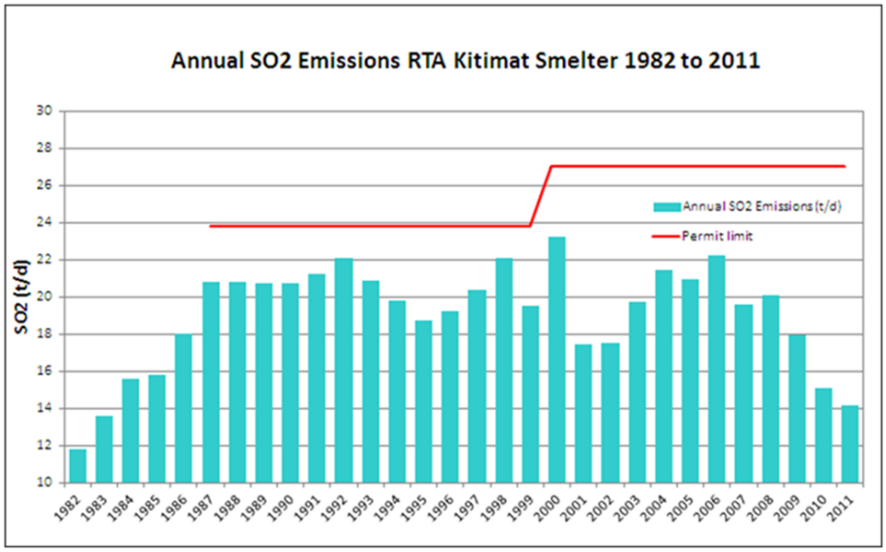


Figure 1.2-1: Annual total SO_2 emissions from the RTA Kitimat smelter between 1982 and 2011.[1]

1.3 PERMIT APPLICATION DETAILS

RTA B.C. Operations Kitimat aluminum smelter has a Pollution Prevention Multimedia Permit, P2-00001 (issued December 7, 1999, with the last comprehensive amendment dated November 9, 2007), which authorizes the discharge of air emissions, effluent and refuse from the aluminum smelter. The land upon which the facility is situated, and where the discharges occur, is comprised of District lots 90, 91, 92, 93, 96, 102A, 186, 7596 and 5469 (water lot), Ranges 4 and 5, Coast District, Kitimat, British Columbia, located at/on/near the north end of the Douglas Channel, within the District of Kitimat. For the purpose of modernizing the 60 year old smelter into a state-of-the-art pre-bake aluminum smelter, the current SO_2 permit limit associated with the VSS smelting process needs to be increased from 27 t/d SO_2 plant-wide emissions to 42 t/d SO_2 plant-wide emissions. Additionally, the old sources of SO_2 emissions that are being decommissioned through modernization need to be removed from the Permit and the new KMP-related SO_2 sources need to be added into the Permit. The proposed amendment to the P2-00001 Multimedia Permit is presented in Section 5.0 of this report.

[1] Annual SO2 emissions have been amalgamated from data in the 1998 B.C. Ministry of Environment P2 Technical Report, Table 3.16 (B.C. Ministry of Environment 1998) and RTA internal SO_2 emission tracking and reporting file (1990 to 2011). Where there is a discrepancy between data sets, the RTA SO_2 emission and tracking file data are used.

1.4 OVERVIEW OF COMPANY

The proponent for this project is Rio Tinto Alcan (B.C. Registration #A0073589). Rio Tinto Alcan (RTA) is one of five product groups operated by Rio Tinto, a leading international mining group. RTA is one of the world's largest producers of bauxite, alumina and aluminum.

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V8C 2H2
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Alcan's operations in British Columbia (B.C.) were built between 1950 and 1954 at a cost of $500 million – about $3.5 billion in today's dollars – and represented the largest single project ever undertaken by the Canadian private sector at that time. In addition to the industrial elements, the project included construction of the two communities that would be home to Alcan's workforce: Kitimat, a model of urban planning at the time, and the village of Kemano (which was decommissioned in 2000 but was home to power station workers and their families for more than 40 years).

The project was built in a sparsely populated region, accessible only by air and sea and featuring some of the most challenging terrain on earth. Survey work undertaken by provincial surveyor Frederick Knewstubb in 1928 demonstrated the hydroelectric potential of the region. The Province realized that developing this potential would mean attracting an energy-intensive industry to the area and approached Alcan, then the Aluminium Company of Canada, to validate the region's appeal to the aluminum industry. Before Alcan could consider developing this resource, World War II broke out, resulting in an eight-fold increase in the size of the company's Arvida complex as it expanded to meet the needs of the Allied Forces to wage war in the air.

After the war, B.C. invited Alcan to revisit its earlier investigations and, in 1950, the Province passed the Industrial Development Act, granting Alcan rights to the waters of the Eutsuk/Tahtsa water basin in B.C.'s Central Interior in exchange for Alcan's commitment to create an aluminum industry in B.C., opening up the north to industrial development. Alcan committed resources and expertise to complete the project within a mere five years.

Construction began in 1951, and the reservoir at the power works was already filling by the fall of 1952. Drilling crews completed the power tunnel under Mount DuBose at the end of 1953, and by the summer of 1954 power generation was under way. In August of that year, HRH Prince Philip presided over a ceremonial pour of the first Kitimat-produced aluminum. Some 35,000 construction workers were part of this achievement. Smelter production capacity more

than doubled over the first few years of operation, and a multi-ethnic workforce put down increasingly deep roots in B.C.'s northwest.

Today, Rio Tinto Alcan's B.C. Operations remain a defining feature of the northern B.C. landscape and economy, and an important player in the global aluminum industry. Rio Tinto Alcan currently contributes significantly to the B.C. Gross Domestic Product (GDP), representing an economic injection of $300 million year over year. RTA B.C. Operations provides close to 1,400 direct jobs and many more indirectly.

The Kitimat smelter is located on a deep water port on the Douglas Channel at Kitimat. Rio Tinto Alcan owns and operates wharf and terminal facilities at this port, from which raw material and finished products are transported to and from the Kitimat smelter.

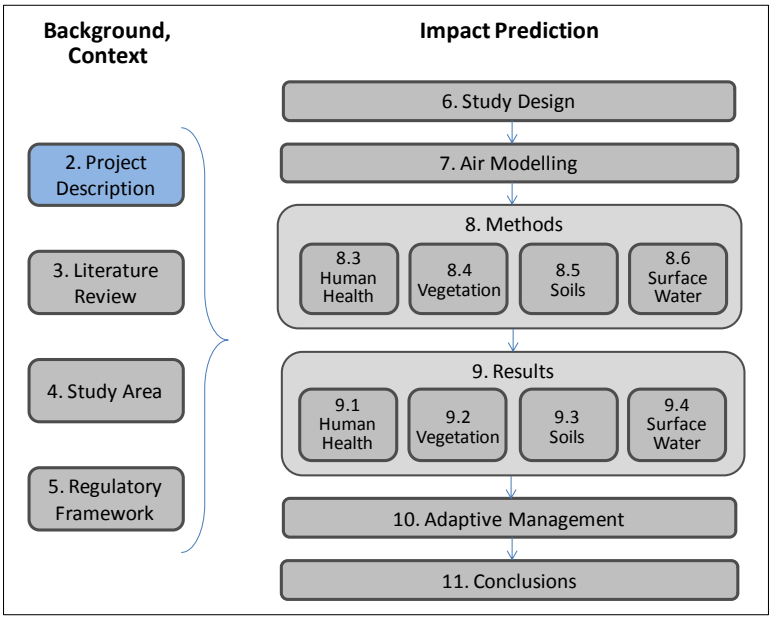
The original smelting facilities included seven potlines, housed in 15 buildings at the smelter site with an annual rated production capacity of 282,000 t/yr. The modernized smelter, projected to be complete in 2015, will include one potline housed in four buildings with an annual rated production capacity of 420,600 t/yr. Additionally, the Kitimat smelter site includes an anode plant, casting facilities, transportation facilities, waste handling facilities, equipment and vehicle depots, workshops, office buildings, employee facilities, and other related support infrastructure. RTA's B.C. Operations also include Kemano Power Operations, and Community Relations and Corporate Affairs offices in Vanderhoof, Burns Lake, and Vancouver.

The Kitimat smelter currently produces two types of ingots: sheet (angular) and trilock (remelt). Sheet is a value-added product while the trilock is sold for re-melting. Products are shipped to markets in Asia and North America, with Korea, Japan, Southeast Asia and the United States being the most common destinations.

1.5 TECHNICAL ASSESSMENT SCOPE

This Technical Assessment Report focuses solely on total sulphur dioxide emissions from the modernized Kitimat Aluminum Smelter and their associated impacts on human health and the environment within the defined study area of this permit application. The emission sources, as further described in Section 2.0, include end-of-pipe SO_2 emissions from the coke calciner (existing source), and emissions from the gas treatment centre for the new potrooms, the new potroom roof vents, and the new anode baking furnace. The other emissions that are typical to the aluminum smelting process, such as hydrogen fluoride emissions and particulates, are outside the scope of this technical assessment report. Non-SO_2 emissions will be addressed in a separate permitting exercise to update the P2-00001 Multimedia Permit for the overall Kitimat Modernization Project.

2.0 Project Description



2.1 OVERVIEW OF THE KITIMAT MODERNIZATION PROJECT SCOPE

The Kitimat Modernization Project will replace the old VSS smelting technology with a modern pre-bake AP-40 smelter. The project will be constructed overtop the footprint of the north end of the smelter (potlines 7&8 area). KMP is an important project for RTA that will deliver both financial and environmental returns. The improvements are due to the change in technology that will deliver efficiencies in aluminum production (reduced raw materials consumption intensity) and improved emissions control. To support the AP-40 smelting technology, KMP will install a number of services, e.g., for carbon anode production, and a cast house to freeze the expanded metal production.

The Kitimat Modernization Project has taken many years to develop, announce, and proceed to construction. On 1 December 2011, KMP – with its $3.3 billion (U.S) investment to sustain the aluminum industry in British Columbia – received full approval from RTA's Board of Directors. The regional public had been poised for this announcement since 1997, but more specifically since 2006 when KMP was first announced.

Rio Tinto Alcan's commitment to local stakeholders was evident throughout the waiting period; during this time, KMP-related construction activity continued, and RTA made a commitment in 2010 to the Haisla First Nation by signing the Haisla Nation - Rio Tinto Alcan Legacy Agreement.

Rio Tinto Alcan has taken many opportunities during the five years leading up to the final approval announcement of KMP to share information about the project with the regional stakeholders. Such information has consistently included statistics about the overall environmental improvements that the smelter modernization will realize, as well as highlighting the fact that the sulphur dioxide (SO_2) levels will be elevated due to the increase in aluminum production.

2.2 PROJECT LOCATION

Rio Tinto Alcan Primary Metal North America's smelter at Kitimat is the only aluminum smelter in British Columbia (Figure 2.2-1). The Kitimat smelter is located west of the mouth of the Kitimat River, at the head of the Kitimat Arm, on District Lots 88, 90, 91, 92, 93, 96, 102A, 186, 7596 and 5469 (water lot), Ranges 4 and 5, Coast District, Kitimat, British Columbia (Figure 2.2-2). The existing smelter site covers an area of approximately 243 ha (600 acres). The site is bounded to the north by Anderson Creek and to the south by the Kitimat Arm of the Douglas Channel and industrial lands owned by Rio Tinto Alcan. To the east, the smelter is bounded by the Eurocan Wharf site and Haul Road and the Methanex Wharf site area; to the west it is bound by RTA's Private Industrial Road. KMP has been scoped and designed to fit within the bounds of the site and existing operational area.

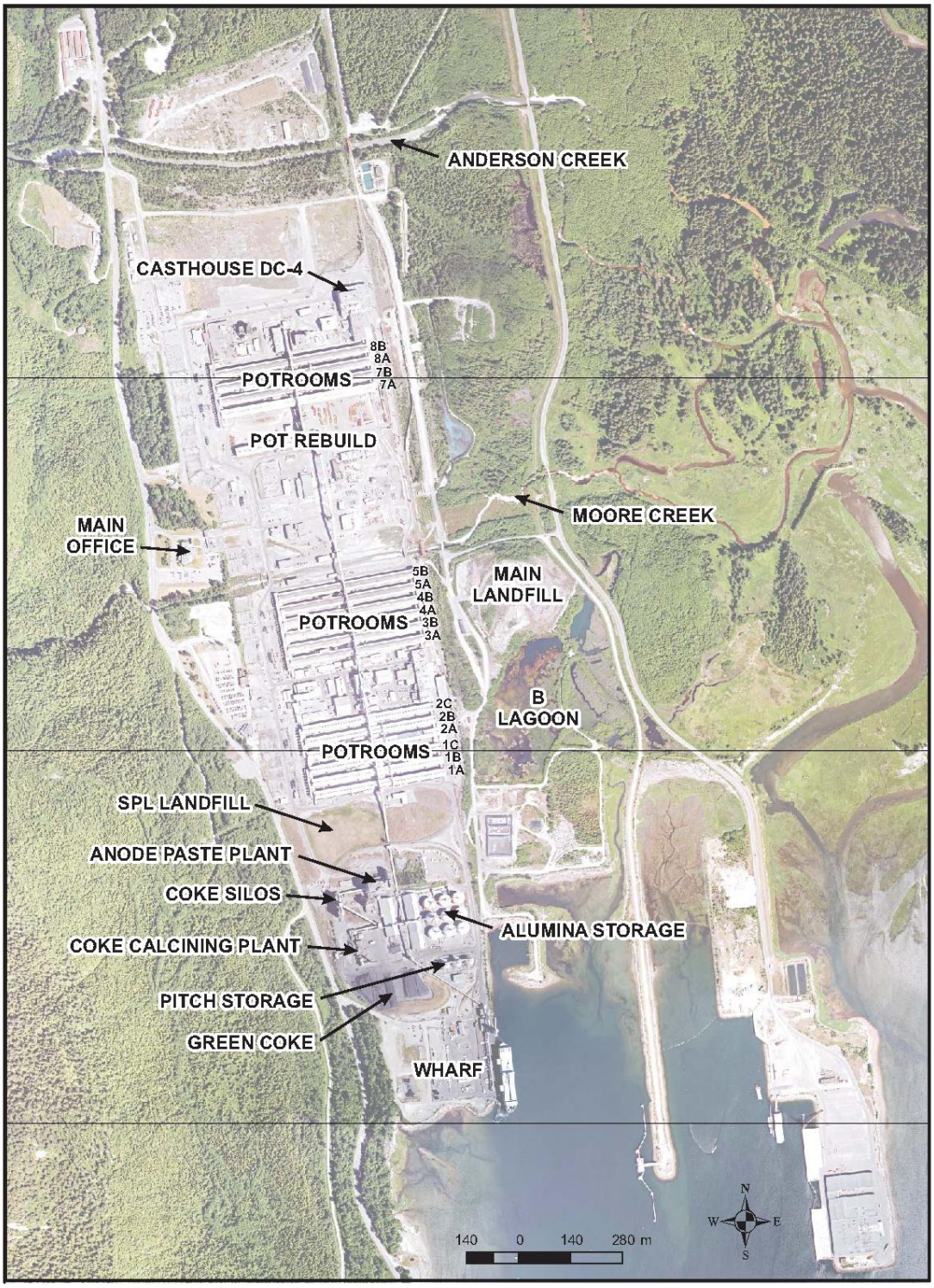


Figure 2.2-1: Site plan: existing smelter components.

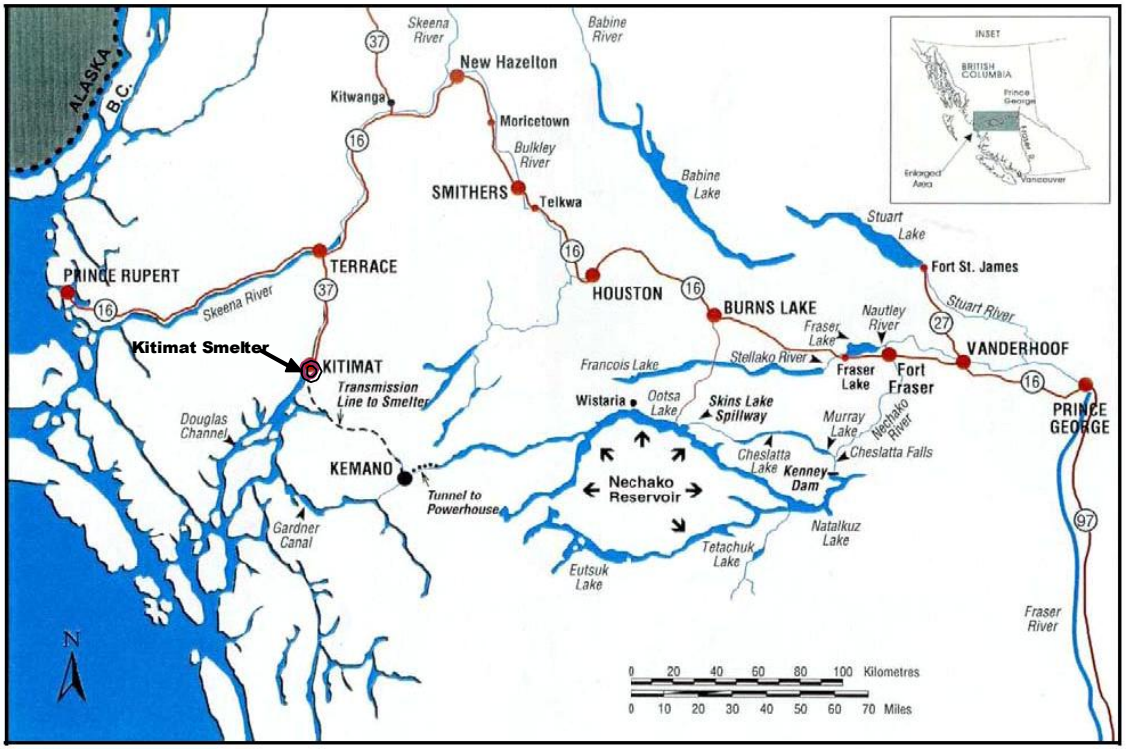


Figure 2.2-2: Geographical location.

2.3 PROJECT SCOPE

KMP's scope is the demolition of VSS smelting operations north of Moore Creek, construction of new pre-bake AP-40 smelting operations, expansion of carbon facilities south of Moore Creek, and the relocation of critical VSS operations that are required to sustain the existing smelter south of Moore Creek (while KMP is being constructed).

2.3.1 Existing smelter

Initial smelting operations were constructed between 1951 and 1954 with additional potlines added in the 1960s and 1970s to achieve the existing configuration. Conversion from wet to dry anode Söderberg technology occurred in all potrooms from the mid-1970s to mid-1990s. Conversion from wet scrubbers to dry scrubbers also occurred around the same period. An anode paste plant was constructed on-site in 1983 and a vacuum alumina unloader was added at the wharf in 2000. Incremental upgrades to technology and continuous improvements in process have occurred continuously over the history of smelter operations.

The operating capacity of the existing smelter is 282,000 tonnes of aluminum per year (t/yr). Current production is approximately 182,000 t/yr. Current associated infrastructure includes:

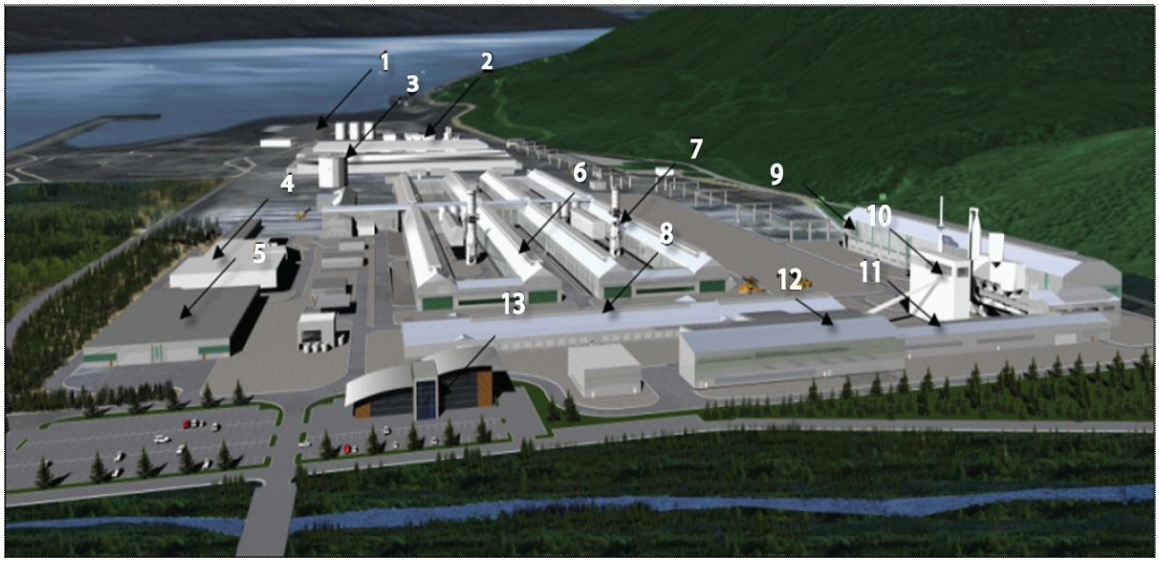
- An existing port facility where raw materials such as alumina, petroleum coke and liquid pitch are unloaded and aluminum products are loaded;
- Storage silos for alumina and liquid pitch;
- A coke calciner, where green petroleum coke is calcined prior to being used in the fabrication of anode briquettes;
- An existing carbon plant (existing Anode Paste Plant) where anode briquettes are produced and stored;
- Seven potlines (1, 2, 3, 4, 5, 7, and 8) and 900 pots in 15 buildings;
- Two casthouses where liquid aluminum is cast into three products: sheet, billet and ingot;
- Potshell relining centre;
- Power Operations control building;
- Administration building; and
- Additional service and support buildings, warehouses and storage buildings distributed throughout the plant.

RTA's Kemano Power Generating Station is located 85 km southeast of the smelter site. Water for power generation is stored in the Nechako Reservoir (Figure 2.2-2).

2.3.2 Kitimat works modernization

The Kitimat Works Modernization Project consists of the demolition and relocation of some existing buildings and services, and the construction and operation of some new on-site and off-site components (Figure 2.3-1 and Figure 2.3-2). The following items are within the project scope:

- One new potline and 384 pots in four buildings;
- Two gas treatment centres for the potline (for fluoride and particulate capture);
- A new reduction services building;
- A retrofit of the existing Paste Plant to manufacture green anodes while maintaining production of Söderberg paste during the transition period;
- A new anode baking furnace, rodding shop, pallet storage building and carbon recycling facility;
- A new bath recovery facility;
- An expansion to the existing casting centres consisting of two water-cooled ingot casting machines;
- New air compressor station;
- A new electrical substation and modifications to existing on-site substation and power distribution infrastructure; and
- Construction camp, including ancillary facilities.



1: Kitimat Port Facilities
2: Carbon South
3: Alumina Silo
4: Existing Casthouse B
5: New Casthouse C
6: Potroom
7: GTC
8: Pallet Storage
9: Anode Baking Furnace
10: Bath Treatment Plant
11: Anode Storage
12: Rodding Shop
13: Main Office

Figure 2.3-1: 3D schematic of project layout.

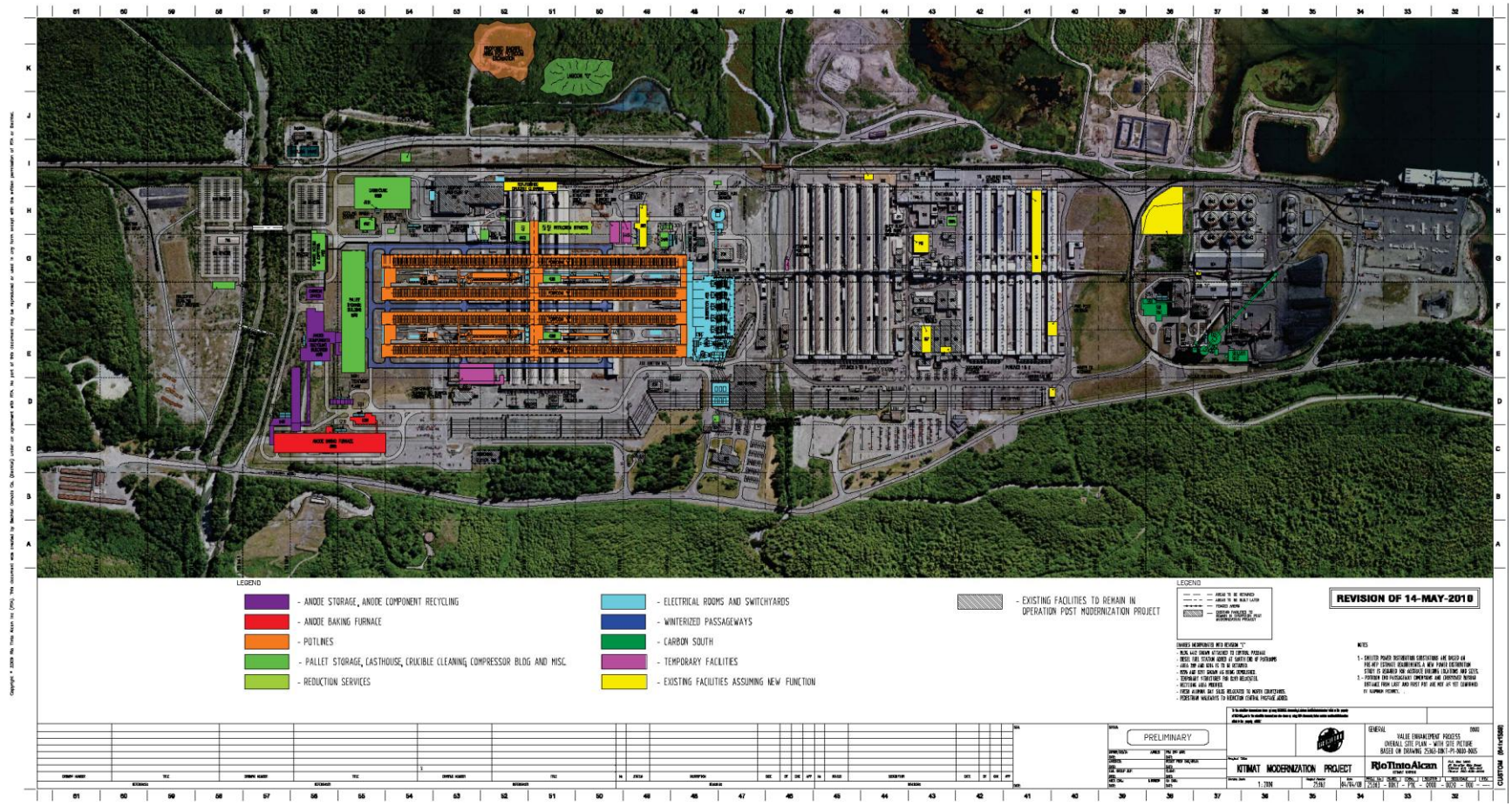


Figure 2.3-2: Kitimat Modernization Project layout.

2.4 ECONOMIC AND ENVIRONMENTAL BENEFITS OF THE KITIMAT MODERNIZATION PROJECT

2.4.1 Economic benefits

The Kitimat Modernization Project is a net beneficial project to northwestern British Columbia. Not proceeding with the project would have very significant adverse impacts to the regional economy of northern British Columbia.

RTA B.C. Operations is a significant contributor to the economy of northwestern British Columbia and is the only remaining large industrial employer for both Terrace and Kitimat. In 2011, the smelter contributed $281.1 million (Rio Tinto Alcan Primary Metal B.C. 2011:22) to the economy of British Columbia with notable expenditures of:

- $13.1 million in property taxes;
- $161.8 million in payroll and benefits; and
- $65.7 million in goods and services, of which $33.7 million was spent in northwestern British Columbia (supporting 271 vendors in the region).

The current operation employs 1,275 fulltime workers, and indirectly supports an estimated 3,143 workers in the northwest region of British Columbia.

RTA B.C. Operations has established a Regional Economic Development (RED) office in Kitimat. The goal of this office is to strengthen the economic and social fabrics of the region in order to sustain long-term regional development and job creation. The Kitimat Modernization Project will be leveraging the RED office to optimize spending for local and regional job creation. Additionally, specific targeted spending will be allocated to First Nations for economic growth and capacity building. In 2011, KMP purchased $95.8 million of goods and services in British Columbia, with $21.9 million spent in Kitimat.

Once commissioned, KMP will bring an additional 35 years of sustained economic contributions to British Columbia. The existing 1,275 smelter positions (primarily labour), will be replaced with approximately 1,000 technically enhanced jobs.

2.4.2 Environment and community health benefits

The current smelting operation is challenged with environmental performance due to the age of the smelting technology and supporting infrastructure, as well as declining qualities of raw materials. The operation has reached a plateau for reducing emissions of fluoride, particulates, polycyclic aromatic hydrocarbons (PAH) and greenhouse gases (GHG), and further reductions are not possible without significant investment in infrastructure and technology. The Kitimat Modernization Project is the best available technology for aluminum smelting emissions control.

The modernization will have significant environmental benefits, reducing total authorized waste discharge by approximately 22%, despite an approximate 48.9% increase in aluminum production. Importantly, PAH releases to the environment will decrease by about 97%, GHG intensity reduced by 57% and fluorides will be reduced by 37%. There will also be a 30% reduction in the amount of energy required to produce a tonne of aluminum. Total power consumption required for aluminum production will increase from about 565 MW to 710 MW at project completion, effectively using all of the available firm power production at Kemano.

2.5 PROJECT JUSTIFICATION AND RATIONALE

2.5.1 Aluminum production and demand

World production of primary aluminum was an estimated 45.6 Million tonnes (Mt) in 2011; production is expected to increase by 3% in 2012. Global demand for aluminum was an estimated 45 Mt in 2011. North America accounts for 12% of global demand, followed by Western Europe (14%), China (43%), and the rest of Asia (20%). The aluminum production industry is transforming as production shifts from North America and Europe to China, Russia and the Middle East in response to changing patterns of consumption and benefits from low-cost labour and energy. Since energy is the single biggest driver in aluminum smelting, sustained high energy prices will intensify this shift. Accelerated growth in China will likely also occur as lower alumina costs enable production by off-line and new smelters to take advantage of high metal prices.

Canada produced an estimated 7% of primary aluminum in 2010 and is the third largest producer behind China (39%) and Russia (9%) (CRU 2012a).

2.5.2 Uses for aluminum

Aluminum is a light metal widely used to make a variety of products for the consumer and capital goods markets. Its qualities of lightness, strength, corrosion resistance, formability, conductivity and its many attractive surface finishes have made it the second most widely used metal in the world. The primary markets are transportation (26%), building and construction (25%), packaging (16%), electrical (13%), consumer durables (5%), and machinery and equipment (10%) (CRU 2012b).

Specific uses in the transportation sector are the manufacturing of automobiles (engines, cylinder heads, transmission housings, and body panels), trucks and buses (sheet and plate for bodies), railway rolling stock and aircraft. In the building and construction sector, aluminum is used as sheet products for roofing and wall cladding, in extrusions for windows and doors, and in casting for builders' hardware. In the packaging sector, aluminum is used in the form of alloy sheets for beverage can bodies and tops, as foil for household and commercial wrap, and in manufactured packaging products such as cartons for fruit juice and packaging for

pharmaceuticals. In the electronics sector, aluminum is used in the form of wire, usually reinforced with steel, to form cables.

2.5.3 Need for the proposed project

The Kitimat smelter currently employs vertical stud Söderberg (VSS) technology that is being replaced in most locations around the globe with the more modern 'pre-bake' technology. Ten years ago, Rio Tinto Alcan undertook a general modernization program of its Söderberg facilities, which involved the closure/replacement of horizontal stud Söderberg (HSS) pots in Isle-Maligne and Jonquière (in Quebec). Rio Tinto Alcan has only one other operating Söderberg – an HSS located in Shawinigan Quebec – which is scheduled for closure within the next decade. Kitimat is RTA's only vertical stud Söderberg smelter. With the acquisition of Pechiney Inc. in 2003 and its technological solutions, RTA has become the world's leader in the development of advanced aluminum technologies. Internal experts have extensively studied the introduction of the modern pre-bake technology to the Kitimat operation, and are confident that it is the answer to extending the smelter's life for several more decades. When the project is complete, RTA's Kitimat smelter will be a modern world-class aluminum producing facility with one of the lowest operating costs in the world.

2.6 ANALYSIS OF ALTERNATIVES TO THE PROPOSED PROJECT

2.6.1 Global changes in technology for aluminum production

Three main types of aluminum reduction configurations are currently used in the primary aluminum industry: pre-baked anode pot, horizontal stud Söderberg pot (HSS), and vertical stud Söderberg anode pot (VSS).

All three aluminum pot configurations require a "paste" (petroleum coke mixed with a pitch binder). Paste preparation includes crushing, grinding, and screening of coke and blending with a pitch binder in a steam-jacketed mixer. For Söderberg anodes, the thick mixture is added and baked directly in the pots. In contrast, the pre-baked anodes are produced as an ancillary operation of the reduction plant (refer to Figure 2.7-1). To make a pre-baked anode, the paste mixture is formed into green anode blocks that are baked in an anode-baking furnace.

Approximately 17% of the world's production in 2012 was from Söderberg smelters. Most Söderberg smelters that are still in operation are VSS plants. However, all Söderberg smelters are characterized by higher emissions, lower energy efficiency and higher labour intensity than the modern pre-bake plants. For these reasons, no new Söderberg smelters are being built.

Since the early 1990s, almost all new aluminum capacity has been Point Feeder Prebake (PFPB) technology. Automatic point feeders of alumina are distributed along the central axis of the pot. Combined with appropriate process controls, it is possible to maintain a steady

composition of the electrolyte and stable process conditions. The pots are oriented side-by-side, whereas earlier pot types were oriented end-to-end. This side-by-side orientation has allowed increased pot size and higher amperage. Consequently, the output of a modern potline has increased significantly without increasing the footprint of the smelter.

The pre-baked anode pot technology is the technology currently selected for all modern aluminum smelters world-wide because it is electrically more efficient, produces far fewer emissions and waste, and produces aluminum at a cost that is competitive in the global market. These are the attributes that keep aluminum smelters operating over the long run in a highly competitive, ever changing, global market.

2.6.2 Rio Tinto Alcan's efforts to find the best long-term solution for the Kitimat smelter

Rio Tinto Alcan has put much effort into finding the best long-term solution for the Kitimat smelter. Obviously, there is clearly a strong interest in maintaining a sustainable aluminum production capacity in Kitimat for various reasons including access to power with competitive rates, the availability of a competent workforce that can be trained to operate a PFPB smelter, and the proximity to a year-round ice-free port providing deep, wide and sheltered passage to/from Pacific Rim and NAFTA markets. Kitimat is a beautiful, natural coastal community, and it offers a good quality of life for the residents.

In 1997-1998, a study was conducted to examine the feasibility of a 250,000 t/yr expansion of the Kitimat smelter north of Anderson Creek. However, at that time the estimated capital costs were considered to be high ($1.8 billion) and there were serious concerns about the soil bearing capacity at the site. Expansion north of Anderson Creek would have required the integration of measures for controlling differential settlement, as well as measures to control flood levels from Anderson Creek, substantially lowering the water table level, and provisions to prevent soil liquefaction during a seismic event.

Three other sites in the Kitimat area were then identified as potential alternate locations for the expansion. These sites included a location adjacent to the smelter, another located 3 km from the smelter towards Kitimat, and a third site (called "Onion Lake") located 40 km east of Kitimat. However, without knowing if special measures were needed to improve the bearing capacity of the soils, the capital costs would be of the same order of magnitude as the Anderson Creek site and the advantages of keeping all the facilities at the same location would be lost.

Between 2000 and 2004, several technology scenarios were investigated using the site's existing footprint. P155, P225, and AA240 technologies were assessed. AA240 technology proved to be the most feasible at the time, but the modernization project was put on hold due to economic conditions. Following the 2004 acquisition of Pechiney, AP technology was assessed. AP50 failed to meet economic returns and AP35+ with a carbon plant retrofit proved

to be the most viable technology for Kitimat. Approximately $25 million has been spent on modernization studies.

In 2006, Alcan announced a modernization plan for Kitimat, with an approximate investment of $1.8 billion (U.S.). The total capacity of the plant would increase the production up to 420,600 t/yr with a new PFPB pre-bake potline, taking advantage of all the firm power capability from the Kemano Power Generating Station. The project would be built at the location of existing potlines 7 and 8, and allow for continued aluminum production with the existing smelter. The proposed layout of the new PFPB potline minimized the footprint required for aluminum production. The Söderberg pots would be phased out and dismantled, which represented an important overall potential reduction in discharges to the environment, including greenhouse gases, while producing more aluminum in a more efficient way. Unfortunately, due to the global economic recession of 2008 and 2009, Rio Tinto's Board of Directors did not provide the project with a notice to proceed. Work on the project continued in 2009, albeit at a slower pace, allowing time for the economy to stabilize. During this time, a value engineering process was conducted to optimize the project. This optimized scope represents a long-term sustainable and economic solution for the Kitimat smelter in an ever competitive global market.

2.7 ALUMINUM SMELTING OVERVIEW

2.7.1 Principals of aluminum smelting

Aluminum ore, most commonly bauxite, occurs mainly in tropical and sub-tropical areas including parts of Africa, South America and Australia. Bauxite is refined into aluminum oxide trihydrate (alumina, Al_2O_3) and then electrolytically reduced into metallic aluminum. Four to five tonnes of bauxite are required to produce approximately two tonnes of alumina, which in turn yields one tonne of aluminum.

Rio Tinto Alcan imports the majority of alumina from Australia to Kitimat where it is dissolved in large carbon- or graphite-lined steel "pots" containing a molten electrolytic bath of cryolite (Na_3AlF_6) and aluminum fluoride (AlF_3). A low voltage/high amperage (up to 390,000 amperes) electric current is passed through the electrolyte from a carbon anode (positive), made of petroleum coke and pitch, and a cathode (negative), formed by the thick lining of the pot. As the reduction process occurs, the bonds between the aluminum and oxygen molecules are broken and the heavier aluminum molecules sink to the bottom of the pot. The molten aluminum is siphoned off periodically, taken to a holding furnace where it is alloyed, fluxed and degassed to remove trace impurities. From the holding furnace, the aluminum is cast in different shapes depending on end use and customer requirements. The proposed operations of the Kitimat Modernization Project are illustrated in Figure 2.7-1 and Figure 2.7-2.

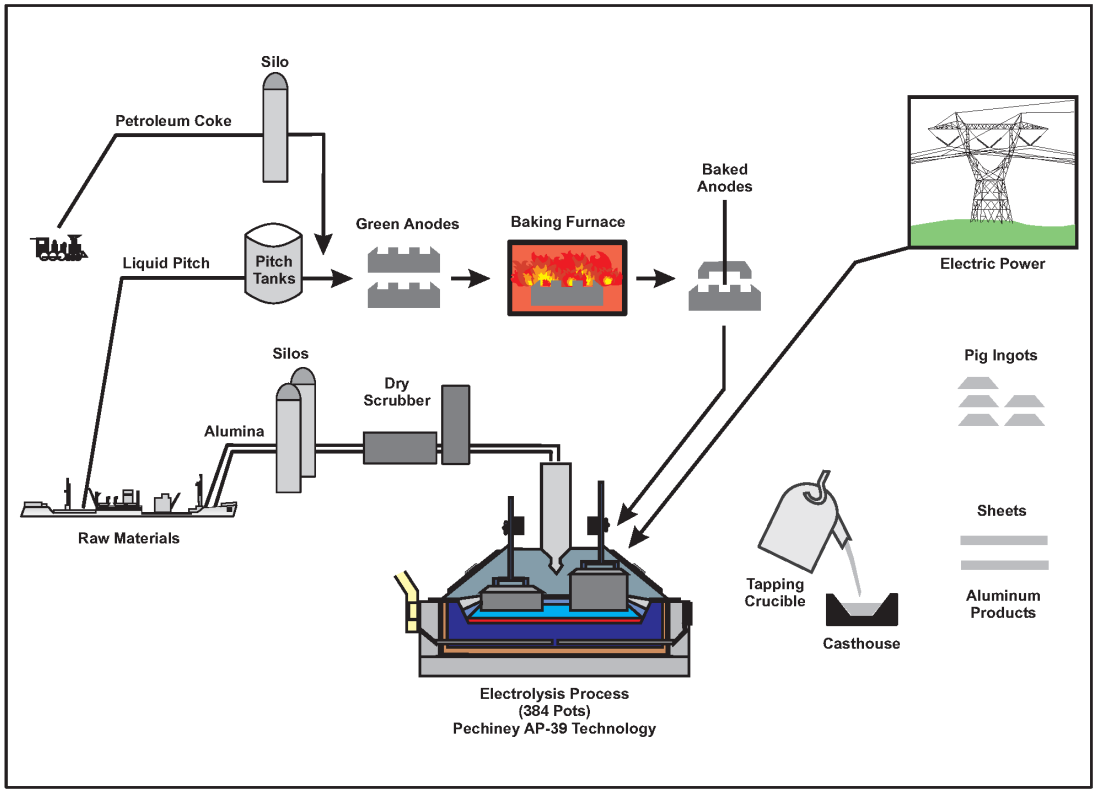


Figure 2.7-1: Conceptual process flow diagram.

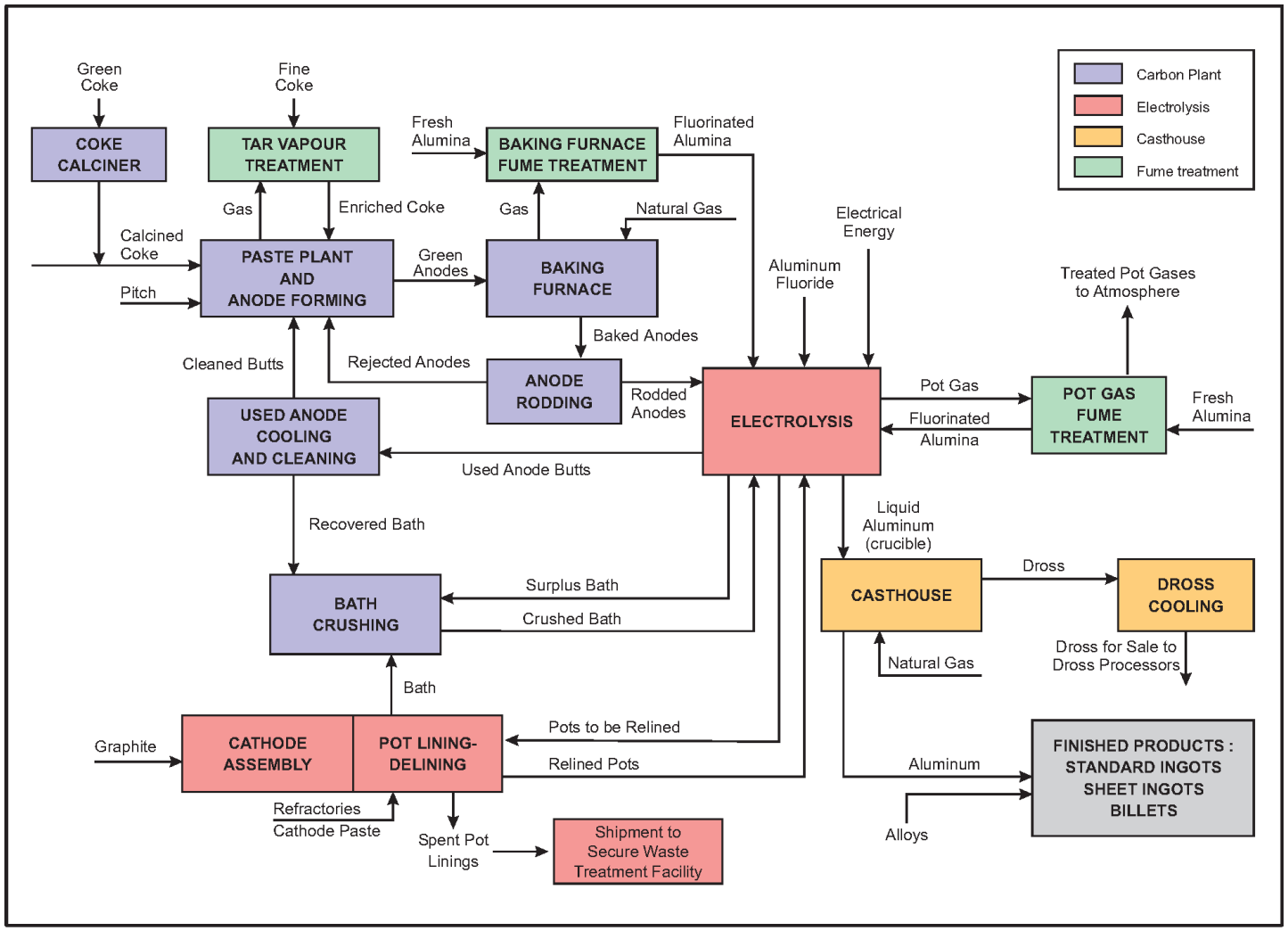


Figure 2.7-2: Schematic diagram of the operations of an aluminum reduction plant.

2.7.2 Technology difference between VSS smelting and AP-40 prebake smelting

Two different technologies are used in modern primary aluminum smelting. Söderberg technology (used at the existing Kitimat smelter) "creates and bakes" the anodes in place in each pot, whereas pre-bake technology "creates and bakes" the anodes in a separate facility. The Kitimat Modernization Project is best described as a rolling retrofit to replace the existing Söderberg technology smelter with proprietary state-of-the-art AP-39 pre-baked anode technology that would increase capacity up to approximately 420,600 t/yr. High-energy efficiency, computer control, low emissions, efficient gas collection and dry scrubbing (cleaning) systems, and high levels of material recovery are features of this technology.

Unlike the existing smelter, the pre-bake pots are totally enclosed and most process operations occur without opening the pot enclosure (refer to Figure 2.7-3). Emissions generated by the process are contained within the enclosed pot and drawn off by an emission collection system. Treatment is carried out in alumina injection dry scrubbers. The alumina, enriched with fluoride emissions, is the raw material used in the electrolytic process. The fluorides, a constituent of the electrolytic bath, are therefore recycled to the pots.

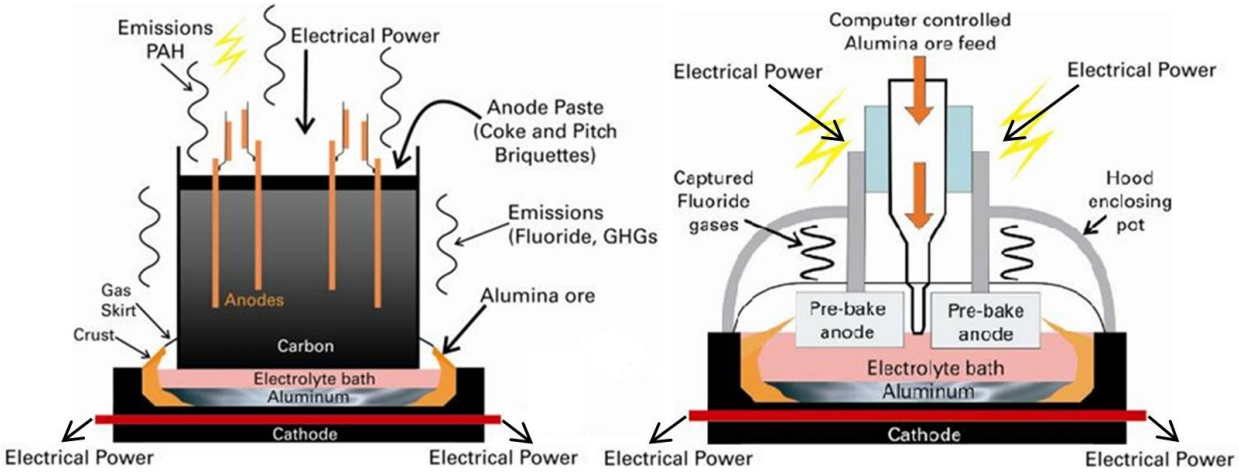


Figure 2.7-3: Difference between VSS and pre-bake smelting.

2.8 PROJECT COMPONENTS, INFRASTRUCTURE, AND RAW MATERIALS

2.8.1 Primary components of the aluminum smelting process

There are three primary components of the aluminum smelting process that generate sulphur dioxide (SO_2) emissions. These are the coke calcincer, the anode baking furnace, and the electrolytic reduction potline. For more specific descriptions of the KMP project components, please refer to the September 2010 Project Description submitted to the B.C. Environmental Assessment Office (Rio Tinto Alcan 2010).

2.8.1.1 Coke calciner

The existing on-site coke calciner that supports VSS operations will be retained by KMP and used to produce calcined coke for the new smelter. The calciner consists of a rotary kiln, cooler, and pyroscrubber. Green petroleum coke, received at the smelter's wharf, is stored in open stock piles by the calciner. The green coke is blended into the calciner from the stock piles to match chemical and physical properties required for the calcined product. The blending balances impurities such as sulphur. The calciner heats the coke to 1,350^{o}C (maximum calcination zone temperature) and removes both moisture and volatiles from the coke. The calcined coke exits from the calciner and is quenched with water in the cooler; it is then conveyed to a storage silo. The calciner will produce approximately 80,000 t/yr of calcined coke. Emissions from the calciner are primarily CO_2, particulates, SO_2, and NO_x. The emissions that exit the calciner are piped into a pyroscrubber to remove particulates.

The existing coke calciner does not have capacity to produce all of the calcined coke required by KMP. Additional coke will be imported and stored in a new silo.

2.8.1.2 Anode baking furnace

The anode baking furnace receives green carbon blocks from the anode forming shop at the paste plant. The green anodes are made from the calcined coke that is mixed with liquid pitch and compressed into carbon blocks. The green anodes are baked in a multi-sectioned (66 sections – 4 fires) ring-type furnace with a capacity of approximately 216,000 anodes per year. Green anodes are stacked into the baking furnace pits and packed with petroleum coke, where they are subjected to pre-heating, baking and air-cooling cycles. During the baking process, the pitch is partially carbonized and evaporated, leaving a dense hard anode block with the characteristics required for efficient use in the aluminum reduction process. Baking is assured through a mobile gas-firing system, providing furnace temperatures that peak at 1,150^{o}C. The baking is a multiple-batch process that takes approximately 26 days and provides a continuous supply of baked anodes.

After air cooling in the furnace, the baked anodes are removed and conveyed to a cleaning station to remove the loose granular coke material from the surface. The coke recovered during the cleaning operation is continuously reused as packing coke for the baking furnace. With time, packing coke agglomerates into nodules that are screened and sent to the paste plant for recycling.

Baked anodes are transported to the storage area, where they are kept until they are ready to be 'rodded'.

The Anode Baking Furnace will have a Fume Treatment Centre (FTC) to treat fumes from the bake furnace for particulates and fluorides. The FTC will be equipped with a water spray gas

cooling system and will dry scrub exhaust fumes from the anode baking furnace. Primary emissions from the FTC are CO_2, fluorides and SO_2.

2.8.1.3 Electrolyte reduction potline

The reduction process occurs in large refractory-lined steel containers, called reduction pots. The pots are arranged in buildings called potrooms. Each potroom can house up to 96 AP-39+ pots arranged side-by-side. The pots are electrically connected together in series to form an electrical circuit of aluminum conductors. It is expected that each pot will produce approximately three tonnes of aluminum per day.

Pots are fitted with a superstructure that supports the anodes, and stores and feeds alumina into the pots (Figure 2.8-1). Lightweight aluminum hoods, triangular side panels and doors are fitted to the superstructure to confine the process gases, which are ducted to a gas collection system and delivered to a gas treatment center (GTC). The side hoods are removed for anode changing and pot servicing.

The potrooms are ventilated by continuous roof gravity ventilators and open areas on both external walls between the basement and the operating floor. Secondary emissions are released from the potroom ventilation. These emissions arise from openings in the pots, and from the cooling of anode butts and process residues from the pots.

The current enters the pot via the anodes (positive) and flows through the electrolyte to the cathode (negative), after which it flows to the anode of the following pot. The electrolyte (bath) consists principally of cryolite (Na_3AlF_6) and aluminum fluoride. The alumina (Al_2O_3), a white powder known as aluminum oxide, is added automatically to the bath and is reduced to aluminum via electrolysis. The solidified bath crust is regularly broken at the feeding point by the point feeder to enable the additions of alumina or aluminum fluoride. This operation is completely mechanized and is done without opening the hoods, which reduces pollutant emissions to the atmosphere.

Molten aluminum is formed on the bottom of the cathode, below the surface of the cryolite bath. This process of conversion to metal occurs at a temperature of approximately 950°C, with the temperature being maintained by fine adjustment of the pot voltage. The electrolytic reduction of alumina (Al_2O_3) occurs as follows:

$$\mathbf{2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2}$$

The anode provides the carbon required for the reduction process. SO_2 emissions are released during consumption of the carbon to form the anode.

In each pot, the anodes consist of pre-baked carbon blocks connected to the electrical system by conductive rods. These anodes are suspended in the bath above the cathode, where they

are consumed in the conversion of alumina to aluminum, necessitating their regular replacement.

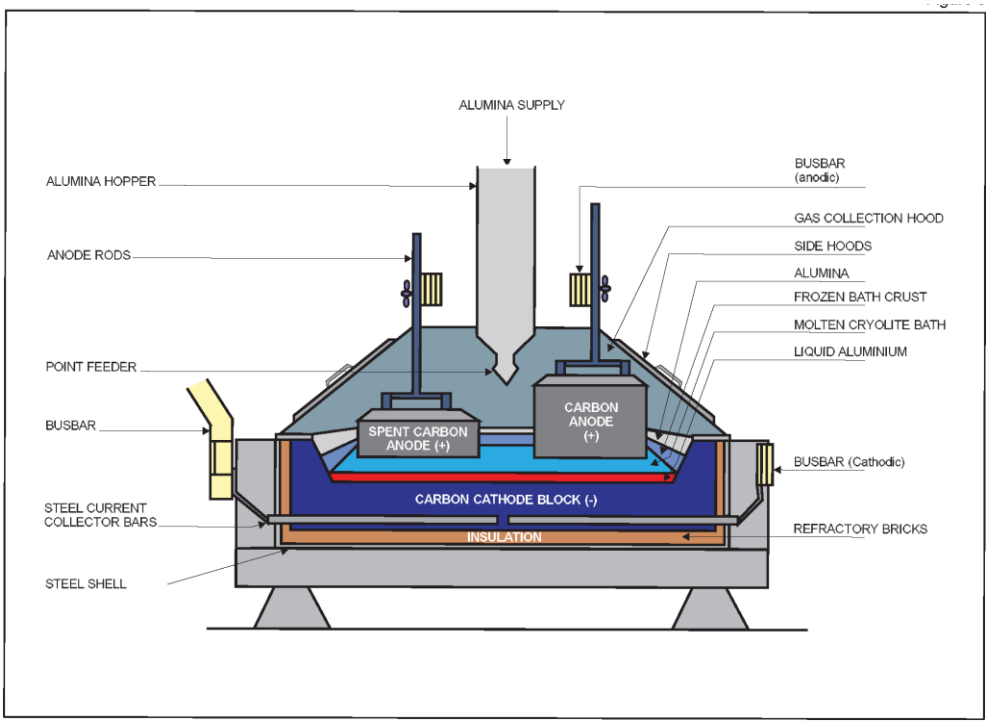


Figure 2.8-1: Schematic presentation of a pre-baked anode pot.

During the electrolytic process, particulates and gases are emitted. Emissions from the aluminum reduction process are primarily gaseous hydrogen fluoride (HF) and particulate fluorides, carbon dioxide (CO_2) and monoxide (CO), sulphur dioxide (SO_2) and perfluorocarbons. These emissions are collected and the HF treated by reacting the pot gases with fresh alumina to promote adsorption of HF onto alumina in the two Gas Treatment Centres (GTCs) for the pot rooms. The GTCs have bag filters to capture the fluorinated alumina and other particles emanating from the pots. There is one stack per scrubber unit with an open access platform to monitor emissions performance. Most of the fresh alumina is reacted in the dry scrubbers before subsequently being used as the principal raw material in the reduction pots. The GTCs are the primary emitters from the potrooms. The GTCs are similar in principle to the Fume Treatment Centre (FTC), except that the GTCs are larger and handle significantly more gas flow. The FTC also filters pitch fumes and carbon dusts.

2.8.2 The raw material challenge

Petroleum coke is a key strategic raw material for the primary aluminum industry. Coke is used as the carbon source for the anodes in the electrolysis process. Coke is a waste product from

the petroleum refinery industry – a residual product after the volatile fuels and oils have been distilled from crude oil. Although it is a waste product, coke provides value for other industries that require carbon sources, and that value is strongly influenced by global economic and market place conditions. The aluminum industry is sensitive to the quality of coke and only certain grades of coke are considered suitable for use in anodes to make aluminum. Anode grade coke supplies are under tight pressure and are declining in quantity and quality (due to impurities such as sulphur). The predicted shortfall of suitable coke is of concern because a shortfall would drive up coke prices and lead to process instabilities resulting from the use of lower coke grades.

2.8.2.1 Petroleum coke description

Coke is a process-residual formed at the tail end of the petroleum refinery or distillation process (Figure 2.8-2). Crude oil is heated in distillation columns to extract hydrocarbon liquids and vapors. The residual from the distillation process is a heavy oil, often referred to as a residual fuel oil. This oil is feedstock for the coking process that produces the end coke waste product. It is important to note that the coking process is not intended to produce coke; rather, it is a process to extract the last remaining light fuels from the residual oil. Coke produced from the refinery without going through a calcination process is referred to as green coke.

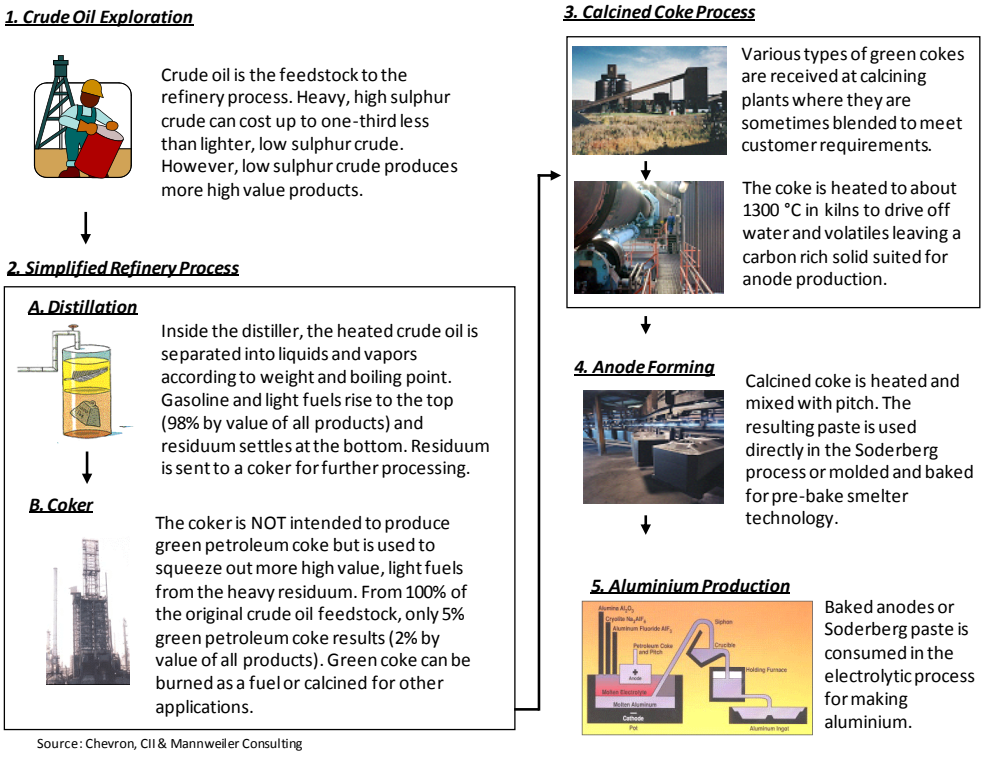


Figure 2.8-2: Product cycle – crude oil to aluminum.

Coking is a process that uses thermal decomposition of the heavy residual oil to extract residual hydrocarbons. The coking feedstock is heated to thermal cracking temperatures and pressures that create petroleum liquids and gas products. The material left over from the coking process is a concentrated carbon material that is referred to as green coke. There are three primary coking processes used by refineries - delayed, fluid, and flexicoking. The delayed process is a semi-continuous batch process. A fluid coker uses a fluidized bed process, while a flexicoker uses a variant of a fluidized bed to produce low heating value gas for use within the refinery. Delayed and fluid cokers produce different types of coke. Fluid cokers usually produce small spherical particles of coke that have low levels of remaining volatiles. Delayed cokers produce three different physical forms of coke – shot, needle, or sponge coke. The type of coke is dependent on the feedstock for the coking process. Shot coke essentially occurs as small hard spheres, while needle coke (also called acicular coke) has long crystalline needles. Sponge coke is a combination of needle and shot coke, and has an amorphous and aerated appearance. Anode grade coke has the structure and characteristics of sponge coke.

Green coke contains impurities of volatiles, moisture, metals (nickel and vanadium), ash and sulphur. To remove volatiles, moisture and some of the sulphur, green coke is calcined. Calcination is a process of heating the coke (normally) in a rotary kiln to 1,200 to 1,400^{o}C. This process drives off volatile hydrocarbons and moisture, and increases both the electrical conductivity and physical strength of the coke. The end calcined product is essentially a dense hard carbon product with high electrical conductivity.

2.8.2.2 Anode grade coke

The aluminum industry uses a very specific type and grade of coke. Coke that has the required qualities is referred to as anode grade coke. Anode grade coke must be calcined, and be produced from a delayed coking process that produces needle or sponge coke. The coke must also have low contents of nickel, vanadium, sulphur and ash. Properties of anode grade coke are presented in Table 2.8-1 below. Coke that varies from the anode grade range of properties can affect the calcination process, the smelting process, and/or the final aluminum metal quality.

Table 2.8-1: Anode grade coke properties (from API 2007).

Property	Anode grade quality acceptability range
Sulphur (wt%)	**1.7 to 3.8%** [a]
Ash (wt%)	**0.1 to 0.3%**
Nickle (ppm)	**165 – 350**
Vanadium (ppm)	**120 – 350**
Volatile matter (wt%)	**<0.25**
Real Density (g/cm^3)	**2.06**
Bulk Density (g/cm^3)	**0.8**

[a] Upper sulphur content specified by KMP.

2.8.2.3 Industry challenge with anode grade coke availability

The specific and limited range in acceptable quality and physical structure of anode grade coke creates a small market segment from which suitable coke can be procured. There are competing market forces within the global aluminum industry for access to anode grade coke, and there is competition for coke from other industries such as the steel and energy industries. Competition within the declining market space for anode grade coke has created shortages and has led to the use of marginal quality cokes with a greater range of properties (Edwards et al. 2012). Globally, there is a projected shortfall of anode grade coke available to the market. The imbalance in the supply of anode grade coke results in the use of the marginal cokes that contain higher sulphur and metal contents. Availability of anode grade coke is expected to be an ongoing challenge for the aluminum industry, despite the strong excess capacity to produce the calcined coke required by the industry.

Another challenge facing the anode grade market is a decline in the availability of low sulphur coke, which has reached a critical level for the aluminum industry. Sulphur levels in green coke blends increased by 40% between 1999 and 2007, and levels are continuing to rise. The sulphur levels are determined by the sulphur content in the crude oil used by the refineries. Refineries choosing low sulphur crude oil will produce low sulphur coke. Refineries that choose higher sulphur crude oil to lower their costs, or because they do not have access to low sulphur crude oils, will produce higher sulphur cokes. Most of the new sources of green coke have higher sulphur content than what was previously available. Trends in the growth of coke production do not support any significant growth in sustainably available low sulphur coke production.

As a consequence of refinery economics, many cokes that have been defined as high sulphur content cokes have further increased sulphur levels in addition to metals, especially vanadium.

Low sulphur content cokes are needed to balance this trend, but there is limited availability of low sulphur cokes worldwide.

Procurement and coke management practices have had to adapt to the new market conditions. Sourcing strategies have had to extend further afield than the traditional North American coke market. Sourcing has also had to extend to multiple refineries and coke calciners to obtain supplies of coke with different quality ranges that are blended to balance physical properties, metals impurities and sulphur content into an acceptable range for anode use. As coke is a waste product that does not contribute significantly to a refinery's bottom line, there is little incentive or ability for the aluminum industry to influence the coke quality available for making aluminum.

2.8.2.4 KMP coke requirements

KMP will require approximately 200,000 tonnes of coke per year. The project will utilize the full capacity of the existing calciner (approximately 80,000 t/yr) and the remainder will be procured and imported to Kitimat. As coke sulphur contents in green and calcined coke are trending upwards, there is an expectation that KMP will be using cokes with sulphur levels averaging 2.9% and ranging as high as 3.8%. KMP will use blending as a method of combining multiple cokes to produce an average coke blend that meets quality requirements for anode production.

2.9 SO_2 EMISSION SOURCES AND EMISSIONS FORECAST

SO_2 emissions are shaped by two factors: aluminum production and the petroleum coke market. The quantity of coke required by the smelting process is directly proportional to the quantity of metal produced, typically in the 0.4 to 0.5 range (the ratio of kg carbon per kg aluminum). The sulphur content is driven by market forces for the economically available coke that meets the strict criteria for aluminum smelting.

SO_2 emissions are projected to range between 33 t/d on smelter commissioning to an upper steady state average of 42 t/d (Figure 2.9-1). This technical assessment report is based on an application for 42 t/d SO_2, which is required to meet smelting capacity and coke market concerns (described in Section 2.8). The 42 t/d SO_2 limit is based on a 3.8% sulphur content in coke. The sulphur level in the blended calcined coke is expected to be approximately 2.9% on smelter commissioning. The timing for the trend for higher sulphur content in the coke is dependent on coke market and metal production conditions. The current SO_2 limit in the P2-00001 Multimedia permit is 27 t/d.

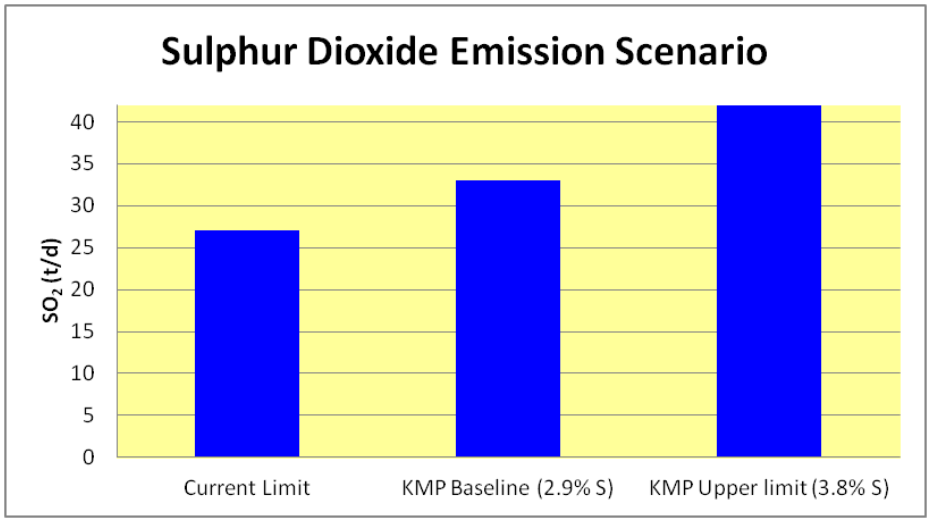


Figure 2.9-1: SO_2 emissions projection.

2.9.1 Primary SO_2 emission sources

There are three primary SO_2 emission sources for an aluminum smelter: the coke calciner, anode baking furnace, and potrooms. There are other minor sources of SO_2 (such as from fuel consumption) but these sources are trivial compared to the three primary sources. Table 2.9-1 presents an average breakdown of the main SO_2 sources for KMP.

Table 2.9-1: Average SO_2 emission contribution by source.

Source	Average SO_2 Contribution (%)
Anode Bake Furnace	5%
Coke Calciner	20%
Potrooms	75%

2.9.2 Sulphur mass balance

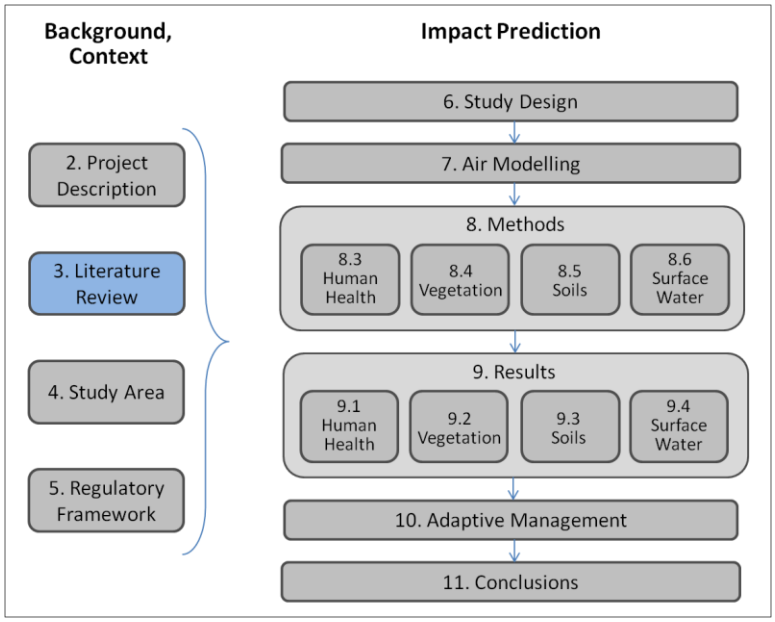
The chemistry of sulphur conversion and the consumption of petroleum coke are processes that are well understood, making it possible to report SO_2 emissions based on calculation rather than on direct measurement. Emissions are calculated using a branch of chemistry called stoichiometry, which deals with relative quantities of reactants and products in chemical reactions. This approach, however, tends to overestimate SO_2 emissions because, in practice, not all carbon is consumed in the process.

Plant-wide SO_2 emissions in tonnes per day (t/d) are calculated based on the mass fraction of sulphur in green coke, calcined coke, and pitch consumed in the carbon life cycle on a monthly basis. SO_2 emissions can be calculated from the following simple mass balance equation:

$SO_2 = (GC \times \%S_{GC} + CC \times \%S_{CC} + P \times \%S_P) \times 1.9981$ / days per month

Where GC is the green coke (t/month), S_{GC} is the average % sulphur content of the green coke, CC is the imported calcined coke (t/month), S_{CC} is the average % sulphur content in the calcined coke, P is the liquid pitch (t/month) and lastly, $\%S_P$ is the percent sulphur in the pitch. The equation is multiplied by 1.9981, which is the molecular weight ratio of SO_2 to S.

3.0 Sulphur Dioxide Literature Review



3.1 DESCRIPTION OF THE SOURCE-PATHWAY-RECEPTOR MODEL FOR SO_2 EMISSIONS

Conceptual models lie at the heart of both impact assessments and adaptive management studies. At an initial SO_2 permitting workshop held in Kitimat on February 6-7, 2012, participants developed a preliminary conceptual model, also called a source-pathway-receptor (SPR) model, to describe the ways in which SO_2 and acidic deposition affect the environment, biota, and human health. This preliminary model was subsequently revised, prior to, during and following a second workshop, held March 19-20, 2012 in Vancouver (Figure 3.1-1).

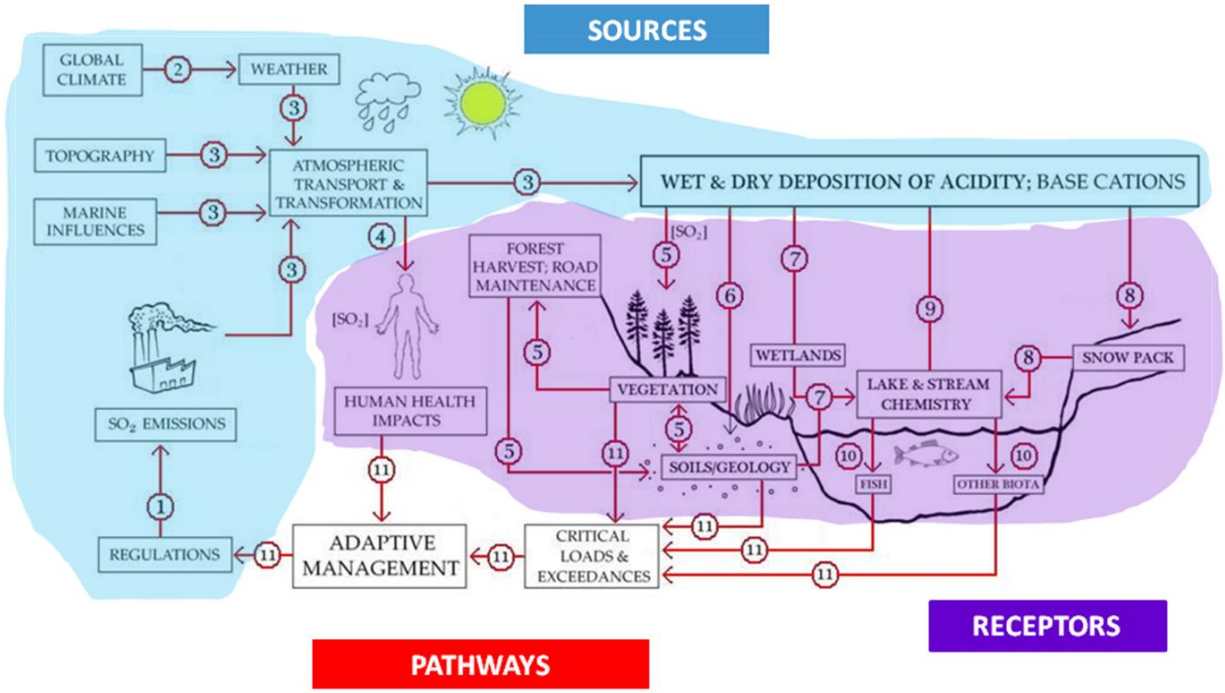


Figure 3.1-1: Conceptual (Source-Pathway-Receptor) model of SO_2 emissions in the environment, showing linkages between sources and receptors.

3.1.1 SO_2 Sources

Sulphur dioxide enters the atmosphere and ecosystem by way of both natural phenomena and anthropogenic activities. Natural sources include biological decomposition (e.g., organic acids), forest fires, volcanic eruptions, and marine influences (e.g., sea salt episodes). The burning of fossil fuels constitutes the single largest anthropogenic source of SO_2, accounting for about 70% of global emissions in 2005 (Smith et al. 2011). Other anthropogenic sources include international shipping (about 10%), biomass burning (<1%), metal smelting (about 13%), and certain industrial processes (about 6%) (Figure 3.1-2).

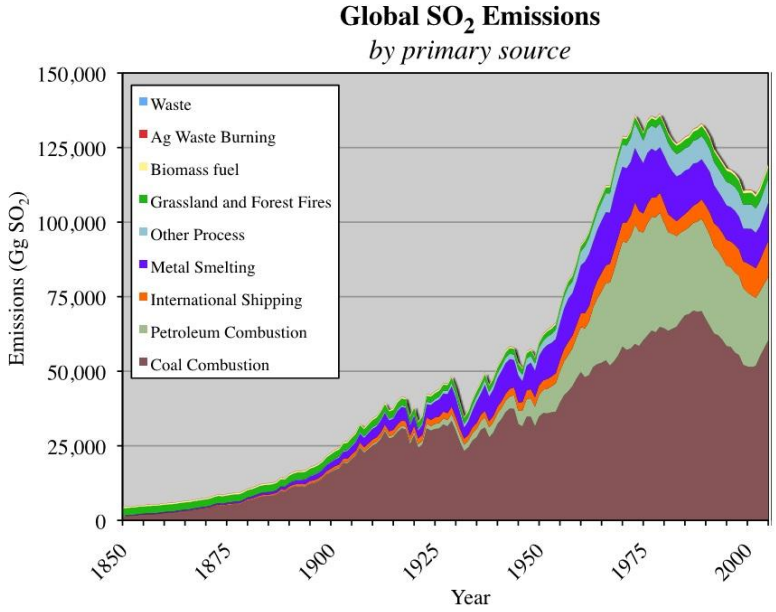


Figure 3.1-2: Trends in global SO_2 emissions from 1850 to 2005 (from Smith et al. 2011).

In the Kitimat Valley, the primary source of SO_2 is the Rio Tinto Alcan aluminum smelting operation (see Section 2.9). This SO_2 source is the primary focus of the source-pathway-receptor model and this technical assessment report, and the subject of Rio Tinto Alcan's application to amend its P2-00001 Multimedia Waste Discharge Permit. Smaller anthropogenic contributions of SO_2 arise from the shipping sector and from distant sources via atmospheric transport. Marine traffic is expected to increase in the Kitimat area as development there intensifies; the sulphur content of marine diesel fuel, however, is strictly controlled by Environment Canada to align with U.S. Environmental Protection Agency standards within the 200-mile North American Emission Control Area (Environment Canada 2012).

3.1.2 Pathways

The SPR conceptual model developed for this SO_2 technical assessment was used as an organizing framework for a literature review of surface water acidification and adaptive management (ESSA Technologies Ltd. 2012), and to guide the design of field and modelling studies conducted in 2012. Each of the eleven numbered pathways (links) in the conceptual model is briefly described in Table 3.1-1.

Table 3.1-1: Descriptions of links in the conceptual model of SO_2 in the environment (from ESSA Technologies Ltd. 2012).

Link #	Explanation of the Process
1	**Regulation of SO_2 emissions:** Local emissions of SO_2 coupled with any long-range transport of S and N oxides add S and N oxides to the air – the first step in the generation of acid rain, snow or mist. The level of regulation of SO_2 emissions affects how much acid rain, snow or mist is created.
2	**Global Climate:** Via its ultimate control of local precipitation and wind conditions, global climate has an overarching influence on the transport and transformation of SO_2. Under dry and cold conditions with stable winds, SO_2 may be transported long distances. Global climate also influences ocean temperatures and circulation, which in turn alter coastal and inland weather conditions including the occurrence and frequency of droughts and storms. Droughts can influence the movement of S through watersheds (see Link 7).
3	**Atmospheric transport and transformation/sea salt episodes and acidic deposition:** SO_2 emissions are transported and transformed in the atmosphere under the influence of local topography and weather (e.g., sun, wind, precipitation), combining with marine contributions of sea salt to determine the levels and spatial distribution of wet and dry acidic deposition.
4	**Human Health impacts:** Human health is vulnerable to S emissions in a number of ways: directly via inspiration of SO_2 or fine sulphate aerosols; and indirectly if increased lake sulphate levels or acidity increase the accumulation of mercury in fish or, in theory, levels of toxic metals in drinking water.
5	**Vegetation impacts/forest interactions:** Wet and dry deposition of acidity may: (1) increase the leaching of base cations from soils, thus reducing base cation availability to growing trees; (2) increase levels of porewater Al (and other metals) in forest soils to toxic levels; and (3) leach the calcium from conifer needles, increasing their vulnerability to injury during cold spells.
6	**Watershed acid neutralization/geology:** Acid deposition can be neutralized by processes occurring in the soil or underlying bedrock. Acid deposition increases the leaching of base cations that can lead to the long term acidification of soils, particularly at sites characterized by shallow, base-poor soils with low weathering rates. At sites with deeper soils, upper soil horizons may acidify but surface waters are protected from acidification by processes occurring deeper in soil or in bedrock. Most of coastal British Columbia has a relatively low ability to neutralize acidity, though with considerable local variation (see discussion in Section 4.3).
7	**Wetlands and organic acids:** Wetlands have diverse influences on watershed acidity;

Link #	Explanation of the Process
	they are sources of weak organic acids, which can contribute to freshwater acidity. These same weak organic acids, however, can also help to buffer strong acid inputs. Additionally, sulphate from acidic deposition can be temporarily stored in wetlands through a process called sulphate reduction. However, the acidity associated with this sulphur can be regenerated during droughts that lower water tables in wetlands and littoral zones of lakes.
8	**Acidic episodes, snowmelt and fall rains:** In areas of eastern North America with high levels of acidic deposition, there are three main kinds of acidic episodes: (1) snow meltwater flowing over still-frozen ground (particularly from rain on snow events); (2) extreme storm events during which watershed soils become saturated; and (3) fall rains following long, summer droughts during which reduced S is re-oxidized as water tables fall. In maritime regions there can be a fourth kind of acidic episode, sea salt events.
9	**Lake and stream chemistry:** Lake and stream acid-base chemistry largely reflects the base saturation or exchangeable base cation levels in watershed soils. Base cation levels depend largely on watershed geology (Link 6), coupled with the duration and intensity of local acid deposition which in turn is driven by emissions and transport of SO_2 on a continental scale.
10	**Acidification effects on biota:** Species of aquatic biota vary by more than a hundred-fold in their acid sensitivity, from species that can tolerate pH levels below 4, to those that are adversely affected as pH falls from 7 to 6. In general, as pH levels fall just below 6, damage occurs across all trophic levels of the food web, from fish to phytoplankton.
11	**Adaptive management/critical loads:** Adaptive management is a **systematic process** for continually improving management policies and practices by learning from the outcomes of operational programs. In the case of acidic deposition, monitoring and evaluating effects on ecosystem components (i.e., water, aquatic biota, soils, vegetation) and human health can lead to changes in the regulation of SO_2 emissions. Around the world acidic deposition is now usually managed by controlling so-called critical loads of S, i.e., by managing emissions of S into large regional airsheds so that its eventual deposition will not lower alkalinity of specified percentages of lakes (often 95%) in a region to the point where sensitive valued species (often salmonids) are damaged by acidity. In Canada, this is often interpreted as not lowering lake or stream pH below 6. Critical loads have also been developed for soils and vegetation.

The rate and distribution of acid deposition on the landscape is a function of the amount of SO_2 (and other compounds) emitted from local sources and deposited in various forms, plus the amount that is transported into the area from distant sources. A portion of SO_2 emissions gets

directly deposited on the land in gaseous form and as sulphur particles (dry deposition), and additional amounts get transformed in the atmosphere, via oxidation and hydrolysis, into sulphate-containing compounds (e.g., sulphuric acid) which fall to the earth in rain, snow and fog (wet deposition) (Saski et al. 1988; Hicks et al. 1993).

Acidification of the environment occurs along both direct and indirect pathways, depending on the receptor. Deposition of sulphur particles and exposure to SO_2 gas can directly impact human health and vegetation. Direct effects on human health spring from increases in SO_2 levels in the air which, at high concentrations for sensitive individuals, can lead to acute respiratory problems, increased risk of hospitalization, and higher health costs (Dales et al. 2006; Elliott et al. 2007; Li et al. 2007; Kassomenos et al. 2008; Min et al. 2008; Johns et al. 2010). There is also some evidence, at high levels of nitrogen oxide, carbon monoxide, and sulphur dioxide pollution, of a link between exposure and certain types of cancer (Vineis et al. 2006; Liaw et al. 2008). However, a review of human epidemiological studies by the Scientific Advisory Committee of the U.S. EPA (U.S. EPA 2008a) concluded that evidence for a causal link between SO_2 and cancer in humans was inconclusive. More detailed information about direct SO_2 effects on human health is presented in Section 3.4.

Acidic deposition may indirectly affect human health through bioaccumulation of metals in food, and contamination of drinking water (McDonald 1984). For example, mercury concentrations in fish tend to be highest in low pH waters, and they increase with increasing fish body weight (Watras et al. 1998; Hrabik and Watras 2002). In a study that experimentally acidified some small lakes in Northern Wisconsin, mercury concentrations in yellow perch (*Perca flavescens*) were over 40% higher at pH 5.5 (200 ng/g wet weight) than at pH 6.2 (140 ng/g wet weight) (Hrabik and Watras 2002) (Figure 3.1-3).

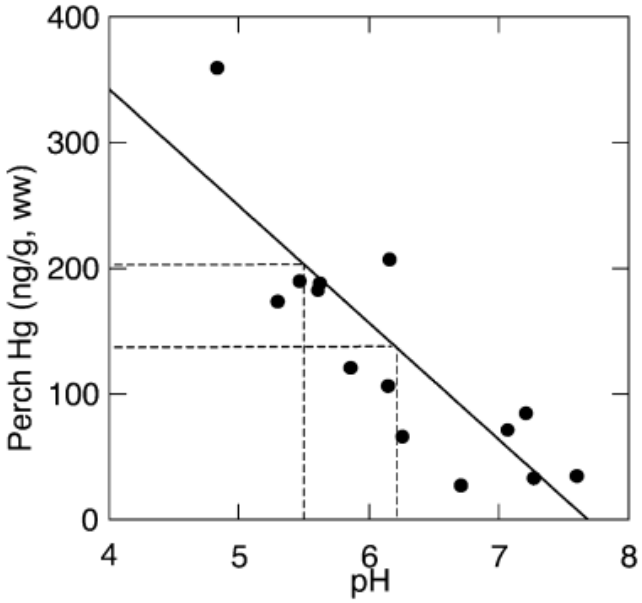


Figure 3.1-3: Relationship between pH and levels of mercury in fish tissue (after Hrabik and Watras 2002).

Health Canada has set the guideline for mercury in commercial fish for consumption at between 0.5 and 1.0 ppm (Health Canada 2007). These values equate to 500 ng/g and 1000 ng/g in fish tissue respectively, suggesting that fish from waters with pH 5.5 or greater are unlikely to accumulate mercury to levels that are harmful to human health.

Evidence also suggests that adverse health effects may arise from consumption of conventional foods (e.g., vegetables) and drinking water contaminated by toxic metals that have been mobilized by acid deposition (McDonald 1984; Middleton and Rhodes 1984; Gerhardsson et al. 1994). Metal solubility increases as pH declines, and many acidic surface waters have elevated concentrations of aluminum (Baker et al. 1990). Aluminum concentrations begin to rise at pH 6.0, but the largest increase occurs at levels below pH 5.5 (Figure 3.1-4).

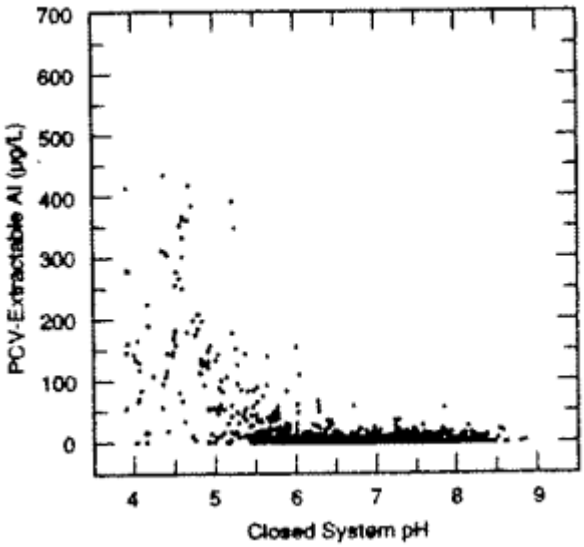


Figure 3.1-4: Relationship between pH and levels of inorganic monomeric aluminum in water (from Baker et al. 1990).

A health-based guideline for aluminum in drinking water has not been established in Canada (Health Canada 2003). However, industries are encouraged to keep residual aluminum levels in treated water as low as possible as a precautionary measure. Operational guidance values of less than 100 µg/L total aluminum for conventional treatment plants, and less than 200 µg/L total aluminum for other types of treatment systems, are recommended (Health Canada 2003). These values suggest that surface waters with pH 5.5 or greater are unlikely to contain aluminum concentrations that would be harmful to human health.

For these indirect effects of acidic deposition to affect human health, surface waters would need to acidify to pH 5.5 or less to mobilize metals and methylate mercury to an extent that exceeds current health standards. Additionally, the affected surface waters would need to be where people gather food, or where they draw water for drinking and/or growing food crops. By monitoring pH changes in lakes and streams, this technical assessment study can assess these risks to human health.

Direct effects of SO_2 on vegetation include the leaching of calcium, magnesium and potassium from leaves and branches (Cape 1993; Wulff et al. 1996; Likens et al. 1998; Horsley et al. 2000), which reduces cold tolerance (Likens et al. 1998), and leads to visible damage on leaf surfaces (Mohnen 1988; Driscoll et al. 2001a).

Vegetation can also be indirectly affected by SO_2 via acidic deposition. Indirect effects arise through altered soil processes. For example, acidification goes hand-in-hand with the decline of calcium in soils (Likens et al. 1998; Lawrence et al. 1999). Calcium is a macronutrient for trees (Lawrence et al. 1995, 1999) that is important for sustaining growth and productivity

(Watmough and Dillon 2003a,b,c). Calcium also contributes to the acid neutralizing capacity of soil and water (Lawrence et al. 1999), so its loss makes forest ecosystems increasingly sensitive to continuing inputs of acid (Likens et al. 1998). Acid deposition can also increase the concentration of aluminum in soil waters, lakes, and streams (Driscoll et al. 2001a). Elevated concentrations of aluminum in the soil can interfere with the functioning of fine tree roots, block the uptake of calcium, and result in decreased growth and increased susceptibility to stress (Mohnen 1988; Lawrence et al. 1995; Driscoll et al. 2001a).

Acidic deposition has indirect effects on lakes and streams via changes in water chemistry that occur over time. The degree of effect varies depending on the geology and physical characteristics of the watershed. Water chemistry in streams and lakes is vitally important to aquatic biota. Direct impacts to aquatic biota occur in response to reduced pH (e.g., impaired reproduction, increased mortality). A pH of less than 6.0 produces conditions that are damaging to many species (Keller et al. 1990; Havens et al. 1993; Holt et al. 2003). Indirect impacts to biota (both aquatic and terrestrial) arise from alterations in the food web that depress the productivity of prey animals and reduce their accessibility to predators.

3.1.3 Concepts of critical loads and exceedance

The term “critical load” can be 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).

In the context of acid deposition, “critical load” refers to the largest amount of acid that can be deposited in an ecosystem without having long term harmful effects on the environment. Different ecosystems will have different critical loads, depending on their sensitivity to acidity. If critical loads for a given area are relatively high, this means that the soils and/or waters can withstand higher levels of acid deposition without being harmed, relative to areas with low critical loads.

The *Canada-Wide Acid Rain Strategy for Post-2000*, signed by federal Ministers of Energy and Environment in 1998, sets a long-term goal of achieving the threshold of critical loads for acid deposition across Canada. The Strategy resolves to take steps over the long-term to solve the acid rain problem in eastern Canada, and to prevent one in western and northern Canada (Watmough et al. 2003).

Laws, regulations and permits can be used to try to ensure that actual loads stay below critical loads to prevent acidification. The challenge is that regulations control not what falls from the sky, but the emissions sent into it (Figure 3.1-1 and Table 3.1-1, Link 1). After sulphur particles are emitted into the air, a lot of different factors and processes affect how much gets deposited where (Figure 3.1-1 and Table 3.1-1, Links 2-4). Once deposited on the landscape (i.e., on water,

soil, snow, trees, etc.), more factors and processes affect how ecosystems will change, and by how much (Figure 3.1-1 and Table 3.1-1, Links 5-10).

The relationships between sulphur emissions and the responses of both humans and ecosystems are not well understood. A careful, structured decision-making approach like adaptive management can help reduce uncertainties and lead to more effective emission regulations (Figure 3.1-1 and Table 3.1-1, Link 11). As part of the Kitimat Modernization Project, research has been done to determine how sensitive the ecosystems in the area are to these processes, and how much deposition – i.e., the "critical load" – they can withstand before harmful effects occur, e.g., declining species diversity with increasing acidity (pH <6). This work included identifying the physical and chemical characteristics of the soils and surface waters in areas exposed to SO_2 emissions from the Kitimat smelter in order to determine their sensitivity and, ultimately, some critical load estimates (see Section 9.3.1 and Section 9.4.1).

3.2 PHYSICAL AND CHEMICAL PROPERTIES OF SULPHUR DIOXIDE

Sulphur dioxide is a very stable chemical compound with the formula SO_2, and the structure O=S=O. Its physical state can be gaseous, liquid, or solid (Hasenberg 2008). SO_2 can be liquefied under moderate pressure at room temperature, and the liquid form can be frozen at -73 ^{o}C or boiled at -10 ^{o}C under normal atmospheric pressure (Encyclopedia Britannica 2012).

With a specific gravity of 2.264, SO_2 gas is more than twice as dense as air. It is colourless and non-combustible, and it has a pungent, irritating odour. Sulphur dioxide is readily soluble in water, and solubility increases with increasing pressure and decreasing temperature. SO_2 is also soluble in aqueous solutions of alkali metal compounds, which can absorb considerably more than pure water because of the formation of bisulfite and sulfite ions.

Some physical and chemical properties of sulphur dioxide are summarized in Table 3.2-1.

Table 3.2-1: Properties of sulphur dioxide (from WBK & Associates Inc.).

Property	Value	Reference
Molecular weight	64.065	Lide 2002
Physical state	Colourless gas	Lide 2002
Melting point	-75.5 °C	Lide 2002
Boiling point	-10.05 °C	Lide 2002
Specific gravity (liquid)	1.50	RSC 1999
Specific gravity (gas) (air = 1)	2.26 (at 0 °C)	Genium 1999; RSC 1999
Vapour pressure	338 kPa (at 21 °C)	RSC 1999
Solubility in water	17.7% (at 0 °C)	Genium 1999

Property	Value	Reference
Acid/Base properties	dissolves in water to form a slightly less aqueous solution of H_2SO_3	Weil and Sandler 1997; Genium 1999
Henry's Law constant	1.42 mol/L/atm (at 25 °C)	Berresheim et al. 1995
Odour threshold in air	0.1 to 3 ppm	Genium 1999
Conversion factors for vapour (at 25 °C and 101.3 kPa)	1 ppm = 2.62 mg/m^3	IARC 1992

3.3 CHEMICAL TRANSFORMATIONS OF SULPHUR DIOXIDE IN THE ATMOSPHERE AND ENVIRONMENT

Sulphur dioxide (SO_2) is transformed in the atmosphere by oxidation and hydrolysis into sulphate-containing aerosol particles (Likens et al. 1979; Mohnen 1988; Saski et al. 1988; Irving 1991; Alebic-Juretic 1995; Galloway 2001), and falls to earth via wet deposition as acidic rain, snow and fog (Saski et al. 1988; Hicks et al. 1993). Sulphuric acid (H_2SO_4) is the predominant acid in acidic precipitation (Environment Canada 2010). Atmospheric deposition of sulphate (SO_4) in kilograms per hectare (kg/ha) is a measure of the input of this acid to the environment. Sulphur dioxide also contributes directly to the environment's sulphate burden through dry deposition of SO_2 gas, which quickly converts to sulphate (SO_4^{2-}) in the presence of water and oxygen (Seung-Muk et al. 1997; Tasdemir and Gunez 2006).

Oxidation of SO_2 in the atmosphere can occur in a gaseous phase, in the aqueous phase of raindrops, on the surfaces of carbon particles (soot), or combinations of all three (Bunce 1994, in WBK & Associates Inc. 2003). Soot-catalyzed oxidation of SO_2 can be a dominant mechanism under certain atmospheric conditions (Chang and Novakov 1978), and converts to sulphuric acid in the presence of oxygen and liquid water (Wilson 1978). The rates of SO_2 oxidation in the atmosphere are influenced by light conditions, humidity, and temperature (Finlayson-Pitts and Pitts 1986, in WBK & Associates Inc. 2003; Khoder 2002), with oxidation rates tending to be higher in the summer than in the winter, and higher at mid-day that at night. No matter the season, weather conditions (rain vs. sun vs. fog) can determine which of the pathways is dominant (see Link 3 in Figure 3.1-1). For example, gaseous phase conversion is dominant during clear, dry conditions (Calvert et al. 1978).

The conversion reaction is played out in the troposphere, the lowest 10 or 12 kilometers of the atmosphere (Mohnen 1988). Gaseous phase oxidation of SO_2 begins when a photon of sunlight strikes a molecule of ozone (0_3), resulting in a molecule of oxygen (0_2) and a lone, highly reactive oxygen atom (O). The oxygen atom combines with a water molecule (H_2O) to form two hydroxyl molecules (OH^-). The concentration of the hydroxyl molecule in the atmosphere is less than one part per trillion, but several of the oxidation processes it triggers end up regenerating

it. Consequently, the reaction is not limited by the amount of hydroxyl molecule; only the amount of pollutant in the air determines how much acid is ultimately produced (Mohnen 1988).

Gaseous phase oxidation of SO_2 is initiated by reaction with OH^-:

$$SO_2 + OH^- (+ M) \rightarrow HSO_3^- + M$$

where M is another molecule (e.g., N_2, O_2 or H_2O in air) that serves to carry excess energy away from the reaction (Calvert and Stockwell 1984, in WBK & Associates Inc. 2003). The HSO_3^- molecule eventually leads to the formation of sulphuric acid aerosol (Calvert et al. 1978; Mohnen 1988). The most common pathway for this conversion involves two reactions (Dillon 2012):

$$HSO_3^- + O_2 \rightarrow SO_3^{2-} + HO_2^+$$

$$SO_3^{2-} + H_2O \rightarrow H_2SO_4$$

Other gaseous phase oxidation processes occur, but their importance is negligible compared to the reaction with the OH^- molecule (Calvert and Stockwell 1984, in WBK & Associates Inc. 2003).

Aqueous phase conversion of SO_2 occurs in solution, in cloud droplets, in fog, on moist surfaces of plants and soil, and at the surface of water bodies (Calvert and Stockwell 1984, in WBK & Associates Inc. 2003). The major route for this reaction (Dillon 2012) can be written as follows:

$$SO_2 + ½O_2 \text{ (dissolved)} + H_2O \rightarrow H_2SO_4$$

These reactions involve the dissolution of SO_2 into aqueous solution to form H_2SO_3, which is rapidly oxidized by molecular oxygen to form H_2SO_4. This process is probably more important than the gas-phase photochemical reaction, particularly when it occurs in the presence of catalysts that speed up the chemical reaction (Kellogg et al. 1972). Examples of catalysts include ammonium (NH_4^+) and certain metal ions (Friend 1973, in WBK Associates Inc. 2003). The catalysts may be present as part of the particulate matter in the air, and may serve as nuclei on which cloud drops form (Kellogg et al. 1972; Mohen 1988).

Another route for aqueous phase oxidation of SO_2 involves atmospheric hydrogen peroxide (H_2O_2) (Radojevica 1983). The chemical reaction is typically written as:

$$H_2O_2 + SO_2 \rightarrow H_2SO_4$$

The mechanism is uncertain (Bunce 1994, cited in WBK & Associates 2003), but the reaction is known to be affected by pH. Modelling work by Seinfeld and Pandis (1998, cited in WBK &

Associates 2003) suggests that oxidation by dissolved H_2O_2 is predominant at pH values less than 4 or 5.

3.4 HEALTH RISKS ASSOCIATED WITH SO_2

Sulfur dioxide (SO_2) is a colourless gas. Inhaled SO_2 and its reaction products can stimulate chemosensitive receptors in the tracheobronchial tree and initiate a reflexive contraction of smooth muscles in the bronchi (bronchoconstriction). Activation of these receptors can also cause cough, rapid shallow breathing and potentially affect the cardiovascular system causing changes in pulse rate and blood pressure (U.S. EPA 2008).

Two sources of information were used to identify health outcomes causally linked with environmental exposure to SO_2:

- An integrated Science Assessment for Sulfur Dioxide by the Scientific Advisory Committee of the United States Environmental Protection Agency (U.S. EPA 2008), the most recent authoritative review of scientific literature on potential health effects of exposures to ambient SO_2; and
- Scientific literature published after the U.S. EPA review.

The U.S. EPA review covers scientific literature up to early 2008. A search for recent literature (published between 2008 and the end of October, 2012) was performed using the PubMed database of the U.S. National Library of Medicine. The material below also provides details of some studies conducted in Canada, even if they were previously reviewed by the U.S. EPA. Additionally, a separate literature review was conducted with respect to the potential for a synergistic relationship between SO_2 and cold temperatures.

3.4.1 Data from the review of the Scientific Advisory Committee of the U.S. EPA

The Scientific Advisory Committee of the U.S. EPA has considered scientific evidence for health effects of short-term and long-term exposure to SO_2. Exposure from several minutes to days was considered as short term, and exposure usually averaged over months or years was considered as long-term. The Committee defined three categories for the weight of evidence: inadequate to infer a causal relationship, suggestive but not sufficient, and sufficient. The Committee has concluded that the scientific evidence is “inadequate to infer the presence or absence of a causal relationship” between:

- short-term SO_2 exposure and cardiovascular morbidity;
- long-term SO_2 exposure and respiratory morbidity, non-respiratory morbidity, mortality.

The Committee has found the evidence to be “suggestive but not sufficient to infer a causal relationship” between short-term exposure to SO_2 and mortality. This “suggestive” evidence came from epidemiological studies that reported associations between increasing ambient SO_2

concentrations and mortality from all causes and from specific causes. The U.S. EPA has 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.

According to the Scientific Advisory Committee, the evidence is "sufficient to infer a causal relationship" for short-term exposure to SO_2 and respiratory morbidity. The key evidence for this conclusion came from human clinical studies. In human clinical studies, volunteers were exposed to SO_2 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 minute duration) to SO_2 at concentrations from 1,048 to 1,572 µg/m^3 (0.4 to 0.6 ppm).[2] Physical exercise was used in these experiments to increase the lung ventilation rate and, as a result, SO_2 uptake. Some asthmatic subjects (5-30%) experienced decreases in lung function at SO_2 concentrations from 524 to 786 µg/m^3 (0.2 to 0.3 ppm). In clinical studies of exercising individuals without asthma, decreases in lung function were observed only at SO_2 concentrations greater than 2,620 µg/m^3 (1.0 ppm). Based on these findings, the Committee has concluded that subjects with asthma are a population particularly sensitive to the respiratory effects of SO_2. Supporting evidence for a causal relationship between short-term exposure to SO_2 and respiratory morbidity came from epidemiologic 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. Results from animal experiments were used to support observations from human studies.

3.4.2 Evidence from recent literature

Evidence from literature published after the U.S. EPA review is generally consistent with the conclusions made by the Scientific Advisory Committee. Information summarized in the following sections will substantiate this statement. Presentation of recent data starts with health outcomes for which, according to the U.S. EPA, the evidence is "inadequate" for causal inference (short-term SO_2 exposure and cardiovascular morbidity, short-term exposure and morbidity other than respiratory or cardiovascular, potential effects of long-term SO_2 exposure), followed by outcomes for which the evidence is "suggestive" of causality (short-term exposure to SO_2 and mortality). Finally, data on short-term SO_2 exposure and respiratory morbidity (the only established causal link) are presented.

3.4.2.1 Short-term SO_2 exposure and cardiovascular morbidity

Several studies examined various physiological indicators of cardiovascular health, such as electrocardiographic parameters, pulse rate, heart rate variability (HRV). HRV is a measure of

[2] The conversion factor used in Sections 3.4.1, 3.4.2, and 3.4.3 was 1 ppm = 2,620 µg/m^3 at 25°C and 1 atm (see http://www.scribd.com/doc/69355960/Air-Dispersion-Modeling-Conversions-and-Formulas).

cardiovascular autonomic control. Its reduction was reported in several cardiovascular diseases. Huang and colleagues (Huang et al. 2012) studied a group of 40 non-smoking patients with cardiovascular diseases and observed significant decreases in HRV associated with increased levels of air pollutants other than SO_2 in Beijing, China. No effect of SO_2 was seen. Mean values of hourly average SO_2 concentration ranged from 6.3 to 29.3 µg/m^3. Min and co-authors (Min et al. 2009) analysed associations between HRV and air pollution over 72 h in 1,023 Korean volunteers. Exposure to SO_2 (levels are not reported) was associated with reduced HRV indices in smokers but not in non-smokers. The effect was short and transient, largely observed within 12 h. Goldberg and co-workers (Goldberg et al. 2008) measured pulse rate and oxygen saturation in 31 individuals with congestive heart failure in Montreal. Daily average SO_2 concentration lagged 1 day (interquartile range 8.6 µg/m^3) was significantly positively associated with pulse rate and significantly negatively associated with oxygen saturation. Pulse rate or oxygen saturation was not significantly associated with SO_2 concentration lagged 0 days or with 3-day mean SO_2 concentration. Baja and colleagues (Baja et al. 2010) found that SO_2 was not significantly associated with changes in QT interval[3] on the electrocardiogram of 580 men – participants of the Veterans Affairs Normative Aging Study (USA). Mean SO_2 concentration during or 10 h before electrocardiography was 13.6 µg/m^3.

Blood pressure

Chen and co-authors (Chen et al. 2012) analysed associations between air pollution and blood pressure in 9,238 non-smoking adults >30 years of age from 6 townships in Taiwan. Daily average SO_2 concentrations (mean values) ranged from 5.0 µg/m^3 in Puli to 18.1 µg/m^3 in Renwu. Diastolic blood pressure significantly increased, systolic blood pressure significantly decreased and pulse blood pressure (the difference between the systolic and diastolic pressures) significantly decreased with increasing SO_2 concentrations. The analyses were adjusted for important determinants of blood pressure but not for other pollutants.

Changes in SO_2 concentrations were not significantly associated with changes in blood pressure in a longitudinal study of 40 non-smoking patients with cardiovascular diseases in Beijing (Huang et al. 2012) (see data on heart rate variability from this study above).

Blood markers of cardiovascular risk

Several groups of authors examined blood markers of cardiovascular risk. Bruske and colleagues (Bruske et al. 2011) found some associations between SO_2 (mean daily average concentration 3.0 µg/m^3, range 2.0 to 8.9 µg/m^3) and plasma concentrations of lipoprotein-associated phospholipase A2 in 200 survivors of myocardial infarction in Augsburg, Germany. Thompson and colleagues (Thompson et al. 2010) reported that interleukin-6, a marker of inflammation, was linked with increased ambient SO_2 concentrations in 45 healthy adult non-smoking

[3] QT interval is an electrocardiographic marker of ventricular repolarization.

individuals in Toronto. No similar link was seen for fibrinogen, another marker of inflammation. The associations reported in these two studies were inconsistent: they were seen for SO_2 concentrations averaged over some periods before the measurements but not for other averaging periods. Mean values of daily average SO_2 concentration ranged from 7.7 µg/m^3 in summer to 12.0 µg/m^3. Steinvil and co-authors (Steinvil et al. 2008) studied possible effects of short-term exposure to air pollutants on biomarkers of inflammation in 3,659 healthy participants (2,203 males and 1,456 females) from the Tel-Aviv Sourasky Medical Center inflammation survey. A statistically significant negative correlation was seen in male participants between SO_2 (mean concentration 7.3±1.3 µg/m^3) and fibrinogen. No associations were found for C-reactive protein or white blood cells in males. No significant associations were found in females.

Myocardial infarction and stroke

Several recent studies examined potential links between ambient SO_2 concentrations and the incidence of stroke and myocardial infarction, fatality among patients with these diseases, mortality among myocardial infarction survivors, and hospital admissions for myocardial infarction.

Turin and co-workers (Turin et al. 2012a) studied the incidence of stroke and acute myocardial infarction in Takashima County, Japan. Full text for this article is not available. Based on the abstract, no association was seen between SO_2 and the incidence of acute myocardial infarction in single- or two-pollutant models. SO_2 was associated with the risk of cerebral hemorrhage but not with the risk of other stroke subtypes.

The same group of authors (Turin et al. 2012b) analysed acute case fatality (within 28 days) of stroke and acute myocardial infarction. In the multi-pollutant model, higher SO_2 levels were not associated with increased fatality risk for acute myocardial infarction, stroke or different subtypes of stroke (cerebral infarction, cerebral hemorrhage). The median value of daily average SO_2 concentration was 9.2 µg/m^3, interquartile range 5.6 µg/m^3.

Berglind and colleagues (Berglind et al. 2009) studied all causes of non-trauma mortality and cardiovascular mortality in 25,006 myocardial infarction survivors in five European cities. Mean values of daily average SO_2 levels ranged from 2.61 µg/m^3 in Stockholm to 11.00 µg/m^3 in Barcelona. Daily non-trauma mortality was significantly associated with an increase in SO_2 concentration averaged over 15 days. No significant associations were seen with 2-day average or with 5-day average SO_2 concentrations. Cardiovascular mortality among the myocardial infarction survivors was evaluated only in relation to a 2-day average SO_2; no significant association was seen.

Bhaskaran and co-authors (Bhaskaran et al. 2009) conducted a systematic review of studies on air pollution and the incidence of myocardial infarction. They identified 10 studies on short-term effects of SO_2. Four studies showed a significant association while six did not.

Cheng and colleagues (Cheng et al. 2009) analysed hospital admissions for myocardial infarction in Kaohsiung, Taiwan. The mean value of daily average SO_2 concentration was 24.3 µg/m^3, ranging from 2.4 to 81.8 µg/m^3. In a single-pollutant model, there was a significant association between SO_2 concentrations and hospital admissions on cool days but not on warm days. There was no significant association after adjustment for particulate air pollution or for carbon monoxide (warm or cool days). After adjustment for NO_2, a significant negative association was seen on cool days.

Hsieh and colleagues (Hsieh et al. 2010) analysed hospital admissions for myocardial infarction in Taipei, Taiwan. Single-pollutant analysis stratified by air temperature with a cut-off at 23°C showed no significant associations with SO_2 concentrations either on "cool" days or on "warm" days. Daily average SO_2 concentrations ranged from 0.34 to 46.6 µg/m^3, with a mean of 11.4 µg/m^3.

Cardiac arrhythmias and cardiac arrests

Anderson and colleagues (Anderson et al. 2010) analysed activations of implantable cardioverter defibrillators among patients attending nine implantable-cardioverter-defibrillator clinics in London National Health Service hospitals. There was a positive but not statistically significant association with 24-h average SO_2 concentrations (mean 2.71 µg/m^3, 95th percentile 7.0 µg/m^3).

Dennekamp and co-authors (Dennekamp et al. 2010) studied air pollution and out-of-hospital cardiac arrests of cardiac etiology (i.e., not precipitated by non-cardiac events such as trauma, poisoning, terminal illness) in Melbourne, Australia. There was no clear relationship between out-of-hospital cardiac arrests and SO_2 concentrations with any lag period in a single-pollutant model. SO_2 was not included in two-pollutant modelling because of its "extremely low" concentrations (mean value of daily average concentration 1.3 µg/m^3, 75th percentile 2.0 µg/m^3).

Emergency department visits/hospital admissions for cardiovascular diseases

Nineteen recent articles on air pollution and emergency department visits/hospitalizations for cardiovascular diseases have been identified. Some of these studies consider all cardiovascular diseases as a group, others consider specific diseases within this group. Eleven studies were conducted in Asian cities. Full text is available for 14 studies. For five studies, only the abstract is available; four of these provide some information regarding SO_2. When pollutants other than SO_2 were not accounted for in the analysis, statistically significant positive associations between SO_2 concentrations and cardiovascular diseases were reported in 10 studies; no significant

association was seen in eight studies. In nine studies, both single-pollutant and multi/two-pollutant analyses were performed. Three of these studies did not find any link between SO_2 and hospitalizations/emergency department visits in either type of analysis; one study showed such a link in both analyses. In four studies, a significant positive association seen in a single-pollutant model was reduced and lost statistical significance in two- or multi-pollutant models. In some studies, the association became significantly negative.

Two of the 19 studies were conducted in Canada. Stieb et al. (2009) analysed emergency department visits for angina/myocardial infarction, dysrhythmia/conduction disturbance and heart failure in seven Canadian cities (Montreal, Ottawa, Edmonton, Saint John, Halifax, Toronto and Vancouver). In a single-pollutant analysis, a 13.4 µg/m^3 increase in SO_2 concentration lagged 1 day was associated with a 2.1% increase (95% CI: 0.2%, 4.0%) in emergency department visits for angina/myocardial infarction. No significant increase in emergency department visits for angina/myocardial infarction was associated with increased SO_2 concentration lagged 0 or 2 days. SO_2 concentrations (any lag) were not significantly linked with emergency department visits for dysrhythmia/conduction disturbance or for heart failure. In a single-pollutant analysis of data on emergency department visits for ischemic stroke in Vancouver, Szyszkowicz and co-authors (Szyszkowicz et al. 2012) found a significant positive association with SO_2 concentrations lagged 0 days in female patients. No significant associations were seen for longer lags in female patients or for any lag in male patients. In two-pollutant analyses of all patients, emergency department visits for ischemic stroke were significantly positively linked with SO_2 concentrations after adjustment for O_3 (lag 3 days) and for CO (lag 3 days). After both O_3 and CO were included in the model, the link was still significant. Results of analyses adjusted for other co-pollutants ($PM_{2.5}$, PM_{10}, and NO_2) are not reported. Mean SO_2 concentration in this study was 6.6 µg/m^3 (SD 1.5 µg/m^3).

In summary, recent studies on short-term SO_2 exposure and cardiovascular morbidity do not show a consistent pattern that would suggest a causal link.

3.4.2.2 Short-term SO_2 exposure and morbidity other than respiratory or cardiovascular

Two studies report on eye problems, ocular signs and symptoms (Camara and Lagunzad 2011) and an increase in outpatient visits for non-specific conjunctivitis (Chang et al. 2012), associated with short-term exposure to SO_2. SO_2 levels in Camara et al. (2001) ranged from ~2.6 to ~10.5 µg/m^3. Daily average SO_2 concentrations reported by Chang et al. (2012) varied by season and area from 5.2 µg/m^3 (Hua-Tung, summer) to 23.1 µg/m^3 (Kao-Ping, winter). In these studies, it is not clear whether the observed effects can be attributed to SO_2 or to other pollutants.

Cakmak and colleagues (Cakmak et al. 2010) reported a significant effect of SO_2 on daily number of hospitalizations for epilepsy in seven urban centers in Chile. Mean daily average SO_2

level ranged from 15.6 µg/m^3 in Las Condes to 29.3 µg/m^3 in El Bosque. The effect estimate lost statistical significance when other pollutants were accounted for in the analysis.

Dales and co-authors (Dales et al. 2010) found a significant link between ambient SO_2 and hospitalizations for venous thrombosis and pulmonary embolism in the same seven Chilean municipalities. The effect on venous thrombosis lost statistical significance in the multi-pollutant analysis, but the effect on pulmonary embolism remained significant.

The same group of researchers (Dales et al. 2012) found that increases in SO_2 were associated with increased numbers of hospital admissions for acute diabetic complications in the Chilean cities; the effect remained significant after adjustment for other pollutants.

Vidotto and colleagues (Vidotto et al. 2012) showed a significant association between SO_2 (mean daily average 44.81 µg/m^3, range 9.62 to 168.98 µg/m^3) and hospital admissions for acute outbursts of rheumatic diseases in children and adolescents in Brazil. The authors suggested, however, that SO_2 could be functioning as a marker of particulate air pollution: fine and ultrafine particles were not measured.

Kaplan and co-workers (Kaplan et al. 2009) saw a significant positive relationship between daily average SO_2 concentrations (levels not reported) and the incidence of appendicitis in the Calgary Health Region, Canada; the relationship lost statistical significance in two-pollutant analyses.

Orazzo and co-authors (Orazzo et al. 2009) demonstrated an increasing trend in emergency department visits for gastroenteric disorders among 0 to 2-year old children in six Italian cities. Mean values of daily average SO_2 ranged from 5.5 µg/m^3 in Florence to 21.1 µg/m^3 in Naples. Multi-pollutant analysis was not performed.

One study (Szyszkowicz et al. 2009a) suggests a link between SO_2 and depression in a multi-city study in Canada. Mean SO_2 level ranged from 6.5 µg/m^3 in Vancouver to 26.2 µg/m^3 in Halifax. Two studies (Szyszkowicz et al. 2010; Yang et al. 2011) demonstrated a statistical association between SO_2 and the risk of suicide. The study by Szyszkowicz et al. (2010) was conducted in Vancouver; mean value of daily average SO_2 was 16 µg/m^3. Yang et al. (2011) studied monthly average deaths by suicide in Taipei, Taiwan; median monthly average SO_2 was 12.3 µg/m^3.

Zhao and colleagues (Zhao et al. 2011) found a significant effect of ambient SO_2 concentrations (mean 51.67 µg/m^3) on the daily numbers of preterm births in single- and multi-pollutant analyses in Guangzhou city, China.

The associations between SO_2 and health outcomes described above were examined in one or two studies each. Most studies have methodological limitations. No inferences regarding causality can be made on the basis of the limited information.

Nine studies examined possible links between SO_2 exposure and migraine/other headaches. Six of these studies were performed by the same research group in different Canadian cities. All Canadian studies employed a single-pollutant analysis. In Edmonton (Szyszkowicz et al. 2009b) and in a multi-city study including Edmonton, Halifax, Ottawa, Toronto, Sunnybrook and Vancouver (Szyszkowicz et al. 2009c), significant increases associated with increased SO_2 concentrations were seen in the daily numbers of emergency department visits for migraine but not for other headaches. In Ottawa (Szyszkowicz 2008a) and in Montreal (Szyszkowicz 2008b), only emergency department visits for headaches other than migraine were studied and a significant effect of SO_2 was found in both cities. In Toronto (Szyszkowicz and Porada 2012) and in Vancouver (Szyszkowicz et al. 2009d) only emergency department visits for migraine were analysed and significant associations with SO_2 were found in both cities. Mean values of daily average SO_2 concentrations in the Canadian cities ranged from ~6.5 to ~26 µg/m^3. Since no multi-pollutant analyses were performed in these studies, interpretation of their findings is complicated. Three studies were conducted by other researchers in other countries. Two studies used single-pollutant analyses. One study in Boston (USA) found no association between SO_2 concentrations (mean 9.4 µg/m^3) and emergency department visits for migraine or other headache (Mukamal et al. 2009). The other study found such an association at higher exposure levels in Hawaii (up to 196 µg/m^3 during increased volcanic emissions) (Longo et al. 2010). SO_2 was significantly positively associated with hospitalizations for migraine and non-migraine headaches in a multi-city study in Chile (Dales et al. 2009). Mean SO_2 levels ranged from 15.6 to 29.3 µg/m^3 in different cities. The associations lost statistical significance in analyses adjusted for other pollutants.

In conclusion, information on potential health effects of short-term exposure to SO_2 other than respiratory or cardiovascular diseases is insufficient for making causal inferences.

3.4.2.3 Potential health effects of long-term SO_2 exposure

Sixteen recent studies exploring outcomes relevant to respiratory health have been identified.

Respiratory health: asthma and asthma symptoms

Asthma and asthma symptoms in relation to SO_2 were addressed in 10 studies, nine of them in children and one in older adults (≥65 years of age). Rusconi and colleagues (Rusconi et al. 2011) found that children living in a polluted area in Italy were more likely to have asthma symptoms than children living in a non-polluted area. Since no analyses by levels of specific air pollutants were performed, this study is not informative regarding SO_2 effects on asthma.

Of the remaining eight studies, six show significant positive associations between SO_2 levels and prevalence of asthma/asthma symptoms in a single-pollutant analysis. In one of the six "positive" studies (Zhao et al. 2008a), both indoor and outdoor pollutant concentrations were considered: significant associations with asthma symptoms were seen only for indoor SO_2 levels

which ranged from 60 to 641 µg/m^3 (samples were taken in winter, from school rooms that lacked mechanical ventilation). Outdoor levels ranged from 476 to 1,015 µg/m^3. Deger et al. (2012) found no significant link between modelled annual average SO_2 level and prevalence of active asthma in children in Montreal: prevalence ratio 1.14 (95% CI: 0.94 to 1.39). The association between SO_2 and "poor asthma control" was marginally significant: prevalence ratio 1.39 (95% CI: 1.00 to 1.94). Modelled annual average SO_2 levels ranged from 11.5 to 14.1 µg/m^3.

Multi-pollutant modelling was performed in two Chinese studies. In one study (Dong et al. 2011), analyses were stratified by gender and allergic predisposition. Significant positive association between SO_2 (3-year average 50 µg/m^3) and asthma seen in a single-pollutant analysis was reduced and no longer significant in children of both sexes without allergic predisposition and in males with allergic predisposition. Significant associations between SO_2 (4-year mean from 14 to 140 µg/m^3 in different districts of different Chinese cities) and asthma/asthma symptoms seen by Pan and co-authors in a single-pollutant analysis (Pan et al. 2010) disappeared in three-pollutant analyses.

No effect of SO_2 on asthma prevalence was seen in older adults in a French study; SO_2 ranged from 5 to 13.7 µg/m^3 and was associated with increased prevalence of "usual" cough and phlegm (Bentayeb et al. 2010).

Respiratory health: allergic rhinitis

Possible associations between ambient SO_2 and allergic rhinitis were addressed in four studies. Two studies (Bhattacharyya 2009; Dong et al. 2011) show a significant link between SO_2 and prevalence of allergic rhinitis in a single-pollutant analysis. Annual average SO_2 levels reported by Bhattacharyya (2009) were from 15 µg/m^3 in 1997 to 10 µg/m^3 in 2006. Multi-pollutant analysis was performed only by (Dong et al. 2011): the effect estimate was reduced and the association lost significance. The three-year average SO_2 concentration was 50 µg/m^3 in the Dong et al. (2011) study. Two studies (Parker et al. 2009; Penard-Morand et al. 2010) found no association between SO_2 and prevalence of allergic rhinitis. Parker et al. (2009) reported a median SO_2 level of 10.2 µg/m^3. Mean SO_2 concentrations in six French cities studied by Penard-Morand et al. (2010) ranged between 4.1 µg/m^3 and 13.2 µg/m^3. Bhattacharyya and Shapiro (2010) studied prevalence of "respiratory allergy" in children included in the National Health Interview Survey (U.S.) and found no significant association with SO_2 levels. It is not clear if "respiratory allergy" included only allergic rhinitis or other allergic conditions. SO_2 levels are not reported.

Respiratory health: lung function

Two studies show significant reductions in some lung function parameters associated with increased SO_2 levels in adults (Forbes et al. 2009a) and in children (Linares et al. 2010). Forbes

and colleagues demonstrated that a 10 µg/m^3 difference in SO_2 across postcode sectors was associated with about a 20 ml decrease in forced expiratory volume in 1 sec (FEV1). Linares and co-authors reported that SO_2 levels (varied between 23 and 36 µg/m^3 by season and area) were negatively related with forced vital capacity, FEV1 and peak expiratory flow.

Other respiratory outcomes

Neupane and co-authors (Neupane et al. 2010) found no significant link between estimated SO_2 concentrations (mean 15.2 µg/m^3, maximum 27.9 µg/m^3) and hospitalizations for community acquired pneumonia among older adults (≥65 years) in Hamilton, Ontario. Bhattacharyya and Shapiro (2010) showed that prevalence of frequent ear infections in children included in the National Health Interview Survey (USA) was significantly associated with SO_2 concentrations. SO_2 levels are not reported.

Summary on long-term SO_2 exposure and respiratory outcomes

The Scientific Advisory Committee of the U.S. EPA (U.S. EPA 2008) has reached the following conclusion: "Overall, the available evidence from the generally limited number of epidemiologic and animal toxicological studies is inadequate to infer that respiratory effects occur from long-term exposure to SO_2 at ambient concentrations". Results of recent epidemiological studies summarized in this section are not consistent. Potential confounding effects of other air pollutants were addressed in relatively few studies. Therefore, some of the observed effects cannot be unequivocally attributed to SO_2.

Long-term SO_2 exposure and cardiovascular effects

Several recent studies in humans provide mostly negative findings regarding potential effects of long-term exposure to SO_2 on indices of cardiovascular health. Studied endpoints were: heart rate variability (Chow et al. 2010), blood pressure, biochemical and cellular markers relevant to cardiovascular health (Chuang et al. 2011), blood markers of inflammation (Forbes et al. 2009b), and blood pressure changes in pregnant women (Lee et al. 2012).

Lenters and co-authors (Lenters et al. 2010) studied two indicators of vascular damage in a cohort of young adults: pulse wave velocity as a measure of arterial stiffness, and carotid artery intima-media thickness as an indicator of preclinical atherosclerosis. No associations were found between any air pollutant and carotid artery intima-media thickness. However, an increasing trend in pulse wave velocity was seen with increasing SO_2 concentrations. Mean estimated residential exposure to SO_2 was 3.4 µg/m^3, 95th percentile 5.2 µg/m^3.

Increases in some molecular indices of inflammation and injury in the heart and brain were seen in two animal experiments with rats exposed to very high SO_2 concentrations via inhalation (Sang et al. 2010; Yun et al. 2011). SO_2 concentrations used in these studies (7 to 28 mg/m^3) are irrelevant to exposures of the general population.

The U.S. EPA (U.S. EPA 2008) has concluded: "The available toxicological and epidemiologic evidence to assess the effect of long-term exposure to SO_2 on cardiovascular health is too limited to make any conclusions at this time". The recent literature summarized in this section does not change this conclusion.

Long-term SO_2 exposure and morbidity other than respiratory or cardiovascular

Hart and co-authors (Hart et al. 2012) conducted a case-control study of air pollution and rheumatoid arthritis using data from the Swedish Epidemiological Investigation of Rheumatoid Arthritis study. After adjustment for smoking and education, there was no significant association between rheumatoid arthritis and SO_2 in the 10^{th} year before onset. The odds ratio per 8 µg/m^3 interquartile increase in SO_2 was 1.18, 95% CI 0.97 to 1.43. Full text for the article is not available.

Kaplan and colleagues (Kaplan et al. 2010) conducted a case-control study of inflammatory bowel diseases (Crohn's disease and ulcerative colitis) in the United Kingdom using data from the health improvement network database. No significant concentration-response association was seen between estimated SO_2 concentrations (values are not reported) and inflammatory bowel diseases.

Several animal studies examined neurotoxicity-related outcomes (Liu et al. 2008; Yun et al. 2010; Qin et al. 2012) and other outcomes (Zhao et al. 2008b; Bai and Meng 2010a). High concentrations used in these studies are irrelevant for exposures of the general population.

Long-term SO_2 exposure and cancer

Human studies of lung cancer

Beelen and co-authors (Beelen et al. 2008a) analysed lung cancer incidence in the Netherlands Cohort Study on Diet and Cancer including 114,378 subjects. Exposures to SO_2 and other pollutants were estimated at the home address. No significant associations were seen between estimated SO_2 concentrations (mean 13.7 µg/m^3, range from 4.4 to 33.8 µg/m^3) and lung cancer incidence.

The same group of researchers (Beelen et al. 2008b) found no association between long-term exposure to SO_2 and lung cancer mortality in this cohort.

Cao and co-authors (Cao et al. 2011) found a significant 4.2% (95%CI: 2.3%, 6.2%) increase in lung cancer mortality per 10 µg/m^3 increase in SO_2 concentration in a cohort of 70,947 individuals from 31 cities in China. This association remained virtually unchanged after adjustment for total suspended particles or nitric oxides. Average SO_2 concentration for all cities was 73 µg/m^3 and ranged from 11 to 174 µg/m^3 in different cities.

Katanoda and colleagues (Katanoda et al. 2011) found a significant increase in lung cancer mortality associated with an increase in the 10-year average concentration of SO_2 in a cohort including about 63,500 Japanese participants. The 10-year average SO_2 concentrations for the period 1974 to 1983 ranged between 6.3 and 49.7 µg/m^3 in different areas, and for the period 1984 to 1993 between 15.7 and 72.57 µg/m^3. The authors used single-pollutant models and pointed out difficulty in isolating health effects of individual pollutants.

Tseng and co-workers (Tseng et al. 2012) conducted an ecological study in Taiwan to examine associations between ambient SO_2 concentrations and female lung cancer incidence by major histological type (adenocarcinoma and squamous cell carcinoma). The prevalence of smoking among females in Taiwan is low, and male lung cancers were excluded to minimize confounding by smoking. Analyses were adjusted for age and other air pollutants (CO, NO_2, NO, O_3, and PM_{10}). For both histological types of lung cancer, there was a statistically significant increasing trend with increasing SO_2 concentration. The association was stronger for squamous cell carcinoma. Estimated SO_2 concentrations are not reported. Concentration ranges used for computation of relative risks were ≤9.8, 9.8-14.5, 14.5-20.3 and >20.3 µg/m^3.

Human studies of other cancers

Liu and colleagues (Liu et al. 2009a) performed a case-control study of air pollution and bladder cancer in Taiwan. Exposure to air pollutants was estimated on the basis of air monitoring data and municipality of residence. SO_2 was positively associated with the risk of death from bladder cancer in a categorical analysis using three categories of estimated SO_2 concentrations: ≤11.3, 11.5-15.9, 17.0-46.8 µg/m^3. A major weakness of this study is the absence of information on smoking (a well-established risk factor for bladder cancer), on occupational exposures to carcinogens, and on socio-economic status.

Wei and co-authors (Wei et al. 2012) conducted an ecological study of possible associations between ambient air pollution and female breast cancer in the U.S. Age-adjusted incidence rates of female breast cancer were obtained from the Surveillance, Epidemiology, and End Results Program of the U.S. National Cancer Institute. The national air pollutant emission data were obtained from the U.S. Environmental Protection Agency. Time trends and regional variations in the incidence rates of breast cancer during 1973 to 2007 were analysed in relation to the emissions of air pollutants. Air pollutant data for 1953 to 1987 were used to account for a latent period of 20 years for breast cancer. Emissions of SO_2 were correlated with the incidence of breast cancer. This study is ecological, i.e., no individual-level data on exposure, outcome, or on risk factors for breast cancer (confounders) were available.

Animal experiments relevant to carcinogenicity/genotoxicity

Several studies examined the expression of cancer-related genes in the lung (Bai and Meng 2010b; Qin and Meng 2010a) and in the liver (Qin and Meng 2010b) of rats after inhalation of

SO_2 at very high concentrations (up to 56 mg/m^3) irrelevant to the ambient exposure levels. They found increased expression of some oncogenes (genes that help turn a normal cell into a cancer cell) and decreased expression of some tumor suppressor genes.

Ziemann and colleagues (Ziemann et al. 2010) performed a bone-marrow micronucleus test (a standard test for genotoxic potential of chemicals) in mice exposed to SO_2 from 0 (control mice) to 80 mg/m^3. SO_2 did not induce micronuclei in polychromatic erythrocytes of the bone marrow, whereas the positive control (cyclophosphamide, a known genotoxic substance) did. The authors have concluded that their study "could not reproduce the genotoxicity findings of the previously reported studies".

In vitro studies relevant to carcinogenicity/genotoxicity

Qin and Meng (2009) observed activation of oncogenes and inactivation of tumor suppressor genes in human bronchial epithelial cells exposed to SO_2 derivatives (bisulfite and sulfite).

Uren and colleagues (Uren et al. 2012) studied endpoints related to genotoxicity (sister chromatid exchange as an index of chromosomal stability, micronuclei formation and cell growth kinetics) in human lymphocytes. Only the abstract from this article is available. The authors concluded: "the results have confirmed that SO(2) has potent mutagenicity and it can cause genetic damage leading to a malignancy". It should be noted that these in vitro studies used high concentrations of the substances.

The Scientific Advisory Committee of the U.S. EPA (U.S. EPA 2008) has reviewed studies on SO_2 genotoxicity, animal toxicological studies, and human epidemiological studies published before 2008. Genotoxicity studies and animal toxicological experiments indicated that at high concentrations not relevant for ambient levels, SO_2 could cause DNA damage but did not cause cancer. The Committee characterized the results from epidemiological studies as inconclusive. Studies published after the U.S. EPA (2008) review do not change this conclusion.

Long-term SO_2 exposure and prenatal/neonatal outcomes

Low birth weight

Brauer and colleagues (Brauer et al. 2008) evaluated the effects of air pollution on infant birth weight in Vancouver, B.C. A statistical association approaching significance was seen between SO_2 and babies that were small for their gestational age. No significant association was seen between SO_2 and babies with low full-term birth weights. Mean SO_2 concentrations were 5.7 µg/m^3 (estimated by nearest monitor) and 5.3 µg/m^3 (estimated by an inverse-distance weighting approach).

Darrow and colleagues (Darrow et al. 2011) examined associations between birth weight in full-term infants in Atlanta and air pollution levels during the first month of gestation, during the

third trimester, and in each month of pregnancy. The mean value of a four-week average SO_2 concentration during the first month of pregnancy was 28.0 µg/m^3; the interquartile range was 10.5 µg/m^3. Mean SO_2 concentration for the third trimester of pregnancy was 24.9 µg/m^3, the interquartile range was 7.9 µg/m^3. A significant decrease in birth weight was associated with increasing SO_2 concentration during the third trimester. This association was no longer significant when the analysis was restricted to births for which the maternal residential address was within 4 miles of an air monitor (data with more precise exposure estimates). No significant associations were detected for SO_2 concentrations in the first month of pregnancy.

Ebisu and Bell (2012) explored possible associations between chemical components of $PM_{2.5}$ and low birth weight in the Northeastern and Mid-Atlantic Regions of the United States. Gaseous pollutants were also measured. Full text for the article is not available. In the abstract, it is reported that most exposure levels were in compliance with U.S. Environmental Protection Agency air pollution standards; "…gaseous pollutants showed associations, but were not statistically significant in multi-pollutant models".

Morello-Frosch and co-authors (Morello-Frosch et al. 2010) analysed full-term birth weight and air pollution in California, USA. Full-term pregnancy SO_2 exposure was associated with higher birth weights within 5 and 10 km radius from an air monitor. Analysis of exposure by trimester of pregnancy demonstrated that a significant increase in birth weight within 5 and 10 km distance was seen for exposures during the first trimester. Estimated SO_2 exposure averaged over the length of pregnancy was 5.5 µg/m^3.

Nascimento and Moreira (2009) saw a higher frequency of low birth weight babies at higher SO_2 concentrations in a medium-sized city in Brazil. However, no clear exposure-response trend was seen. The mean value of estimated SO_2 concentration was 535.6 µg/m^3, range 364.6 to 744.9 µg/m^3.

Zou and colleagues (Zou et al. 2011) studied a possible relationship between maternal exposure to SO_2 and the risk of low birth weight babies in the Dallas-Fort Worth area of the United States. The risk of low birth weight was not higher in exposed compared to unexposed mothers. When data were restricted to mothers aged ≥35 years, the risk of low birth weight babies was higher in the exposed group. The article is in Chinese, and only the abstract is available.

Intra-uterine growth retardation

Hansen and co-authors (Hansen et al. 2008) examined possible associations between fetal ultrasonic measurements conducted at a private ultrasound clinic in Brisbane, Australia at 13 to 26 weeks of gestation, and ambient air pollution during early pregnancy. Mean estimated SO_2 concentration was 3.1 µg/m^3. A reduction in fetal abdominal circumference was associated with SO_2 concentration during days 61 to 90 of gestation. A reduction in biparietal diameter was associated with SO_2 concentration during days 0 to 30. There were no significant effects of

SO_2 on head circumference or femur length. The authors note lack of individual data on socio-economic status as a limitation of their study.

Preterm births

Darrow and co-workers (Darrow et al. 2009) analysed preterm births in Atlanta, USA. Daily counts of preterm births were analysed in relation to air pollution exposure during three gestational windows (first month of gestation, 1-week lagged moving average, 6-week lagged moving average). An inverse relationship was seen between exposure in the first month of pregnancy and preterm births: the relative risk per interquartile change in SO_2 (10.5 µg/m^3) was 0.97 (95% CI 0.96–0.99). No significant associations were seen for the other two exposure windows. When the data were restricted to births for which maternal residential address was within 4 miles of an air monitor, no significant effects of SO_2 on preterm birth were seen.

Brauer and colleagues (Brauer et al. 2008) found no statistically significant association between estimated SO_2 exposure and preterm births in Vancouver. Mean SO_2 concentrations were 5.7 µg/m^3 (estimated by the nearest monitor) and 5.3 µg/m^3 (estimated by an inverse-distance weighting approach).

Systematic reviews and meta-analyses of data on low birth weight and preterm birth

Shah and Balkhair (2011) conducted a systematic review of studies on air pollution and birth outcomes. Nineteen studies published between 1987 and 2010 reported data on SO_2. Five studies reported increased risks of low birth weight associated with SO_2 exposure, one reported significant risk of very low birth weight, and 11 studies reported no association between SO_2 and low birth weight. An association of higher SO_2 exposure and preterm birth was reported in four of five studies. One study reported a significant association between SO_2 during the first, but not the last month of pregnancy and births of babies that were small for their gestational age.

Stieb and colleagues (Stieb et al. 2012) conducted a systematic review and meta-analysis of data on air pollution, birth weight and preterm births. They concluded that results for SO_2 and O_3 were “less consistent” than those for CO, NO_2, $PM_{2.5}$ and PM_{10} showing “reduced birth weight and increased odds of low birth weight in relation to exposure”.

Birth defects

Dadvand and co-authors (Dadvand et al. 2011a) analysed maternal exposure to air pollution and the occurrence of congenital heart disease in the offspring. The study was conducted in Northeast England from 1993 to 2003. Inverse relationships were detected between SO_2 (estimates are not reported) and all cases of congenital heart disease, and between SO_2 and some specific cardiac malformations. No significant positive associations were seen.

The same group of authors (Dadvand et al. 2011b) analysed maternal exposure to air pollution and congenital heart diseases in the same area for the period 1985 to 1996. Estimated SO_2 concentrations were not significantly associated with all congenital heart diseases or with individual groupings of congenital heart diseases.

Rankin and co-authors (Rankin et al. 2009) studied maternal exposure to black smoke and SO_2 in early pregnancy and the risk of congenital anomalies in the Northern Health Region of the United Kingdom during 1985-1990. For SO_2, a significant negative association was seen with congenital heart diseases as a group, and with patent ductus arteriosus. No clear associations were found between SO_2 and other anomalies.

Dolk and colleagues (Dolk et al. 2010) conducted a geographical correlation study of air pollution and congenital anomalies in four regions of England using data from population-based registries of congenital anomalies for the period 1991 to 1999. Cases were classified into non-chromosomal and chromosomal anomalies. SO_2 (mean value 7.86 µg/m^3) was not significantly associated with either chromosomal or non-chromosomal anomalies in this study.

Strickland and co-authors (Strickland et al. 2009) examined associations between exposure to ambient air pollution during weeks 3 to 7 of pregnancy and risks of cardiovascular anomalies in one of five central Atlanta counties (Georgia, USA) for the period 1986 to 2003. The mean 5-week weighted SO_2 concentrations were 22.8 µg/m^3 in 1986-1991, 14.4 µg/m^3 in 1992-1997, and 10.5 µg/m^3 in 1998-2003. No significant associations were seen between SO_2 and any category of cardiovascular malformations.

Hwang and Jaakkola (2008) conducted a nationwide study in Taiwan to assess possible effects of exposure to air pollution during pregnancy on the risk of cleft lip. The mean SO_2 concentration for all 4 seasons was 10.4 µg/m^3 (median 9 µg/m^3; maximum 30.1 µg/m^3). No significant associations were seen for SO_2 in single-pollutant, two-pollutant or three-pollutant models.

Marshall and co-authors (Marshall et al. 2010) conducted a case-control study of possible associations between maternal exposure to air pollutants in early pregnancy and oral cleft defects in New Jersey, USA. Two groups of anomalies were studied: cleft lip with or without cleft palate (CLP) and cleft palate only (CPO). A critical exposure period was defined as a 6-week period from 5 to 10 weeks of gestation. Mean SO_2 concentration during the critical period was around 13.4 µg/m^3 for controls, 13.9 µg/m^3 for CLP and 12.6 µg/m^3 for CPO. In a single-pollutant analysis using all data (residences within 40 km of the monitor), there was some indication of an association between SO_2 and CLP (a significant increase in the risk of CLP in the highest exposure category). No increase in the risk of CPO was seen in any SO_2 exposure category. When the data were restricted to residences within 10 km from the closest monitor, the increase seen for CLP was no longer significant. The results did not change substantially when multi-pollutant analysis was conducted.

Vrijheid and co-authors (Vrijheid et al. 2011) conducted a systematic review and meta-analysis of data on ambient air pollution and the risk of congenital anomalies. Ten original epidemiologic studies that met inclusion criteria (English language, well-defined outcome and measured exposure levels) were identified. In the meta-analysis, SO_2 exposure was related to increases in risk of coarctation of the aorta and tetralogy of Fallot. No significant increases in the risk of other cardiac anomalies and oral clefts were detected by the meta-analysis.

Stillbirths

Faiz and colleagues (Faiz et al. 2012) analysed exposures to air pollution in the first, second, and third trimesters of pregnancy and the risk of stillbirths in New Jersey, USA from 1998 to 2004. The mean SO_2 concentration for the entire pregnancy was 15.4 µg/m^3. Mean SO_2 concentrations for each trimester were 15.2 to 15.4 µg/m^3. A significant increasing trend in the risk of stillbirth was seen with increasing SO_2 concentration in the first and third trimesters of pregnancy.

Hwang and co-authors (Hwang et al. 2011) conducted a study in Taiwan and observed a significant increase in the risk of stillbirth associated with increasing SO_2 concentrations during first, second and third months of pregnancy. The increasing trend was seen in a single-pollutant model and in three-pollutant models (including SO_2, CO and O_3 or SO_2, NO_2 and O_3). Mean SO_2 concentration was 15.0 µg/m^3, maximum 41.7 µg/m^3, interquartile range 4.8 µg/m^3.

Infant mortality

No studies on neonatal mortality have been identified. Woodruff and co-workers (Woodruff et al. 2008) found no associations between ambient SO_2 concentrations (county-level data) and post-neonatal infant mortality in the USA. Infant mortality from all causes, respiratory causes, sudden infant death syndrome and other causes was analysed. The average concentration of each pollutant over the first 2 months of life was calculated as a measure of chronic exposure. The median SO_2 concentration was 7.4 µg/m^3 for survivors, and 8.2 µg/m^3 for deceased infants.

Other endpoints

In Allegheny County (PA, U.S.A), Lee and colleagues (Lee et al. 2011) studied the effects of air pollution on blood concentrations of C-reactive protein (CRP) during early pregnancy. The focus of this study was particulate air pollution. The authors do not report quantitative estimates of the associations between SO_2 and CRP but state that for SO_2, “associations were negligible”.

Legro and co-authors (Legro et al. 2010) examined possible effects of air quality on assisted human reproduction, namely effects of air pollution during different stages of in vitro fertilization (IVF), on live birth rates in the Northeastern U.S.A. No adverse effect of exposure to SO_2 during any IVF stage was seen. Air pollutant concentrations were estimated at the patient’s

address and at the IVF lab. Mean values of daily concentrations of SO_2 ranged between 154 and 165 µg/m^3 during different stages of IVF.

Summary on prenatal/neonatal outcomes

The U.S. EPA (U.S. EPA 2008) reached the following conclusion based on pre-2008 literature: "…epidemiologic studies on birth outcomes have observed positive associations between SO_2 exposure and low birth weight; however, toxicological studies provide very little biological plausibility for reproductive outcomes related to SO_2 exposure. The inconsistent results across trimesters of pregnancy and the lack of evidence regarding confounding by co-pollutants further limit the interpretation of these studies. The limited number of studies addressing preterm delivery, intra-uterine growth retardation, birth defects, neonatal hospitalizations, and infant mortality make it difficult to draw conclusions regarding the effect of SO_2 on these outcomes".

Results of studies on SO_2 and low birth weight published after the U.S. EPA review are inconsistent. Very few recent studies address intra-uterine growth retardation, preterm births, stillbirths and infant mortality. Eight studies examining potential associations between ambient SO_2 and birth defects have been identified (seven original studies and one systematic review). Of the seven original studies, six did not show positive associations between ambient SO_2 concentrations and birth defects. One study provides some indication of such an association. Overall, studies reviewed by the U.S. EPA and more recent literature do not provide clear evidence for an adverse effect of SO_2 on prenatal and neonatal outcomes.

Long-term SO_2 exposure and mortality[4]

Eight recent articles on long-term SO_2 exposure and mortality have been identified. One article on-infant mortality (Woodruff et al. 2008) is summarized in the section on prenatal/neonatal outcomes. This study shows no effect of SO_2. An article by Brunekreef and colleagues (Brunekreef et al. 2009) describes a study in the Netherlands that was previously reported by Beelen and co-authors (Beelen et al. 2008b) and summarized by the U.S. EPA in their 2008 review. No associations between SO_2 and mortality from all causes and specific causes were seen in this study. Estimated long-term average SO_2 concentrations ranged from 4 µg/m^3 to 34 µg/m^3 with the median value of 13 µg/m^3 and a mean value of 13.7 µg/m^3.

Of the remaining six studies, five are studies of large cohorts in China (Cao et al. 2011; Zhang et al. 2011; Dong et al. 2012a), Japan (Katanoda et al. 2011) and in the USA (Krewski et al. 2009).

Cao and colleagues (Cao et al. 2011) demonstrated significant increases in total, respiratory and cardiovascular mortality associated with increased SO_2 concentrations in analyses adjusted and

[4] Only data on non-cancer mortality is summarized in this section. Cancer mortality is considered in section "Long-term SO_2 exposure and cancer".

unadjusted for other pollutants. After adjustment for important demographic, medical and lifestyle determinants of mortality, a 10 µg/m^3 increase in estimated SO_2 concentration was associated with 1.8% increase in total mortality, an equal increase of 3.2% in cardiovascular and respiratory mortality and 4.2% increase in lung cancer mortality. Adjustment for NO_x and total suspended particles did not change the magnitude of the association.

Full text for the article by Dong and co-authors (Dong et al. 2012a) is unavailable. Based on the abstract, there was no significant relationship between SO_2 concentrations and respiratory mortality in a cohort of 9,941 adult residents (aged ≥35 years) of Shenyang, China. Zhang and co-workers (Zhang et al. 2011) found no significant effects of SO_2 on mortality from cardiovascular and cerebrovascular diseases in a single-pollutant analysis of data from the same cohort of Shenyang residents. The mean annual SO_2 concentration was 63 µg/m^3 (range 26 to 106 µg/m^3).

Single-pollutant analysis of Katanoda and colleagues (Katanoda et al. 2011) demonstrated significantly increased mortality from respiratory diseases associated with an increase in 10-year average SO_2 concentration. Ten-year average concentrations of SO_2 in different study areas were 6.3 to 49.7 µg/m^3 in 1974-1983, and 15.7 to 72.57 µg/m^3 in 1984-1993.

Krewski and co-authors (Krewski et al. 2009) demonstrated significant increases in mortality from all causes, cardiopulmonary diseases, and ischemic heart disease associated with increased SO_2 concentrations in the American Cancer Society cohort of about 1.2 million adult participants. The associations lost statistical significance when analyses were stratified by exposure time window (1-5 years, 6-10 years and 11-15 years before deaths) and by educational attainment.

A study in Brisbane, Australia by Wang and co-authors (Wang et al. 2009) is an ecological study of mortality from cardiorespiratory diseases. Population data, mortality data and socio-economic indices for areas were obtained from administrative databases. Results of single- and multiple-pollutant modelling demonstrated a positive association between the annual average SO_2 concentration and cardio-respiratory mortality. The "overall average" SO_2 concentration was 14.1 µg/m^3. Findings from studies of this design have less weight than findings from cohort studies with individual-level data on exposures, outcomes and potential confounders.

The results of recent studies summarized in this section are in line with the conclusion made by the U.S. EPA: "The available epidemiologic evidence on the effect of long-term exposure to SO_2 on mortality is inadequate to infer a causal relationship at this time… The lack of consistency across studies, inability to distinguish potential confounding by co-pollutants, and uncertainties regarding the geographic scale of analysis limit the interpretation of a causal relationship".

3.4.2.4 Short-term exposure to SO_2 and mortality

Twenty-eight recent studies have been identified. Most (23) studies were conducted in Asian countries, with 15 of them in China where levels of SO_2 exposure were relatively high. Mean values of daily average concentrations reported in different Chinese studies ranged from 16 to ~100 µg/m^3, with most being between 40 and 60 µg/m^3. The studies examined associations between ambient SO_2 concentrations and mortality from all causes, all non-accidental causes, and cause-specific mortality (in particular from respiratory and cardiovascular diseases). Full text was available for 16 articles; only the abstract was available for 12 (some of them are in Chinese). No recent Canadian studies on short-term SO_2 exposure and mortality have been identified.

When pollutants other than SO_2 were not accounted for in the analysis, 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 found in one study. Since SO_2 is only one of many air pollutants, such analyses cannot rule out the possibility that SO_2 is 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 the statistical model simultaneously was made in seven studies (two- or multi-pollutant analyses). One of these studies reported a positive association in both a single-pollutant model and in multi-pollutant analyses, and one study reported a negative association in both types of analyses. In five studies, when other air pollutants were accounted for, the positive association seen for SO_2 in a single pollutant model became smaller in magnitude and not statistically significant. Such reduction was seen in most cases after inclusion of NO_2 in the statistical model. Overall, despite many positive associations reported between ambient SO_2 concentrations and mortality, the data suggest that these may not be "true" associations but reflect the effects of other air pollutants.

3.4.2.5 Short-term exposure to SO_2 and respiratory morbidity

Twenty-four epidemiological studies published between 2008 and October 26, 2012 have been identified; two of them (Liu et al. 2009b; Stieb et al. 2009) were conducted in Canadian cities. Most studies report positive associations between ambient SO_2 and respiratory symptoms, numbers of hospitalizations and emergency department visits for respiratory diseases, and decreased lung function. Liu et al. (2009b) studied 182 children with asthma in Windsor, Ontario for four weeks. The authors reported a significant decrease in forced expiratory flow and a significant increase in markers of oxidative stress in breath condensate associated with a 14.2 µg/m^3 increase in 3-day average SO_2 levels. Stieb et al. (2009) analysed emergency department visits for respiratory conditions in seven Canadian cities (Montreal, Ottawa, Edmonton, Saint John, Halifax, Toronto and Vancouver). In a single-pollutant analysis, emergency department visits for asthma, chronic obstructive pulmonary disease or respiratoy infections were not significantly linked with SO_2 concentrations lagged 0, 1 or 2 days.

Three human clinical studies in non-smoking, healthy[5] volunteers have been published after the U.S. EPA review (Raulf-Heimsoth et al. 2010; van Thriel C. et al. 2010; Kleinbeck et al. 2011). Rauf-Heimsolth and colleagues (Raulf-Heimsoth et al. 2010) demonstrated that 4-hour exposure to SO_2 at concentrations up to 5,240 µg/m^3 (2.0 ppm) for 4 hours did not induce increases in markers of airway inflammation or irritation. Van Thriel and co-workers did not see significant effects of SO_2 exposure for 4 hours at concentrations up to 5,240 µg/m^3 (2.0 ppm) on lung function, eye blink frequency or nasal airflow. The study participants were administered light physical exercise for 15 minutes during each session. Kleinbeck and colleagues (Kleinbeck et al. 2011) found a clinically significant decrease in breathing depth (deviation of ~10% from the baseline) at an SO_2 concentration of around 25,000 µg/m^3 with exposure for 25 seconds.

Data from recent studies and those reviewed by the U.S. EPA suggest that SO_2 does not induce respiratory diseases in healthy people but rather exacerbates existing diseases. It has been clearly demonstrated that individuals with asthma represent a sub-population susceptible to short-term exposures of SO_2.

3.4.3 Susceptible and vulnerable populations

3.4.3.1 Data from the U.S. EPA review

The U.S. EPA in its Integrated Science Assessment for Sulfur Dioxide (U.S. EPA 2008) 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". Based on a comprehensive literature review, the U.S. EPA ascertained several populations potentially susceptible to adverse effects of SO_2. The U.S. EPA conclusions regarding the weight of evidence for susceptibility are summarized in Table 3.4-1.

Table 3.4-1: Conclusions of the U.S. EPA Scientific Advisory Committee regarding the weight of evidence for susceptibility to the effects of SO_2.

Population	Weight of evidence
Pre-existing respiratory diseases	"…substantial evidence from epidemiologic studies suggests that individuals with preexisting respiratory diseases, particularly asthma, are more susceptible to respiratory health effects, though not mortality, from SO_2 exposures than the general public. The observations from human clinical studies indicating increased sensitivity to SO_2 exposures in asthmatic subjects compared to healthy subjects provide coherence and biological plausibility for these observations in

[5] In this report, "healthy" means without restrictive airway diseases.

Population	Weight of evidence
	epidemiologic studies"
Pre-existing cardiovascular disease	"…the very limited evidence examining the susceptibility of individuals with preexisting cardiovascular disease to adverse health effects from ambient SO_2 exposures is inconclusive"
Genetic factors for oxidant and inflammatory damage from air pollutants	"At this time, there are insufficient data on which to base a conclusion regarding the effect of SO_2 exposure on genetically distinct subpopulations"
Age-related susceptibility	"There is limited epidemiologic evidence to suggest that children and older adults (65+ years) are more susceptible to the adverse respiratory effects associated with ambient SO_2 concentrations when compared to the general population."
Other potentially susceptible populations	"Although data specific to SO_2 exposures is lacking for the susceptibility factors listed below, several other potentially susceptible groups deserve specific mention …. These include individuals in a chronic pro-inflammatory state (e.g., diabetics), obese individuals, and children born prematurely or with low birth weight."

The U.S. EPA has introduced the concept of vulnerability to a pollutant. Some populations may have increased vulnerability to pollutants "due to factors including socio-economic status (e.g., reduced access to health care) or particularly elevated exposure levels" (U.S. EPA 2008).

According to the U.S. EPA, the following populations may be vulnerable to adverse effects of SO_2.

"…Those who spend a lot of time outdoors at increased exertion levels, for example outdoor workers and individuals who exercise or play outdoor sports".

"Children, who generally spend more time playing outdoors, may qualify as both a susceptible population (due to their developing physiology) and as a vulnerable population since ambient SO_2 concentrations are several-fold higher than indoor concentrations".

Individuals with lower socio-economic status may be more susceptible to the effects of SO_2.

The U.S. EPA concluded that existing information on SO_2 effects in vulnerable populations was limited.

3.4.3.2 Data from recent literature

Pre-existing respiratory diseases

Recent data on the effects of short-term SO_2 exposure summarized in the previous sections provide further support to the U.S. EPA conclusion regarding increased susceptibility of individuals with respiratory diseases, and particularly with asthma, to adverse respiratory effects of SO_2.

Pre-existing cardiovascular disease

Data summarized in the previous sections regarding potential effects of SO_2 on various cardiovascular parameters in individuals with pre-existing cardiovascular diseases, and data on emergency department visits/hospitalizations for cardiovascular diseases (assuming that SO_2 exacerbates existing diseases) do not provide a consistent picture. The evidence remains "inconclusive".

Genetic factors

Baja and colleagues (Baja et al. 2010) examined modification by oxidative stress gene polymorphism of the effects of air pollution on QT interval as an electrocardiographic marker of ventricular repolarization in 580 men, all participants of the Veterans Affairs Normative Aging Study (USA). No effect on QT interval was detected for SO_2; effect modification for SO_2 was not evaluated.

Genetic factors were investigated in five other studies (Li et al. 2008; Wood et al. 2009; Xie et al. 2009; Wood et al. 2010; Wang et al. 2011). None of these studies is relevant for identifying potentially susceptible populations; no gene-environment interaction was examined. These studies are more relevant to identifying potential mechanisms of action.

Age- and gender-related susceptibility

Recent studies provide limited information regarding age- and gender-related susceptibility to potential effects of SO_2. Most of the newly identified studies examined health outcomes for which a causal link with SO_2 is not established.

Cakmak and co-authors (Cakmak et al. 2011) found a significantly greater risk ratio for mortality from non-accidental causes per interquartile increase in SO_2 in individuals aged ≥85 years vs. individuals aged <64 years ($p<0.05$). No effect of gender was seen.

Kan and co-workers (Kan et al. 2008) found that an SO_2-associated increase in total mortality was slightly greater among females (the significance of the gender difference was not reported but was likely non-significant); the increase was significant in the age group ≥65 (likely due to greater number of deaths) but not in age groups 5 to 44 or 45 to 64 years. No age- or gender-specific data were reported for cardiovascular or respiratory deaths.

Namdeo and colleagues (Namdeo et al. 2011) studied hospital admissions for respiratory diseases in age groups 0 to 59, 60 to 69, 70 to 74, 75 to 79, 80+ years. Associations between admissions and SO_2 were significant only at ages 75 to 79 years and only for SO_2 concentrations on the same day (lag 0). SO_2 concentrations lagged 1 and 2 days were also examined. Multi-pollutant modelling was conducted only for significant associations found in the single-pollutant models. The association seen in the single-pollutant model for age 75 to 79 remained significant after inclusion of PM_{10} (lag 2) in the model. In summary, no discernible age effect was seen for SO_2.

Only the abstract from the article by Son and colleagues (Son et al. 2012) is available. The authors stated: “Results indicate that some populations are more susceptible than others. For total or cardiovascular mortality, associations were higher for males, those 65-74 years…”. Data on age-related susceptibility to SO_2 specifically were not reported in the abstract.

Szyszkowicz and co-authors (Szyszkowicz et al. 2012) found a significant positive association between emergency department visits for ischemic stroke and SO_2 concentrations lagged 0 days in female patients in Vancouver. No significant associations were seen for longer lags in female patients or for any lag in male patients.

No studies have been identified regarding children as a potentially susceptible population.

Diabetes and obesity

Dong and co-authors (Dong et al. 2012b) studied modifying effects of obesity on air pollution-associated respiratory symptoms and asthma. Only the abstract from this article is available. The authors reported that “the associations between each pollutant's yearly concentrations and respiratory symptoms and asthma were consistently larger for overweight/obese children than for normal-weight children”. Results for SO_2 are not presented in the abstract.

Baja and colleagues (Baja et al. 2010) analysed modification by obesity and diabetes of the effects of air pollution on electrocardiographic QT interval. No effect on QT interval was detected for SO_2; therefore, effect modification for SO_2 was not evaluated.

Other potentially susceptible populations

Two studies on smoking and one study on positive HIV status as potential susceptibility factors have been identified. Information is too limited to make conclusions regarding these factors.

Min and colleagues studied lung function (Min et al. 2008) and heart rate variability (Min et al. 2009) in relation to ambient SO_2 concentrations in adult Korean volunteers. The results suggest that smokers experience greater SO_2-associated decline in lung function and greater SO_2-associated reduction in indices of heart rate variability compared to non-smokers. These effects lasted for up to 20-30 hours after exposure.

Djawe and co-authors (Djawe et al. 2012) analysed potential environmental risk factors for Pneumocystis pneumonia in HIV-infected patients in the United States. Climatological and air pollution data were analysed. Only the abstract from this study is available. The authors found that increases in SO_2 levels were associated with hospital admissions for Pneumocystis pneumonia. The effects of SO_2 were modified by increasing carbon monoxide levels.

Vulnerability to SO_2: socio-economic factors

Recent data relevant to this subject are limited. Some studies explore modification by socio-economic variables of the effects for which a causal link with SO_2 is not established.

Burra and co-authors (Burra et al. 2009) studied physician visits for asthma in Toronto. Estimates of risk for the low socioeconomic status group were significantly greater than those for the high socioeconomic status group in several analyses.

Cakmak and colleagues (Cakmak et al. 2011) found that the risk of mortality from non-accidental causes in Chilean urban centers was significantly greater in individuals living in the area with income <$8,800 vs. individuals living in the area with income >$13,395. The risk was greater in individuals who did not complete primary school vs. individuals with a university diploma.

Kan and co-workers (Kan et al. 2008) reported that an SO_2-associated increase in total, cardiovascular and respiratory mortality in Shanghai (China) was greater among individuals with low education (illiterate or primary school) compared to individuals with middle-school education or above.

Laurent and co-authors (Laurent et al. 2008) found no significant effect of socioeconomic deprivation (estimated using a block-level index constructed from census data) on the association between SO_2 concentrations and telephone calls to physicians for asthma attacks in the Strasbourg metropolitan area (France).

Son and co-authors (Son et al. 2012) reported the results of their study in Seoul, Korea: “For total or cardiovascular mortality, associations were higher for… those with no education or manual occupation for some pollutants. For example, the odds ratio for SO(2) and cardiovascular mortality was 1.19 (1.03-1.37) times higher for those with manual occupations than professional occupations”. Full text for this article is not available.

Wong and colleagues (Wong et al. 2008) studied mortality in relation to air pollutants in Hong Kong and concluded: "Health outcomes, measured as all non-accidental, cardiovascular, and respiratory mortality, in people residing in high SDI (social deprivation index) areas were more strongly associated with SO_2 and NO_2 compared with those in middle or low SDI areas".

Interaction between cold temperatures and SO_2

Cold temperatures (below zero) can trigger exercise-induced bronchoconstriction (Rundell and Jenkinson 2002) especially in atopic individuals (Helenius et al. 1996). The concentrations of SO_2 in ambient air are generally higher during cold winter months (e.g., Qian et al. 2010; Zemek et al. 2010; Ito et al. 2011; Kim et al. 2012). In general, cold temperatures exacerbate bronchoconstrictive effects of SO_2 in asthmatics (Johns and Linn 2011).

Human clinical studies

Bethel and co-authors (Bethel et al. 1984) measured specific airway resistance (sRaw) and collected data on respiratory symptoms in seven asthmatic volunteers before and after voluntary eucapnic hyperpnea challenge (a test that simulates an exercise challenge test) through a mouthpiece on four different days. The study participants breathed four different gas mixtures: 1) humidified air at room temperature (≈23°C, control); 2) 0.5 ppm SO_2 (1,310 µg/m^3) in humidified air at room temperature; 3) cold (≈-10°C) dry air; and 4) 0.5 ppm SO_2 (1,310 µg/m^3) in cold dry air. The control condition, SO_2 alone, and cold dry air alone did not cause a significant increase in sRaw. sRaw was significantly increased after the combined exposure to 0.5 ppm SO_2 and cold dry air ($p<0.001$). The combined exposure exacerbated the symptoms of shortness of breath and wheezing in six study participants; two participants had to use an inhaled bronchodilator at the end of the study. No appreciable symptom exacerbation was seen after exposure to SO_2 alone or to cold dry air alone.

Sheppard and colleagues (Sheppard et al. 1984) studied the interaction between exposure to dry cold air and SO_2 in eight volunteers with mild asthma. sRaw was measured before and after the voluntary eucapnic hyperpnea challenge at a constant ventilation rate (30 to 40 L/min) with doubling concentrations of SO_2 in dry cold air (-20°C, 0% relative humidity), in dry warm air (22°C, 0% relative humidity), and in humidified warm air (22°C, 70% relative humidity). On a separate day, sRaw was measured before and after the voluntary eucapnic hyperpnea challenge at the same ventilation rate, breathing dry cold air without SO_2. Dry cold air without SO_2 had no effect on sRaw. The concentration of SO_2 that caused a 100% increase in sRaw was significantly lower in dry cold air than in humidified warm air.

The combined effect of SO_2 and air temperature appears to depend not only on the relative humidity but also on the degree of the cold stress. Linn and colleagues (Linn et al. 1984a) exposed 24 asthmatics to clean air, or to 0.6 ppm SO_2 at 5°C and also at 22°C, during 5 minutes of heavy exercise. Relative humidity was always ≈85%. The bronchoconstriction response to

SO_2 was not significantly different between the two temperature conditions. The authors concluded that the "moderate cold stress exacerbated the untoward response to SO_2 only slightly and inconsistently in these asthmatic subjects."

Linn and co-workers (Linn et al. 1984b) evaluated airway resistance and respiratory symptoms in 24 asthmatic volunteers exposed to 5 minute bouts of heavy exercise, SO_2 at concentrations 0, 0.3 or 0.6 ppm (0, 0.786 and 1.572 mg/m^3) and at air temperatures 21°C, 7°C or -6°C. Relative humidity was ≈80%. There was a significant increasing trend in sRaw and in respiratory symptom number/severity with increasing SO_2 concentrations and with decreasing temperature. There was little evidence in this study of synergism; SO_2 and cold "acted more or less additively" to increase the respiratory symptoms.

Epidemiological studies

Kim and co-workers (Kim et al. 2012) analysed data on exacerbations in 82 adults with refractory asthma (RA) in the metropolitan city of Seoul or Kyunggi Province in South Korea. The subjects were recruited at the Soonchunhyang Hospital and were followed for at least 2 years. Air pollution data were obtained from the monitoring sites closest to each patient's home address. Meteorological data, including mean daily temperatures, were obtained at the monitoring sites closest to the hospital. The analyses were adjusted for seasonality, smoking and allergen sensitivity. Mean SO_2 concentration was ≈13 µg/m^3 in summer and ≈23 µg/m^3 in winter. Mean air temperature was ≈1.5°C in winter and ≈23°C in summer. In a multi-pollutant analysis of data on smoking RA patients, RA exacerbations were not significantly associated with SO_2 levels or meteorological conditions in any season. However, among non-smokers in winter, a 1°C decrease in temperature and 1 ppb (2.62 µg/m^3) increase in SO_2 were associated with a 14.8% (95% CI 0.9-26.7%) and 19.7% (95% CI 3.3-38.7%) increase in the risk of RA exacerbation, respectively on lag 1 day. On lag 2 days, a 1°C decrease in temperature and 1 ppb (2.62 µg/m^3) increase in SO_2 were associated with a 28% (95% CI 13.7-39.9%) and 16.4% (95% CI 3.0-31.6%) increase in the risk of RA exacerbation, respectively. Similar results were obtained in a single-pollutant analysis. Among epidemiological studies identified for this report, this is the most informative in terms of the interaction between SO_2 and cold. Methodological strengths of this study include the use of multi-pollutant analyses, a well-defined cohort followed for a long time, and strict diagnostic criteria for RA and RA exacerbation.

Other epidemiological studies contain limited and inconsistent information on the subject.

Abe and co-authors (Abe et al. 2009) studied the relationships between air pollution, meteorological conditions and emergency department visits for asthma exacerbation between January 1 and December 31, 2005 in Tokyo, Japan. Separate analyses were performed for adults and children (aged <15 years). For air temperature, the daily minimum level was used in the analyses. Daily data on air pollutants including SO_2 were obtained from official publications by the Ministry of the Environment. Air pollution monitoring was performed at 22 monitoring

sites in Tokyo. Data from the metropolitan central site were used in the analyses. The temperature ranged from -0.7°C to 27.9°C (mean 13.1°C). Daily average SO_2 concentrations ranged from 0 to 191.3 µg/m^3 (mean 13.9 µg/m^3). The seasonal mean number of emergency department visits for asthma was greatest in winter and lowest in summer. Because emergency department visits for asthma were not significantly associated with ambient SO_2 concentrations in this study, the interaction between the two factors could not be evaluated.

Orazzo and co-authors (Orazzo et al. 2009) analysed emergency department visits for wheezing in children 0-2 years of age from six Italian cities. Mean air temperature ranged from 12.7 ± 7.5°C in Varese-Gallarate to 18.6 ± 7.0 in Naples. Mean SO_2 ranged from 5.5 ± 4.3 µg/m^3 in Florence to 21.1 ± 25.2 µg/m^3 in Naples. SO_2 was significantly positively associated with wheezing. When data were stratified by season, the association was stronger in summer than in winter. However, the confidence intervals for risk estimates stratified by season were wide, and the difference was not statistically significant.

Tramuto and co-workers (Tramuto et al. 2011) analysed data on emergency department visits for respiratory symptoms among adult residents of Palermo, Italy. The mean air concentration of SO_2 was 3.4 µg/m^3 (10th percentile 0.6 µg/m^3; 90th percentile 6.9 µg/m^3), and the mean air temperature was 18.6°C (10th percentile 10.7°C; 90th percentile 26.7°C). In the full year analysis, SO_2 was significantly positively associated with the number of emergency department visits for respiratory symptoms. The association was strongest in the summer.

Animal experiments

Three animal experiments identified for this report (Barthelemy et al. 1988; Halinen et al. 2000a; Halinen et al. 2000b) are of limited relevance to the subject in question. All three experiments were performed on anesthetized, paralyzed and artificially ventilated animals. Barthelemy and co-authors (Barthelemy et al. 1988) studied changes in lung resistance induced by an air temperature change from 38°C to 15°C, and the two experiments by Halinen and colleagues did not use a group exposed to SO_2 in warm air; therefore, the effect of SO_2 alone on respiratory parameters could not be evaluated.

Summary for Interaction between cold temperatures and SO_2

There is evidence of a potential synergistic relationship between cold temperatures and short term SO_2 exposure at high concentrations (e.g., 1,300 µg/m^3). However, the evidence is inconsistent. It is not currently possible to quantify the magnitude of any increased risk during cold weather, and to extrapolate the identified effects to the much lower exposures in the Kitimat area. The effect of this potential increased risk would be limited to outdoor exercise exposures during cold weather.

3.4.4 Conclusions

1. Data from literature reviewed by the Scientific Advisory Committee of the U.S. EPA in 2008 and findings from more recent studies consistently demonstrate a link between short-term exposure to SO_2 and respiratory morbidity. The evidence is sufficient to establish a causal relationship.
2. Scientific literature suggests that SO_2 does not induce respiratory diseases in healthy people but rather exacerbates existing diseases.
3. Individuals with pre-existing respiratory diseases, in particular with asthma, are susceptible to the effects of SO_2. SO_2 causes a decrease in lung function accompanied by respiratory symptoms in exercising asthmatics. Physical exercise increases lung ventilation and SO_2 uptake.
4. There is suggestive evidence of a relationship between short term SO_2 and mortality, but the evidence is not sufficient to infer a causal relationship.
5. There is inadequate evidence for a causal link between short-term SO_2 exposure and non-respiratory morbidity and between long-term SO_2 exposure and any health outcome.
6. Information on populations potentially vulnerable to the effects of SO_2 (e.g., individuals with low socio-economic status) is limited.
7. Both SO_2 and cold temperatures are known to exacerbate asthma symptoms during exercise. There is some evidence of synergy at high SO_2 concentrations from clinical studies, but the overall evidence is inconsistent. It is not currently possible to quantify the potential for increased risk.

3.5 EFFECTS OF SULPHUR IN THE ENVIRONMENT

This section of the technical assessment report contains a summary of the relevant components of a background literature review (ESSA Technologies Ltd. 2012) that synthesizes information about acid deposition. Acidic deposition is caused by emissions of sulfur dioxide and nitrogen oxides which react in the atmosphere with other compounds to produce acids that settle out onto the earth's surface (wet deposition), or get directly deposited in gaseous or particulate form (dry deposition) (Driscoll et al. 2001b). The review focused primarily on sulphur, and was organized around the linkages in the source-pathway-receptor conceptual model of SO_2 emissions in the environment (see Figure 3.1-1). This model was developed as a framework for the design and modelling studies to be conducted for the technical assessment study, which focuses entirely on SO_2.

Over the course of the last century, the acidity of rainfall in many regions of the world has increased (Galloway 2001). The principal driver behind this increase is the rise in emissions of sulfur and nitrogen oxides (SO_2 and NO_x) associated with fossil fuel combustion for energy and food production (Likens et al. 1979; Galloway 2001). The acidic products of these emissions

move through soil, vegetation, and surface waters, potentially setting off a cascade of adverse ecological and human health effects (Driscoll et al. 2001b).

3.5.1 Effects of sulphur deposition on soils

The acid neutralizing capacity (ANC) of surface waters is related to the buffering ability of watershed soils (Houle et al. 2006), which is in turn a function of permeability, catchment slope, and the size of the exchangeable base cation pool. Base cations are positively charged ions (magnesium, sodium, potassium, and calcium) that reduce acidity in soil water, and in the surface waters of lakes, streams, and wetlands that are refreshed by water flowing through soils (Mohnen 1988). Calcium in particular plays a major role in the acid neutralizing capacity of soil and water (Lawrence et al. 1999).

Inputs of base cations to the environment occur as particulates in air (e.g., dust deposition), as ions dissolved in precipitation, as products of rock weathering (Hedin et al. 1994), and from forest fertilization (e.g., in reforestation and afforestation projects). Losses occur from acid leaching, soil erosion, timber harvesting, and forest re-growth. Soil calcium depletion makes terrestrial ecosystems increasingly sensitive to continuing inputs of acid (Likens et al. 1998), and threatens tree growth and productivity (Watmough and Dillon 2003a,b,c).

Catchment slope, soil thickness, and soil permeability affect how long percolating water stays in contact with the soil, which determines the degree to which the acids are buffered by replacement (exchange) with base cations. Soils that are sensitive to acid deposition are generally shallow with low weathering rates – characteristics associated with low exchangeable base cation pools.

The exchangeable base cations undergo reactions that neutralize acidic water as it passes through the soil. If the rate of exchange or loss of base cations matches mineral weathering reactions that regenerate base cations from primary bedrock materials, there will be no soil water acidification. If the exchange or loss of base cations exceeds the rate of mineral weathering, soils and soil waters will acidify and concentrations of aluminum (a toxic metal) in water will increase. Additionally, as soils acidify they may become deficient in the base cation calcium (an essential nutrient for wood formation and the maintenance of cell walls), which could compromise forest growth, health and vitality (Lawrence et al. 1995).

The ability of some terrestrial ecosystems to neutralize acid deposition has diminished over time, delaying the recovery of forests, lakes, and streams (Driscoll et al. 2001b).

3.5.2 Effects of sulphur deposition on wetlands

Wetlands are often naturally acidic owing to the presence of weak organic acids that are the products of vegetation decay. Weak organic acids can, to a limited degree, act as a buffer

against inputs of strong mineral acids from atmospheric deposition (Marmorek and Bernard 1990; Monteith et al. 2007). Where this happens, the strong acids essentially replace the weak acids (anion exchange) with little change in overall pH until the weak acids are used up (Erlandsson et al. 2011).

Wetlands can also act as 'acid banks'. In oxygen-limited wetland sediments, SO_4^{2-} from deposition is converted and stored as stable sulphide (Dillon et al. 1997; Environment Canada 2004). Wetland sediments can also release acidity back into catchments. During droughts, water levels fall allowing oxygen to penetrate into formerly anoxic zones, resulting in oxidation of sulphides back to sulphates (Environment Canada 2004). The sulphates are subsequently washed into catchment streamwater during rain events, resulting in episodic acidification (Dillon et al. 1997; Environment Canada 2004; Laudon et al. 2004). The duration of drought prior to a rain event is a good predictor of the acidity of the subsequent stream pulse (Laudon et al. 2004). The same process also occurs in the anoxic littoral sediments of lakes when lake levels fall during a drought (Yan et al. 1996).

Dissolved organic carbon from wetlands can lower the pH of downstream lakes and streams, and affect the relationship between acid neutralizing capacity and pH (Hemond 1990; Marmorek et al. 1996). Wetlands can also influence the release of strong acids, deposited during periods of high acidic deposition and stored in sediments, back into surrounding catchments. In extreme cases, many years of stored acid can be released at once, with the potential to acidify entire lakes (Yan et al. 1996).

3.5.3 Effects of sulphur deposition on lake and stream chemistry

The effects of sulphur deposition on lake and stream chemistry vary depending on the geology and physical characteristics of the watershed. Levels of acidity in lakes and streams will reflect local bedrock anomalies (e.g., a bit of basic rock in an acidic or granitic rock terrain), the thickness and composition of soils, and position in the watershed all affect how lakes and streams respond to acidic inputs. For example, high-elevation lakes are often sensitive to acidification from atmospheric deposition owing to their generally small catchment areas, thin soils and low bedrock weathering rates (Strang et al. 2010). Thicker soils, especially those rich in base cations, imply a longer contact time with percolating water, and more neutralization of acidic rain or meltwater. Receiving waters at the downstream end of a watershed tend to be less acidic than those at the upstream end. As surface waters flow toward downstream receiving waters, some of the acid will be consumed enroute by way of various chemical processes, including cation exchange, and sulphate reduction/storage in wetland and lake sediments.

There is ample evidence that acidic deposition depletes the acid neutralizing capacity of lakes with low levels of base cations (Sullivan et al. 1988), and that it results in higher sulphate levels and lower pH and alkalinity in lakes within acid-sensitive terrain (Neary and Dillon 1988;

Sullivan et al. 1988). The more sensitive the terrain (i.e., the thinner the soil, and the lower its base saturation or buffering capacity) the less deposition it will take for acidity to rise to levels that will damage biota. Over the short term, base cation exchange within soils will help buffer acidic inputs to surface waters. Where base cation pools diminish over time, aluminum concentrations and soil acidity increase, causing both the acidification of surface waters and potential toxic effects on biota. In acid-sensitive regions of eastern North America, atmospheric deposition has been responsible for acidifying most (75%) of the acidic lakes and about half (47%) of the acidic streams (Baker et al. 1991).

One of the consequences of acidic deposition in North America and Europe has been the apparent loss of organic acids (DOC) from surface waters (Marmorek et al. 1988; Irving et al. 1991; Yan et al. 1996; Christensen et al. 2006). Dissolved organic carbon can also be lost from surface waters through a process called photolysis, and the rates of this process are increased at low pH (Gennings et al. 2001). Photolysis is the process by which dissolved organic carbon is decomposed into smaller molecules (including CO_2) by natural light, especially ultraviolet light. Consequently, the more deeply ultraviolet light penetrates into the water column, or the more often deeper waters get moved to the surface under the influence of the wind, the more impact photolysis will have on DOC levels. As DOC levels decline in response to acidification, the depth to which ultraviolet radiation can penetrate increases (e.g., up to 3-fold in one study lake near Sudbury, Ontario) (Yan et al. 1996).

Acid deposition can also increase the concentration of aluminum in soil waters, lakes, and streams to toxic levels (Driscoll et al. 2001a). Metal solubility increases as pH declines, and many acidic surface waters have elevated concentrations of aluminum (Baker et al. 1990). Mercury concentrations in water can also increase with declining pH. Inputs of aqueous sulphate (SO_4) correlate with increased biomass of sulphate-reducing bacteria and increased concentrations of methylmercury in both surface waters and biota (Gilmour and Henry 1991).

3.5.4 Direct effects of SO_2 and indirect effects of sulphur deposition on vegetation

Sulphur is a naturally occurring element that is an essential nutrient for plants, and plant tissues accumulate substantial concentrations of sulphur in the form of sulphate (SO_4^{2-}) and other compounds (Laurence 2012). As concentrations of SO_2 in the atmosphere and length of exposure increase, they become toxic to plants (Laurence 2012). Emissions from the combustion of fuels containing sulphur and the processing of ores that contain sulphur represent major sources of sulphur in the atmosphere. Aluminum smelters are also sources of SO_2, but they typically produce smaller emissions than those associated with fuel combustion and ore processing (Laurence 2012).

Sulphur dioxide is taken up by vegetation through stomata. Consequently, conditions that promote stomatal opening such as temperature, relative humidity, light intensity, moisture status, and time of day/year, affect the uptake of SO_2 and ultimately its effect on the plant

(Laurence 2012). Because the physical environment influences SO_2 uptake, the biological response of plants to elevated sulphur dioxide levels is hard to predict. Different plant species, and genotypes within species, also respond differently to SO_2 resulting in a range of sensitivity. There is a large body of research that clearly establishes a direct effect of prolonged SO_2 exposure on the growth and yield of agricultural crops, the growth of trees, and on the occurrence of foliar injury (e.g., NRC 1978 literature review; U.S. EPA 2008b). However, there are relatively few studies that report the sensitivity of species that are frequently found in the vicinity of Rio Tinto Alcan B.C. Operations. Table 3.5-1 summarizes what NRC (1978) reported for those species.

Table 3.5-1: Ambient exposures to SO_2 that caused visible injury to plant species (after NRC 1978).

SO_2 concentration ($\mu g/m^3$) [a] that caused injury at an averaging time of:				Species
1 hour	2 hours	4 hours	8 hours	
1071	993	862	784	Willow (*Salix* sp.)
1071	993	888	679	Larch (*Larix* sp.)
1097	1019	679	340	Quaking aspen (*Populus tremuloides*)
1202	993	732	549	White birch (*Betula papyrifera*)
2143	1698	1176	679	Balsam poplar (*Populus balsamifera*)
2273	2064	1829	1307	White spruce (*Picea glauca*)
1986	1646	1385	1019	Raspberry (*Rubus idaeus*)

[a] The units in the NRC (1978) table were ppm, and have been converted to be consistent with units used for ambient SO_2 elsewhere in this report. The conversion factor used was 1 ppm = 2,620 $\mu g/m^3$ at 25°C and 1 atm (see http://www.scribd.com/doc/69355960/Air-Dispersion-Modeling-Conversions-and-Formulas).

Vegetation can be directly and indirectly damaged by SO_2 through exposure to acidic rain, fog, and cloud. Direct effects include the leaching of calcium, magnesium and potassium from needles and leaves (Cape 1993; Wulff et al. 1996; Likens et al. 1998; Horsely et al. 2000) and branches (Likens et al. 1998), reduced cold tolerance (Mohnen 1988; Driscoll et al. 2001a), loss of chlorophyll (Laurence 2012), and visible damage to leaf surfaces (Cape 1993; U.S. EPA 2008b; Laurence 2012). In regions with large SO_2 sources – such as electricity generating stations with emissions on the order of 100,000 t/yr (which is over 6.5 times more than KMP's SO_2 load) – cloud bases and fog can be quite acidic. Under these conditions, vegetation (and soils) swathed in acid fog or clouds, as high altitude forests can be, get directly exposed to extremely acidic conditions (Mohnen 1988; Cape 1993). Direct effects of acid rain and acid fog have been documented in the literature as a result of exposure under controlled conditions, although many species are quite resistant (Laurence et. al. 1996, 1997).

Indirect effects on vegetation can arise through altered soil processes (U.S. EPA 2008b). For example, acidic deposition that increases soil acidity can, in turn, increase the concentration of aluminum in soil waters, lakes, and streams to toxic levels (Driscoll et al. 2001a). Too much aluminum in the soil can interfere with the functioning of fine tree roots, block the uptake of calcium, and result in decreased growth and increased susceptibility to stress (Mohnen 1988; Lawrence et al. 1995; Driscoll et al. 2001a).

Calcium is a macronutrient for trees (Lawrence et al. 1995, 1999) and other biota, and it is important for sustaining growth (Watmough and Dillon 2003a). The process of acidification leaches calcium from the soil (Likens et al. 1998; Lawrence et al. 1999; Driscoll et al. 2001a; Watmough and Dillon 2003a), making less available for uptake by roots to replenish losses in the canopy. Acidification may also deplete other soil nutrients such as magnesium and potassium (Watmough and Dillon 2004). The decline and mortality of maple trees, particularly in high elevation stands, is occurring in places where soil calcium and magnesium have been depleted by acidic deposition (Driscoll et al. 2001a). High elevation coniferous stands in the eastern United States have also been severely affected by acidic deposition (Mohnen 1988).

Over the past four decades, technological solutions have dramatically reduced emissions of SO_2 into the atmosphere in North America, and the acute and chronic effects of SO_2 on vegetation have disappeared for the most part (Cape et al. 2003). Along with improved conditions has come a waning of interest in conducting research and experimentation on the effects of SO_2 on vegetation, so little has been added to the scientific literature about the direct effects of the pollutant on plants (Laurence 2012). A literature review by Laurence (2012), reproduced in its entirety in Appendix 3.5-1, outlines the current state of knowledge on the sensitivity of plant species to SO_2, reviews what is known about uptake and accumulation of sulphur, discusses the results of additional studies reported in the scientific literature since about 2000, and reviews the use of critical loads to describe pollutant deposition.

Long-term effects on lichens and epiphytes have also been reported in the literature, but it is unclear whether those effects are direct effects due to SO_2 exposure or indirect effects from acidification. Additionally, there are published studies that describe the effect of SO_2 exposure on the development of plant diseases (generally an inhibitory effect) and on insect infestations (reported increases associated with secondary pests feeding on weakened trees) (Laurence 2012).

The forest in the vicinity of Kitimat experienced a destructive outbreak of saddleback looper (*Ectopus crepuscularia*) and spruce budworm (*Cristoneura orae*) from 1960 to 1969. Studies by Reid, Collins, and Associates (Bunce 1985) calculated the volume loss due to the infestation and estimated growth reductions that could be ascribed to emissions from the smelter, which were substantially greater then, especially in particulate fluoride, than they are today. The stands at the time were classified as “uneven-aged, overmature, decadent and stable climax forest.” The authors advanced seven hypotheses for the outbreak ranging from attraction of insects to lights

in the valley, to emissions from the smelter either weakening the trees or killing parasites of the insects. They state in the end "there is no direct evidence to relate any of these hypotheses to actual events." They note that such infestations have not been documented in the vicinity of other smelters. Also, as of this writing (more than 50 years later), there have been no other noteworthy infestations in the area.

Additional studies of lichen populations by Reid, Collins and Associates (Bunce 1978; Richards 1986) noted that lichen populations had declined on the west side of the valley and that the decline continued after reductions in fluoride emissions. Concentrations of SO_2 from all sources were not quantified.

3.5.5 Direct effects of SO_2 and indirect effects of sulphur deposition on fish and other biota

The biological impacts of acidification, and associated metal contamination, on aquatic systems range from changes in relative abundance of species to extinction of populations (Yan and Welbourn 1990). Even modest amounts of acidity can cause some damage in certain areas. For example, in sensitive areas where acidification is most likely to occur, the early life stages of many freshwater fish species will be close to their survival threshold and only a slight decline in water quality can result in the loss of a complete year class, which would affect recruitment and eventual population status (Sayer et al. 1993).

A surface water pH of less than 6.0 produces conditions that are damaging to many species (Keller et al. 1990; Havens et al. 1993; Holt et al. 2003). Damage occurs directly in response to reduced pH and calcium, and increased aluminum (e.g., impaired reproduction, increased mortality), and indirectly in response to alterations in the food web. The more acidic the water becomes, the more serious the biological consequences. Acidification of surface waters has resulted in a decrease in the survival, size, and abundance of fish and in the loss of fish and other aquatic biota from lakes and streams (Driscoll et al. 2001a).

As pH declines, all levels of the aquatic food web are affected (Mierle et al. 1986). There is clear evidence that the acidification of surface waters to pH levels below 6.0 damages both lake (Conlon et al. 1992; Hesthagen et al. 1999) and river (LaCroix 1985; LaCroix et al. 1985; LaCroix and Townsend 1987; LaCroix and Knox 2005) salmonids and other sport fish (Hulsman et al. 1983; Marmorek et al. 1986; Weiner et al. 1986; Matuszek et al. 1992), zooplankton (Keller et al. 1990; Locke 1992; Brezonik et al. 1993; Havens et al. 1993; Holt et al. 2003), phytoplankton (Nicholls et al. 1992), and aquatic plants (Yan et al. 1985). The early (embryonic and larval) life stages of amphibians are also sensitive to acidification (Baker et al. 1990). Sensitivity varies widely by species (Pierce 1993), but mortality typically begins to occur at about pH 5.0 (Eilers and Berg 1982, cited in Bangay and Riordan 1983:3-102). Water with a pH below 4.5 generally causes complete mortality of embryos among the more sensitive species; tolerant species can achieve 100% hatching success at pH levels as low as 4.0 (Baker et al. 1990).

Species richness (i.e., the number of different species present) falls across all groups of biota as pH declines (Minns et al. 1990), including among higher vertebrates. For example, the reproductive failure of ducks in acid stressed areas of Ontario has been linked to reduced availability of insect prey for ducklings (Mierle et al. 1986). Acidification and increasing levels of toxicants in aquatic systems may also have a negative impact on river otters (*Lutra canadensis*) through reduced abundance of food (primarily fish) and bioaccumulation of toxic compounds (Stenson 1986; Yarrow 2009).

As a general rule, small-bodied, rapid reproducers tend to be more resistant to increasing acidification than are large-bodied species (Yan and Welbourn 1990) with longer life spans (Locke 1992). In aquatic communities, the rate of food uptake and growth are intimately linked to organism size. Changes in the size structure of communities may therefore have profound implications for energy flow (Yan and Welbourn 1990).

The response of fish populations to acidification depends on the sensitivity of the species to acidic conditions, the degree to which sensitive life stages are exposed to toxic levels of pH and aluminum, and the ability of the population to compensate for acid-induced mortality and stress (Baker et al. 1990). Most fish are very sensitive to the toxic effects of increasing acidity. Decreased pH and elevated aluminum, within the range that occurs with acidic deposition, have been shown to increase fish mortality, decrease fish growth, decrease fish egg production and/or embryo survival, and cause other physiological effects (Baker et al. 1990). Early life stages are more sensitive to acidity than later life stages. Many of the most sensitive fish species are commercially and/or recreationally important, e.g., salmonids (Marmorek et al. 1986). In British Columbia, salmonids are not only commercially important, but also culturally and spiritually important for many First Nations communities. Laboratory and field studies rank rainbow trout (aka steelhead) (*Oncorhynchus mykiss*) as the most sensitive to increasing acidity, followed by Atlantic salmon (*Salmo salar*), followed by brown trout (*Salmo trutta*), followed by brook trout (*Salvelinus fontinalis*) (Baker et al. 1990). For rainbow trout, which is a very important commercial and recreational species in the Kitimat area, egg and fry survival is adversely affected by acidification to pH values below 5.5 (Hulsman et al. 1983; Weiner et al. 1986).

Indirect effects of acidification can also impact aquatic ecosystems. Where acidification causes the decline or elimination of prey species, predator species (e.g., commercial and sport fish) are indirectly affected by the impoverishment of their food supply (Yan and Welbourn 1990).

Terrestrial wildlife, particularly species that prey on fish or aquatic invertebrates, can also be indirectly affected by acidification through declining abundance and accessibility of prey (Mierle et al. 1986). The implications for aquatic and riparian birds include impacts to migration and staging, energy acquisition (protein, nutrients), egg production, and brood rearing (Weeber 2008). Acidification may also reduce concentrations of essential elements such as selenium and calcium in prey. Reduced dietary calcium may affect egg production and the growth of young

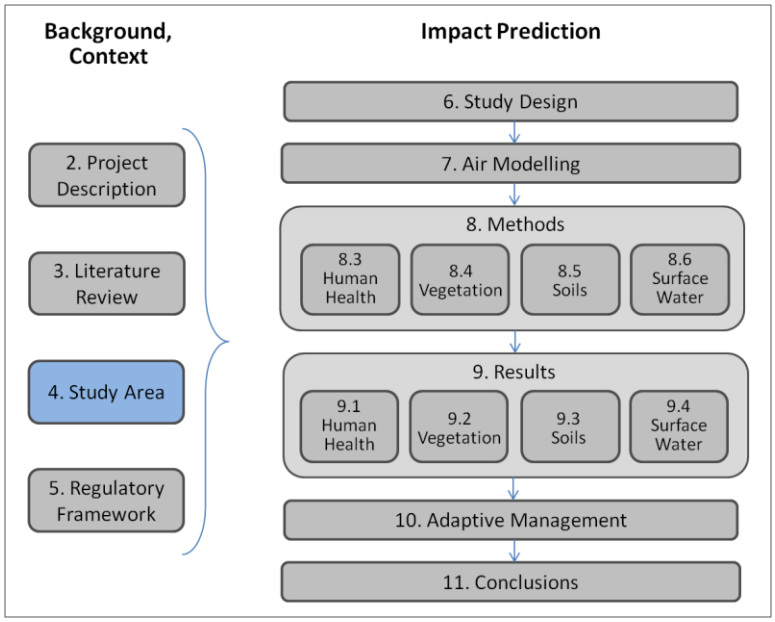
(Mitchell 1989; Weeber 2008). Birds that eat fish such as loons, mergansers, herons, bitterns, ospreys, eagles, and kingfishers are most at risk from increasing acidification (Mitchell 1989). Waterfowl, shorebirds, and many passerines consume invertebrates caught in aquatic systems or flying emergent insects that have aquatic larval stages. Decreases in pH eliminate those invertebrate species that are intolerant. Metal toxicity arising from acidification may also be an issue for birds that feed in or near acid-stressed lakes, wetlands, and streams.

Birds of the forest canopy may also suffer indirect effects from acidification. In Ontario, large scale losses of the tree canopy are predicted to lead to a decreased abundance of birds that rely on the canopy for food and shelter (OMNR 1992). Other forest wildlife may be indirectly affected by acidification through metal toxicity. As soils acidify, metals and other contaminants (especially cadmium) become more available for uptake by the plants on which animals feed, e.g., lichens. In Canada, moose and deer accumulated such high concentrations of cadmium in their livers and kidneys that these organs were declared unfit for human consumption in several provinces (OMNR 1992).

Evidence for direct impacts of SO_2 on terrestrial animal species comes largely from experimental studies on small mammals and domestic livestock. In mice, for example, acute inhalation of SO_2 constricted the airways, increased the production of mucus, and reduced the ability to resist bacterial infection (Costa and Amdur 1996, cited in WBK & Associates Inc. 2003). Even short exposures at low levels (<2,600 $\mu g/m^3$) triggered immediate physiological responses, but did not result in permanent damage to the respiratory system. For rabbits, acute exposure to SO_2 gas (16,000 $\mu g/m^3$ for 4 hours) irritated the eyes, causing conjunctivitis, infection, and watering (WBK & Associates Inc. 2003). For cats and guinea pigs, short exposures (30 minutes) to concentrations up to 26,000$\mu g/m^3$ produced respiratory distress, but the effects disappeared when exposure stopped (Corn et al. 1972 and Amdur 1978, cited in WBK & Associates Inc. 2003). Cattle exposed to SO_2 gas (no concentrations reported) responded with mild bronchial constriction, changes in metabolism, and irritation of the respiratory tract and eyes. Cattle mortality as a result of major incidents of air pollution (SO_2, sulphuric acid, acid fog) has been reported in Europe and in Montana (WBK & Associates Inc. 2003).

Studies of SO_2 exposure on terrestrial wildlife are rare. In Czechoslovakia, low blood calcium and protein levels were reported in wild hares exposed to SO_2 concentrations greater than 150 $\mu g/m^3$ and fly ash (>300t/km^2/yr) (WBK & Associates Inc. 2003). A two-year study at Whitecourt Forest (Alberta) downwind of industries producing SO_2 reported no adverse impacts on moose density, productivity, or habitat utilization. Sulphur dioxide concentrations were not measured in this study, however, releases in the area were thought to be low (the average rarely exceeding 520 $\mu g/m^3$), short (only minutes, rarely hours), and infrequent (Wride 1975, cited in WBK & Associates Inc. 2003).

4.0 Environment and Communities of the Study Area



4.1 THE STUDY AREA

4.1.1 Bounding the study area

The study area for the technical assessment study is defined by the maximum extent of the air dispersion modelling done (see about the study design, Section 6.0), shown by the dashed line in Figure 4.1-1. This rectangular modelling domain has a total area of 2,895 km^2, with an east-west dimension of 30 km and north-south dimension of 96.5 km. It was designed to include the main plume from the smelter, all communities and vegetation which might be affected by [SO_2], and all soil and water receptors which might be affected by dry and wet deposition of sulphur. Our analyses in Section 9.0 confirm that the study area was indeed broad enough to include all anticipated potential effects of KMP on human, vegetation, water and soil receptors.

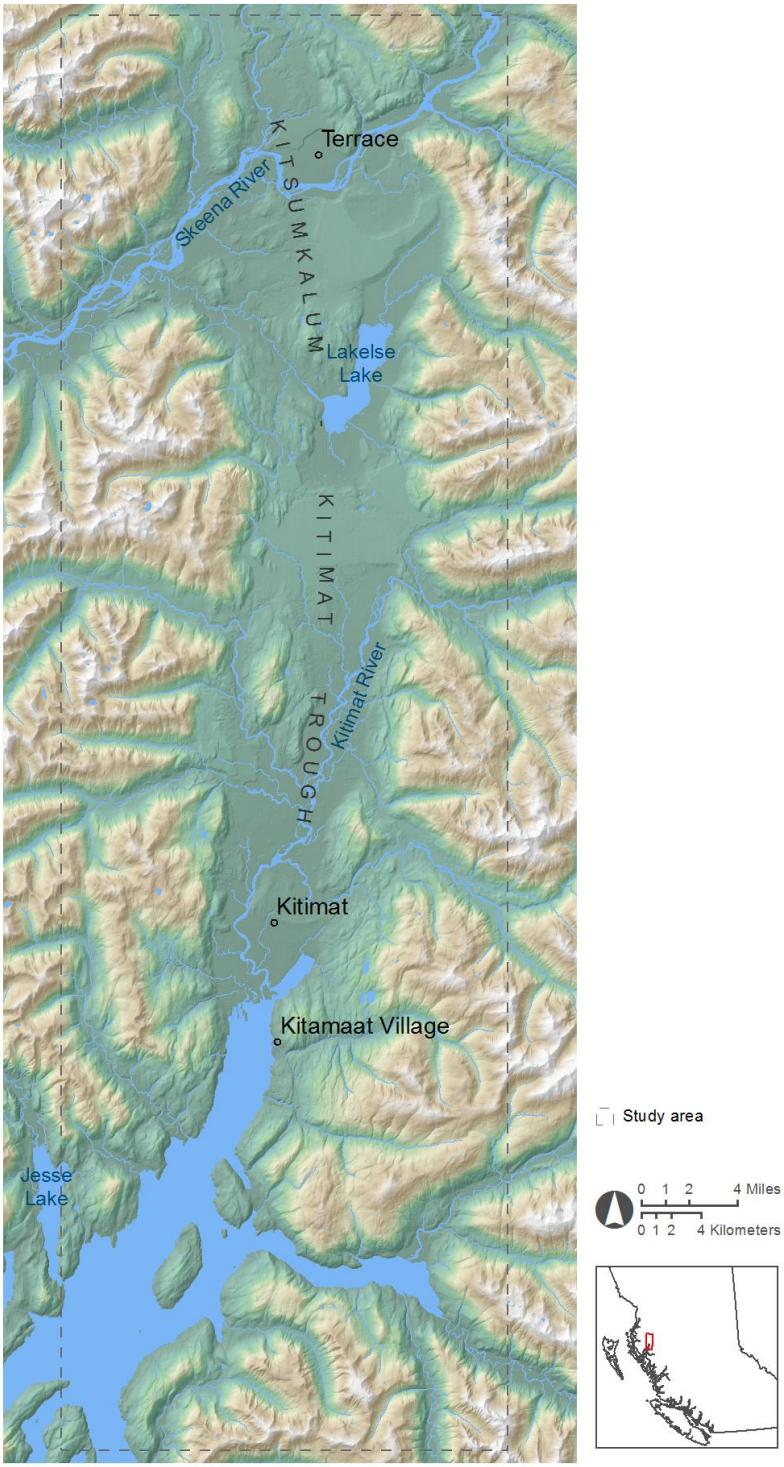


Figure 4.1-1: Technical assessment study area (dashed rectangle), showing Kitimat Valley terrain.

4.1.2 Description of the valley and airshed

The Kitimat Valley is a wide area of low and generally simple terrain (Johnson 1995), stretching from tidewater at the town of Kitimat in the south to beyond the city of Terrace, approximately 50 km to the north (see Figure 4.1-1). It is part of the Kitsumkalum-Kitimat Trough (see Figure 4.1-1), which trends southward from Kitsumkalum Lake, intersecting the Skeena Valley at Terrace, and continuing down the valley to the sea at Kitimat. The trough is up to 15 km wide and its floor is below 300 m in elevation (Clague 1985). Historically, most of the area below 1,500 m elevation was forested, but the 20th century saw large parts of the valley cleared for forestry, agriculture, and other human activities (Clague 1994).

The terrain surrounding the valley is much more complex, and includes mountainous areas with peaks in the range of 1,700 m in elevation (Johnson 1995). The Coast Mountains border the valley to the west, and the Hazelton Mountains rise to the east. Subsequent sections of this report describe the lakes and streams of the Kitimat Valley (Section 4.2), its geology and soils (Section 4.3), flora and fauna (Section 4.4), patterns of land use (Section 4.5), and the human communities in the area (Section 4.6), including First Nations (Section 4.7).

Air temperature and precipitation are strongly influenced by topography (Clague 1984). From late spring through early autumn, the climate in the Kitimat Valley tends to be relatively mild, with the lowest monthly precipitation totals and temperatures in the 15 to 20^{o}C range. The period from late fall through early spring is characterized by much colder temperatures (-5 to 5^{o}C) and heavier precipitation amounts. The presence during the winter months of frequent storm systems, moving inland from the Pacific Ocean, enhances the precipitation events and leads to more overall variability in wind direction (Trinity Consultants 2007). The mean annual precipitation is 2,232 mm, and the town of Kitimat receives nearly 1,400 hours of sunshine per year (Johnson 1995).

In the B.C. Ministry of Water, Land and Air Protection's *Guide to Airshed Planning in British Columbia* (Williams and Bhattacharyya 2004), an airshed is described as an area where the movement of air (and, therefore, air pollutants) can be hindered by local geographical features (e.g., mountains) and by weather conditions. Based on recent history, the climate in the Kitimat area is characterized by southerly winds (blowing northward) throughout the late fall and winter seasons, which carry emissions from Kitimat through the Kitimat Valley towards Terrace (Trinity Consultants 2007). Northerly winds (blowing southward) dominate for the other months of the year, carrying emissions from Kitimat out over the Douglas Channel. Consequently, the Kitimat Valley airshed is primarily contained within the Kitimat Valley, and includes Kitimat and Terrace (Trinity Consultants 2007) (see Figure 4.1-2).

Figure 4.1-2: Kitimat Valley and region, showing topography that strongly influences the movement of air masses through the Kitimat Valley.

Historically, the major sources of air emissions in B.C. have been large industrial operations that are regulated by the province through permits. However, over the past two decades, the relative contributions from other sources, such as motor vehicles and biomass (primarily wood) burning, have increased (Trinity Consultants 2007). The pollutants of greatest concern in B.C. are particulate matter (PM) and ground-level ozone (O_3). These pollutants are widespread and can have serious implications for health and the environment (Williams and Bhattacharyya 2004). Other pollutants of concern include sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), total reduced sulphur (TRS), persistent organic pollutants (POPs), lead (Pb), and volatile organic compounds (VOCs) (Table 4.1-1).

Table 4.1-1: Main air pollutants in British Columbia (after Williams and Bhattacharyya 2004).

Pollutant	Description and Sources	
Particulate Matter (PM) Dust, soot, and tiny bits of solid material.	**PM_{10}** Particles smaller than 10 µm in diameter	• Road dust; road construction • Mixing and applying fertilizers/pesticides • See $PM_{2.5}$ below
	$PM_{2.5}$ Particles smaller than 2.5 µm in diameter	• Combustion (motor vehicles, forest fires, woodstoves and fireplaces) • Industrial activity • Garbage incineration • Agricultural burning
Ground-level Ozone (O3) Bluish gas with a pungent odour.	• At ground level, ozone is formed by chemical reactions between volatile organic compounds (VOCs) and nitrogen oxides (NO_x) in the presence of sunlight. • VOCs and NO_x are released by burning coal, gasoline, and other fuels; and VOCs naturally by vegetation (e.g., the smell from evergreen sap/needles).	
Other Pollutants	• SO_2: sulphur dioxide • CO: carbon monoxide • NO_2: nitrogen dioxide • TRS: total reduced sulphur • VOCs: volatile organic compounds • POPs: persistent organic pollutants • Pb: lead Most of these come from combustion and industrial processes or the evaporation of paints and common chemical products.	

In addition to the compounds listed in Table 4.1-1, polycyclic aromatic hydrocarbons (PAHs) and acid deposition also occur in the Kitimat Valley airshed. PAHs, a class of chemical products that includes over 4,000 compounds, are organic substances made up of aromatic ring structures (Government of Canada 1994; Trinity Consultants 2007). The compounds are products of incomplete combustion of high-molecular-weight hydrocarbon species. Sources of PAH can be natural, such as forest fires and volcanic eruptions, as well as anthropogenic, including fossil fuel combustion and industrial processes.

Ambient air quality in Kitimat and Terrace is monitored by the National Air Pollution Surveillance (NAPS) Network, the B.C. Ministry of Environment, and Rio Tinto Alcan. Unless

otherwise cited, the monitoring data in the following paragraphs for PM, NO_2, and SO_2 in the Kitimat Valley come from BCLA (2007); data for ozone, PAH, and acid rain come from Trinity Consultants (2007).

Over the course of three years, from 2004 to 2006, the average ambient level of $PM_{2.5}$ in the Valley ranged from approximately 9 µg/m^3 (in Kitimat) to approximately 11.5 µg/m^3 (in Terrace). In 2011, levels in both communities were below 4.0 µg/m^3 (BCLA 2012). In each case, concentrations are below the newest (2009) B.C. provincial standard for $PM_{2.5}$ which is 25 µg/m^3 (http://www.bcairquality.ca/regulatory/pm25-objective.html), and rank among the lowest in the province (BCLA 2007). The Canada-wide standard for $PM_{2.5}$ is 30 µg/m^3.

The 2006 ambient concentration of NO_2 in Kitimat was approximately 6 µg/m^3, which is below the National Ambient Air Quality Objective (NAAQO) of 60 µg/m^3 for NO_2. Ambient NO_2 concentrations in Kitimat were among the lowest concentrations monitored in B.C. in 2006. No data for Terrace were available because year-round NO_2 monitoring did not occur there that year. BCLA (2012) did not publish NO_2 monitoring results for either Kitimat or Terrace.

Ambient concentrations of SO_2 in 2006 had a maximum 1-hour concentration of 81.3 µg/m^3, with an annual average of 1.5 µg/m^3 for the Whitesail monitoring station (data from monthly reports to RTA from AGAT Laboratories). The Whitesail monitoring station is located within Kitimat's residential area. Among monitored communities in B.C. that year, the highest annual average SO_2 concentration was in Trail, followed by Prince George, downtown Vancouver, and Kitimat. These are all communities with one or more industrial sources, or where motor vehicles are major SO_2 contributors (Government of British Columbia 2007). No data for Terrace were available because year-round SO_2 monitoring did not occur there in 2006. In 2011, BCLA (2012) reported annual SO_2 levels for Kitimat that ranged from 3.9 to 14.9 µg/m^3, and 1-hour maximum levels for Kitimat that ranged from 164 to 425 µg/m^3.[6] The Whitesail monitoring station collected data between January and May 2011 and detected a maximum 1-hour SO_2 concentration of 34 µg/m^3, with a January through May average of 1.3 µg/m^3 (see footnote) (data from monthly reports to RTA from AGAT Laboratories). All reported levels are below the respective B.C. objectives for SO_2, which are 25 µg/m^3 for annual and 450 µg/m^3 for 1-hour maximum concentrations.

Ozone data were collected in Kitimat by B.C. MOE from May to November, 1997. During that time, the monthly average of 1-hour ozone data ranged from 18.6 µg/m^3 to 32.5 µg/m^3. These ozone concentrations are below the 100 µg/m^3 1-hour NAAQO for ozone.

PAH levels in Kitimat are monitored by Rio Tinto Alcan, on a schedule that coordinates with the NAPS Network. In 2005, PAH concentrations ranged from 18 to 138 ng/m^3. In 2006, levels

[6] SO_2 concentrations are measured at actual temperature and pressure in units of parts per billion; conversions to units of µg/m^3 are made at standard atmospheric conditions of 25°C and 1 atm (101.325 kPa).

ranged from 16 to 70 ng/m^3. No B.C. or national objectives exist for PAH (WHO 2000; Trinity Consultants 2007).

Rio Tinto Alcan also monitors rain chemistry at its Haul Road monitoring station near the smelter site. The pH of normal rain ranges from 5.0 to 6.5. From 2001 through 2006, the average annual pH of rainwater ranged from 4.46 to 4.92. Although no B.C. or national objectives exist for pH, the monitored rainwater was below pH 5.6, and as such complies with the definition of acid rain as defined by Environment Canada (2012). Given how close the monitoring station is to the smelter, it is very likely that this result is not representative of the entire study area.

4.2 SURFACE WATERS – LAKES AND STREAMS

Most watercourses in the Kitimat Valley originate from glacial melt; they carve steep, narrow channels that are sensitive to disturbance and subject to erosion and sediment delivery events (Government of British Columbia 2002). Streams are much more common than lakes in the study area. However, lakes are of particular interest for acidification research because they are less affected by storm flows and snowmelt events, making their water chemistry more stable than that of streams.

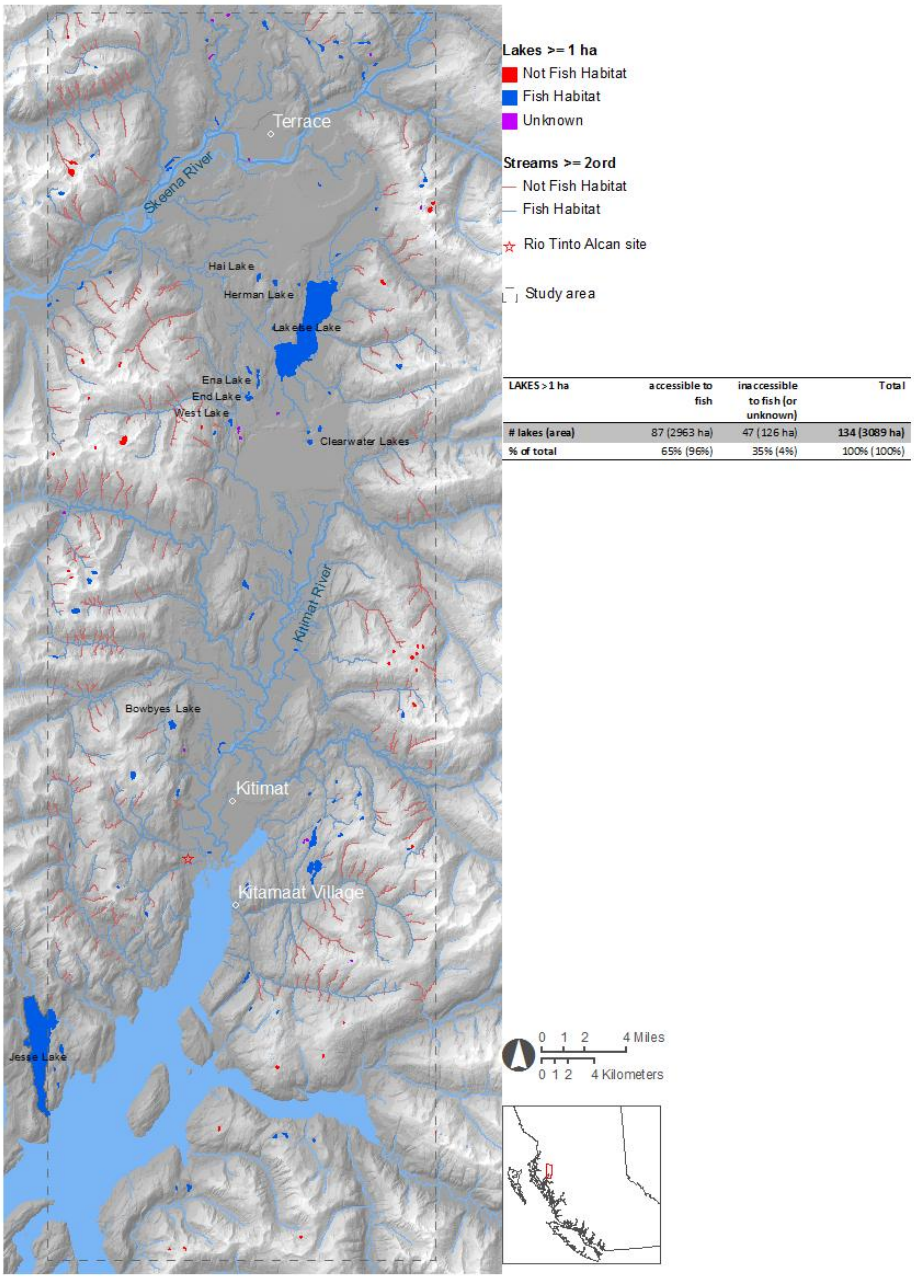
The technical assessment study area is the extended area modelled for [SO_2] and S deposition by Trinity Consultants (Figure 4.2-1). Additional information about the study area can be found in Section 8.6.1 of this report. Within the study area, there are 134 lakes greater than 1 ha in size, and 2,053 km of non-headwater (i.e., second order or higher) streams. Based on GIS analysis, 87 (65%) of the 134 lakes and 1,505 km (73%) of stream in the study area are considered accessible to fish (see Table 4.2-1 and Figure 4.2-1).

Table 4.2-1: Attributes of lakes and streams within the technical assessment study area defined by [SO_2] and S deposition modelling.

LAKES >1 ha	**accessible to fish**	**inaccessible to fish (or unknown)**	**Total**
# lakes (area)	87 (2,963 ha)	47 (126 ha)	**134 (3,089 ha)**
% of total	65% (96%)	35% (4%)	100% (100%)
STREAMS ≥ order 2			
km streams	1,505	548	**2,053**
% of total	73%	27%	100%

Most of the inaccessible lakes and streams are at higher elevations or along the steep gradients of side valleys to the east and west of the Kitimat River. Streams considered accessible to fish are those with a gradient less than 25% and no known barriers to fish movement. Some fish

species (e.g., bull trout, *Salvelinus confluentus* and Dolly Varden char, *Salvelinus malma*), may be able to ascend gradients up to 25%, but it is considered unlikely that any fish could ascend gradients greater than 25% (Mount 2008).



LAKES > 1 ha	accessible to fish	inaccessible to fish (or unknown)	Total
# lakes (area)	87 (2963 ha)	47 (126 ha)	134 (3089 ha)
% of total	65% (96%)	35% (4%)	100% (100%)

Figure 4.2-1: Map of lakes and streams within the study area modelled for [SO_2] and S deposition (dashed line). The lakes and streams considered accessible to fish are shown in **blue**; inaccessible lakes and streams are shown in **red**.

Of the fish-accessible lakes in the study area, **Lakelse Lake** is the largest (1,374 ha in size). It is located in the Kitsumkalum-Kitimat Trough of the Coast Mountain Range, 40 km north of the town of Kitimat (Figure 4.2-1). The lake has a north-south axis and sits approximately 70 m above sea level. It is quite shallow, with 42% of the bottom in the littoral zone (Leggat 2009). The average depth of Lakelse Lake is 8 m, and the maximum depth is 32 m (Skeena Fisheries Commission 2003). The lake is approximately 8.7 km in length, and has an average width of 1.2 km. There are four main tributaries on the east side of the lake that account for 73% of the Lakelse Lake Watershed area – Williams Creek, Furlong Creek, Hatchery Creek, and Schulbuckhand (Scully) Creek. Due to the shallow nature of the lake, and large volumes of water from tributary streams, Lakelse Lake flushes on average every 58 days (Kerby 1984, cited in Skeena Fisheries Commission 2003). The outlet of Lakelse Lake flows into Lakelse River with a mean annual discharge of 20 m^3/s (Skeena Fisheries Commission 2003). Mount Hipp, Mount Catt, and Mount Gordon to the west and the mountainous country of the Kitimat Ranges to the east exert the major hydrological influences. Coastal weather systems also affect the lake, leading to heavy snow packs and precipitation in the mid- and upper elevations of the watershed (Skeena Fisheries Commission 2003).

Lakelse Lake is considered to be oligotrophic because of low phosphorus concentrations, low oxygen depletion rates in bottom waters, and low chlorophyll *a* concentrations (Skeena Fisheries Commission 2003). Water quality is considered to be high. However, there are concerns that rural developments and associated septic systems around the lake may be putting water quality at risk (Skeena Fisheries Commission 2003).

Lakelse Lake is of great importance to local communities and First Nations, as noted by the Skeena Fisheries Commission (2003:17):

> "The Lakelse Watershed possesses very high fisheries values and is one of the premier watersheds of the Skeena system. It is a major producer of sockeye, coho and pink salmon as well as supporting chum, Chinook, and steelhead populations."

Jesse Lake is another large (1,167 ha) fish-accessible lake in the Valley, located in the extreme southwest of the study area (Figure 4.2-1). It is an unusual lake, with an outlet only 50 m from the sea, a surface elevation only 11 m above sea level, and a depth of greater than 100 m. Its deepest point is therefore at least 90 m below sea level. All of Jesse Lake's area was included in this technical assessment study.

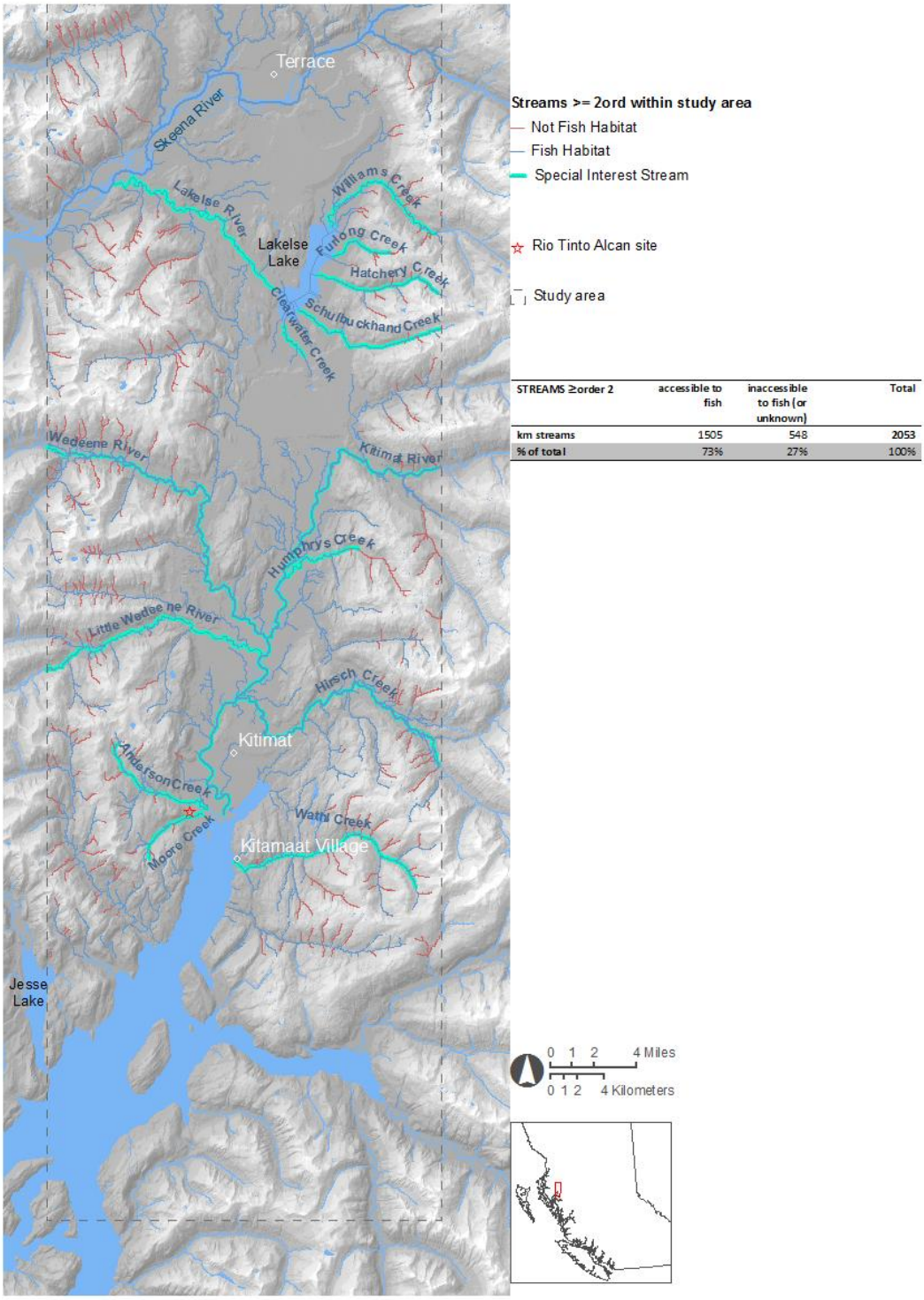
Of the fish-accessible streams and rivers, 14 are considered to be of high public interest, due to their use for fishing, water-based recreation and/or water supply. These special interest streams and rivers are listed in Table 4.2-2, and their locations are shown in Figure 4.2-2. Each of the 14 streams is briefly described below; the accompanying photographs were taken by

Chris Perrin, Limnotek Research & Development Inc., during the field reconnaissance phase of the study (August 12-21, 2012).

Table 4.2-2: Attributes of rivers and streams within the study area selected for closer examination due to high public interest. Locations of these streams and rivers are shown in Figure 4.2-2.

Stream or River	Length within Study Area (km)	Stream Order
Kitimat River	47.0	6,7
Williams Creek	13.6	5
Lakelse River	21.2	5
Scully (Schulbuckhand) Creek	13.4	3
Furlong Creek	5.5	3
Anderson Creek	11.4	3,4,5
Humphreys Creek	5.7	3
Hirsch Creek	25.6	5,6
Moore Creek	6.6	2,3,4
Clearwater Creek	4.3	2,3
Hatchery Creek	10.7	3,4
Wedeene River	32.3	5,6
Little Wedeene River	21.6	4,5
Wathl Creek	17.8	3,4,5

The **Kitimat River** drains an area of 1,966 km^2, arising on the southwestern slopes of Mount Davies and flowing approximately 75 km to discharge onto the tidal flats of the Kitimat Arm (MacDonald and Shepard 1983). The river flows through the Kitimat Valley in a series of meandering channels, where it is joined by its main tributaries – the Wedeene River, the Little Wedeene River, and Hirsch Creek. The Kitimat River is popular for canoeing, kayaking, and class two white-water rafting (District of Kitimat 2012). It is also highly valued for its salmon, trout, and steelhead (*Oncorhynchus mykiss*) fishing (LSM & RM 2003), and is one of the most heavily used sport fisheries in British Columbia.



STREAMS ≥order 2	accessible to fish	inaccessible to fish (or unknown)	Total
km streams	1505	548	2053
% of total	73%	27%	100%

Figure 4.2-2: Streams and rivers identified to be of special interest within the study area.

The water of the Kitimat River is also used for industry, including a fish hatchery, and as a source of drinking water for the people of Kitimat. Drinking water is supplied through a system of three infiltration wells located adjacent to the river. The river also serves as a secondary water source for the Kitimat smelter works. Water quality in the lower reach is affected by sewage outfall from the District of Kitimat, residual (non-operational) industrial effluent from Eurocan Pulp and Paper (which closed in January 2010; West Fraser Timber Co. Ltd. 2009), and by the fish hatchery operated by Fisheries and Oceans Canada. Upstream from these sources, water quality meets current standards for drinking, recreation, and aquatic life most of the time. Downstream water quality is not appreciably different because residence time for water in the river, before flowing into Kitimat Arm, is very short. Surface water in the watershed is characterized by extreme softness and elevated levels of non-filterable residues (MacDonald and Shepard 1983). Additionally, concentrations of aluminum, iron, and mercury are high, particularly in the upper portions of the watershed. In the lower mainstem, phosphorus concentrations are high.

Williams Creek is the most northerly of the streams in the study area (see Figure 4.2-2), and the major tributary flowing into Lakelse Lake (Weiland and Bird 2007). The creek has a watershed area of approximately 210 km^2 that accounts for approximately 44% of the water flowing into Lakelse Lake (Weiland and Bird 2007). The watershed includes a substantial alpine area, and relatively high peak flows are common in late spring (Leggat 2009). Williams Creek originates in a high-elevation valley surrounded by alpine crests ranging from 1,800 to 2,040 m above sea level. It flows through a narrow valley down to a floodplain where it forms a gravel bed channel that leads into a 4 km long alluvial fan. Stream length in the main valley is about 25 km, and bankfull width at the Highway 37 bridge is about 30 m. A very low gradient reach, with high value spawning habitat, connects Williams Creek to Lakelse Lake. Other than the quality spawning habitat at its outlet, Williams Creek is considered to be poor fish habitat (Weiland and Bird 2007).

The sediment regime in Williams Creek is dominated by coarse-textured materials, with limited suspended sediment. Heavy rain events cause increased turbidity which typically clears in 1 to 2 days. Sediment supplies come predominantly from natural hillside sources. Logging and road-related sediment sources that affect the creek are small and infrequent compared to natural sources (Weiland and Bird 2007).

The **Lakelse River** originates at the southwest corner of Lakelse Lake, and meanders in a northwesterly direction for 21.2 km along a very low gradient before draining into the Skeena River (Leggat 2009). Width ranges from 40 to 120 m, and channel stability is high. The Lakelse River is a fifth order system that drains a watershed area of 589 km^2, and takes a mean annual discharge from Lakelse Lake of 20 m^3/s (Skeena Fisheries Commission 2003). The greatest

discharges from the Lakelse River tend to occur in May and June as a result of snowmelt, and again in September/October due to fall rains and snow events.

The Lakelse River is one of the most biologically rich and productive rivers in the region. It is a high fisheries value river, supporting a strong recreational rainbow/steelhead, coho (*O. kisutch*), and cutthroat (*O. clarki clarki*) trout fishery (Skeena Fisheries Commission 2003). Proximity to Terrace and Kitimat, combined with high aesthetic values, contribute to the popularity of this angler destination (Government of British Columbia 2002). Many local people also use the area for other forms of recreation. The Lakelse River Corridor has been designated as a Special Resource Management Zone to maintain the integrity of this highly productive and unique river (Government of British Columbia 2002).

Because it arises from a lake, the Lakelse River has very low total suspended solids (Skeena Fisheries Commission 2003). Turbidity is also low, but the river is moderately coloured by natural organic substances that are not harmful to human health. pH is near neutral, ranging from 6.7 to 7.6 (mean = 7.1). Alkalinity is also low, indicating that the waterbody would be sensitive to acidic inputs (Skeena Fisheries Commission 2003). Nutrients are generally low, with metal concentrations often less than detection limits.

Schulbuckhand (Scully) Creek is one of four main tributaries flowing into Lakelse Lake. It is a third order stream with a total watershed area of approximately 29 km^2, 25% of which is in alpine snow and ice fields (McElhanney 1996, cited in Leggat 2009). The main stem valley is approximately 11.5 km long, and leads into a 3.5 km long low-gradient alluvial fan as it approaches its outlet at the lake. Several hot springs bubble to the surface on the Scully Creek fan; at approximately 85°C and with unique chemistry, there may be some local hydrothermal ecosystems (Leggat 2009).

Development on Scully Creek, in the form of extensive logging on the alluvial fan and agriculture on the floodplain and wetland, has had detrimental impacts on habitat quality for fish (Rabnett 2008, cited in Leggat 2009; Leggat 2009). The results of escapement surveys show that the Scully Creek sockeye (*O. nerka*) population plummeted in the mid-1990s, with no sign of recovery by the early 2000s (Rabnett 2008, cited in Leggat 2009). A combination of flooding (in 1978) and a flow diversion event (in 1993) lead to abandonment of the historic channel along the south side of the alluvial fan. This channel is now primarily groundwater fed, and does not get the freshets required to remove the beaver dams (a legacy of abandoned logging roads) and to recruit and clean the spawning gravels that once provided good spawning habitat (Leggat 2009). The northern and middle channels of Scully Creek flow through excavated

glaciomarine silt/clay material. Fine sediment slumps into the stream from the sides of the trenches, causing elevated levels of suspended sediments downstream (Leggat 2009). There are also concerns about water quality in these channels because there is an underlying layer of organic material. As organic material decomposes in a low oxygen environment, methane (CH_4), hydrogen sulphide (H_2S), and carbon dioxide (CO_2) are produced. Hydrogen sulphide is a highly toxic gas, and can react with oxygen to form sulphate (Leggat 2009).

Furlong Creek is a 5.5 km long tributary to Lakelse Lake, and it drains an area of about 11 km^2 (Leggat 2009). It travels through moderate to steep mountain terrain, and over a large alluvial fan before reaching the lake. The fan has been substantially altered by road construction, channel re-routing, and rural development. Additionally, construction of Highway 37 in 1962 required diversion of Furlong Creek's five original channels into one consolidated channel, and major landslides have been observed in the upper reaches (Maxwell 2002, cited in Skeena Fisheries Commission 2003). Additionally, old logging roads along the creek are suspected of causing drainage issues (Leggat 2009). In its lower reaches, Furlong Creek supports some spawning by Lakelse Lake coho (Skeena Fisheries Commission 2003).

Anderson Creek is 11.4 km in length, and runs east through the northern section of the Kitimat smelter works site. In the upstream reaches, the creek flows over a series of waterfalls (impassable to migrating fish) and into a large pool from which Rio Tinto Alcan draws water for use at the smelter. Downstream of this pool, Anderson Creek flows over a man-made weir (also impassable to fish), and then through a confined channel to an open fluvial fan where it then flows into the Kitimat estuary. Above the most downstream of the waterfalls, Anderson Creek does not support fish. Below the waterfalls, the creek supports resident trout and char. Below the weir, Anderson Creek becomes a productive stream for anadromous fish.

Humpreys Creek is a third order tributary of the Kitimat River. The mainstem of the creek is 12 km in length and between 12 and 32 m in width. The creek's substrate is sand/gravel in the lower reaches and boulder/cobble in the upper reaches. There is a waterfall at 2.5 km that is impassable to migrating fish (Lukuku and Stokes 2001). The Humphreys subbasin was extensively logged between the 1960s and early 1970s, with some harvesting again in the early 1980s and as late as 1992 in the upper reaches. The lowest reach of the creek has virtually no rearing habitat, because it lacks large woody

debris and off-channel habitat. Channel and riparian condition are rated as "fair" (Lukuku and Stokes 2001).

Hirsch Creek is a 42 km long tributary of the Kitimat River, and drains an area of 365.4 km^2.

There is a barrier to fish migration at Hirsch Creek Canyon, 8.1 km from the Kitimat River. Where the creek flows into the Kitimat River, there is a fluvial fan with unstable eroding banks, multiple channels, and non-vegetated bars (Lukuku and Stokes 2001). In this lowest reach, the channel varies in width from 15 to 180 m and has a boulder/cobble substrate. The creek's channel and riparian conditions are rated as "poor" in the first reach, but "fair" to "good" in the upper reaches where large woody debris recruitment is adequate (Lukuku and Stokes 2001).

Moore Creek is 6.6 km in length, and flows east through the central section of the Kitimat smelter works site. In its upstream reach, the creek flows over a large waterfall (impassable to fish migration) that is a local sight-seeing attraction. Tailed frogs are known to be present in the upper watershed. Through the smelter site, the creek has been channelized and straightened; below the site, it becomes unconfined and ultimately discharges into the Kitimat estuary. Where the creek has been channelized, there is no riparian vegetation and no large woody debris, making it poor fish habitat.

Clearwater Creek is a tributary to Lakelse Lake, flowing into it at the south end. Its mainstem is 4.3 km in length, and in many places it winds through wetlands in an undefined channel (C. Perrin, Limnotek, September 2012, pers. comm.).

Hatchery Creek (also known as Granite Creek) is a tributary that flows into the east side of Lakelse Lake. Approximately 24% of the watershed is in the alpine zone (McElhanney 1996, cited in Leggat 2009). The mainstem of Hatchery Creek is about 11.75 km in length and drains an area of 31 km^2. The creek cuts down through a proglacial delta and has created a large, low alluvial fan-delta complex that stretches into Lakelse Lake (Leggat 2009). Most of the alluvial fan was selectively logged during the 1970s, and the original channels have been diked to protect property values along the shoreline of Lakelse Lake. Confinement of the channel has lead to higher energy stream flows and more bedload movement than occurred prior to diking.

The **Wedeene River** (or Big Wedeene River) flows into the Kitimat River from the west, and drains an area of 306.4 km^2. The mainstem is 42.5 km in length, and between 25 and 150 m in width with a boulder/cobble substrate (Lukuku and Stokes 2001). Logging occurred in the watershed from the 1960s through the late 1980s. Culverts installed under logging roads have since become elevated such that they block fish access to historic spawning and rearing tributaries. Channel and riparian conditions in the Wedeene River have been rated as "fair" (Lukuku and Stokes 2001). On the whole, the mainstem is not well supplied with large woody debris, but recruitment is fairly good in the upper reaches where some trees were left standing. Harvesting also destabilized the banks of the river, and reduced the productive capacity of off-channel habitat (Acer 1997, cited in Lukuku and Stokes 2001).

The **Little Wedeene River** flows into the Kitimat River from the west, and drains an area of

197.8 km^2. The mainstem is 30.6 km in length and between 20 and 120 m in width with a boulder/cobble substrate (Lukuku and Stokes 2001). The subbasin was logged between the early 1980s and the early 1990s, and channel and riparian conditions are rated as "fair" (Lukuku and Stokes 2001). Some obstructions to fish passage are present along the mainstem, where road culverts have failed or beaver activity has reduced stream flow. Large woody debris recruitment is fairly good in the reaches where harvesting was less intense. Fish habitat is considered to be fair in the mainstem, but poor in the tributaries and side channel (Lukuku and Stokes 2001).

Wathl Creek flows into the Kitimat estuary from the east. Its mainstem is 17.8 km in length, and it has been an important water source for Kitamaat Village since 1959 (Rocha 2000).

See Section 9.4.1 for detailed information about the current water chemistry of the lakes and streams in the study area.

4.3 KITIMAT VALLEY GEOLOGY AND SOILS

4.3.1 The soil landscape

The study area consists of rugged mountains cut by deep valleys within the Coastal Western Hemlock biogeoclimatic zone (Krajina I973), and Mountain Hemlock and Alpine Tundra zones at higher elevations. In general the vegetation is a coniferous forest blanket. The terrain is underlain mainly by intrusive igneous rock. The major rock types consist mainly of Paleozoic to

early Tertiary granitic rocks and Proterozoic to Paleozoic high-grade metamorphic rocks (Hutchison et al. 1979). The most abundant granitic rocks are quartz diorite and granodiorite; diorite and quartz monzonite are less common; and gabbro and granite are rare. The intrusive rocks are relatively resistant to weathering. The residue from prolonged physical and chemical weathering provides a coarse textured, acid parent material.

The surficial geology of the area was mapped and described by Clague (1984). During the last glaciation the region was covered by the Cordilleran Ice Sheet. The types of sediments deposited were mainly cobbly to bouldery tills. During deglaciation, the Earth's crust slowly rebounded, at a much slower rate than the melting of the ice sheet causing coastal river valleys to be inundated by marine waters. Glaciomarine sediments were deposited as glaciers melted and retreated up the valleys (Geertsema and Schwab 1996).

Glaciomarine sediments cover substantial areas of the valley bottom between Kitimat and Terrace. Slopes above the marine limit (~200 m) are covered by drift and colluvium, or have bedrock at or near the surface (Clague 1984). In general, as slopes become steeper, the drift cover becomes thinner and more patchy. On slopes steeper than 30°, drift generally is subordinate to both thin colluvium and exposed or near-surface bedrock. Relatively large organic areas occur where drainage is poor (e.g., on glaciomarine muds south of Lakelse Lake).

Parent material, bedrock geology, and climate influence soil development in the region. The 'soil landscape' of the Coast Mountains is described in detail by Valentine et al. (1978). A soil landscape is thought of as the total ecosystem within which a particular soil is associated, with emphasis placed on the soil itself. For instance the morphology and chemistry of the Ferro-Humic Podzol soils in the region are described within the context of coarse textured acid parent materials, high rainfall, dense coniferous forest and rugged topography.

In the region, the dominant soils are Ferro-Humic and Humo-Ferric Podzols that have formed on colluvium, glaciofluvial and glaciomarine parent materials. The soils are moist to wet over most of the year. The soil temperature regime is mainly cold to moderately cold cryoboreal and the moisture regimes are dominantly perhumid. Excess moisture and a high incidence of associated poorly drained soils typify this landscape. The main soil processes are the accumulation of complexes of amorphous organic matter, iron and aluminum producing soils with exceptionally strong podzol B horizons. The soils may or may not have thin eluvial (Ae) horizons, are dominated by thick dark reddish B horizons rich in iron, aluminum and organic matter, and are medium- to coarse-textured. Much of the landscape is subject to continuous seepage. This excess moisture is indicative of the higher organic matter content, that may reach or exceed 30 percent (Valentine et al. 1978).

Chemically the soils of the Ferro-Humic and Humo-Ferric Podzol landscape have very low base saturation, low pH values (less than 5.0 is common), high organic carbon, and high Fe and Al contents. The upper part (higher elevation) of the landscape is chemically and morphologically

similar to the lower areas, except that the horizons contain somewhat greater amounts of Fe, Al, and organic matter. The interplay among the various environmental factors produces a boundary zone of considerable interfingering of the Humo-Ferric and Ferro-Humic Podzol soil landscapes.

4.3.2 Acid sensitivity

The acid sensitivity of the soil landscape is largely dependant on the chemical properties of the soil parent material, with the rate of mineral chemical weathering being the most important factor (Nilsson and Grennfelt 1988). There are a number of methods for the determination of weathering, ranging from simple empirical to complex models. Semi-quantitative methods, such as the Skokloster classification (Nilsson and Grennfelt 1988) allocate soils to weathering or acid sensitivity classes based on a mineralogical-based buffering capacity for each soil type. The approach has been widely applied (Hornung et al. 1995; Aherne and Farrell 2000).

The Skokloster classification divides soils into five sensitivity classes based on the mineralogy of the soil parent material. Within the study region, spatial information on soil and soil parent material is limited; as such acid sensitivity was evaluated using bedrock geology (scale 1:250000; MacIntyre et al. 1994) under the assumption that the mineralogy of the soil overburden is related to the underlying bedrock type. The study area comprises 13 bedrock types (Table 4.3-1 and Figure 4.3-1:), ranging in acid sensitivity (Class 1 = Most sensitive). The majority of the study area was classified as moderately acid sensitive (Class 3 >60%; see Table 4.3-1). The acid sensitivity map (Figure 4.3-1:) was subsequently used to inform freshwater and terrestrial studies within the region (See Sections 8.0 and 9.0).

Table 4.3-1: Description of bedrock type, code, class, proportional coverage (%) of the study area, and acid sensitivity class (ASC). Data source: MacIntyre et al. (1994).

Rock Type	Code	Rock Class	Area (%)	ASC
Calc-alkaline	ca	Volcanic rocks	11.1	4
Conglomerate, coarse clastic	cg	Sedimentary rocks	0.1	2
Intrusive rocks, undivided	g	Intrusive rocks	2.5	3
Granodioritic	gd	Intrusive rocks	35.2	3
Granite, alkali feldspar granite	gr	Intrusive rocks	0.6	1
Limestone, marble, calcareous	lm	Sedimentary rocks	1.4	5
Orthogneiss	og	Metamorphic rocks	14.6	2
Quartz dioritic	qd	Intrusive rocks	26.1	3
Quartz monzonitic	qm	Intrusive rocks	0.5	3
Undivided sedimentary rocks	s	Sedimentary rocks	1.4	1
Andesitic	va	Volcanic rocks	3.4	4
Volcaniclastic rocks	vc	Volcanic rocks	2.8	2
Rhyolite, felsic	vf	Volcanic rocks	0.2	1

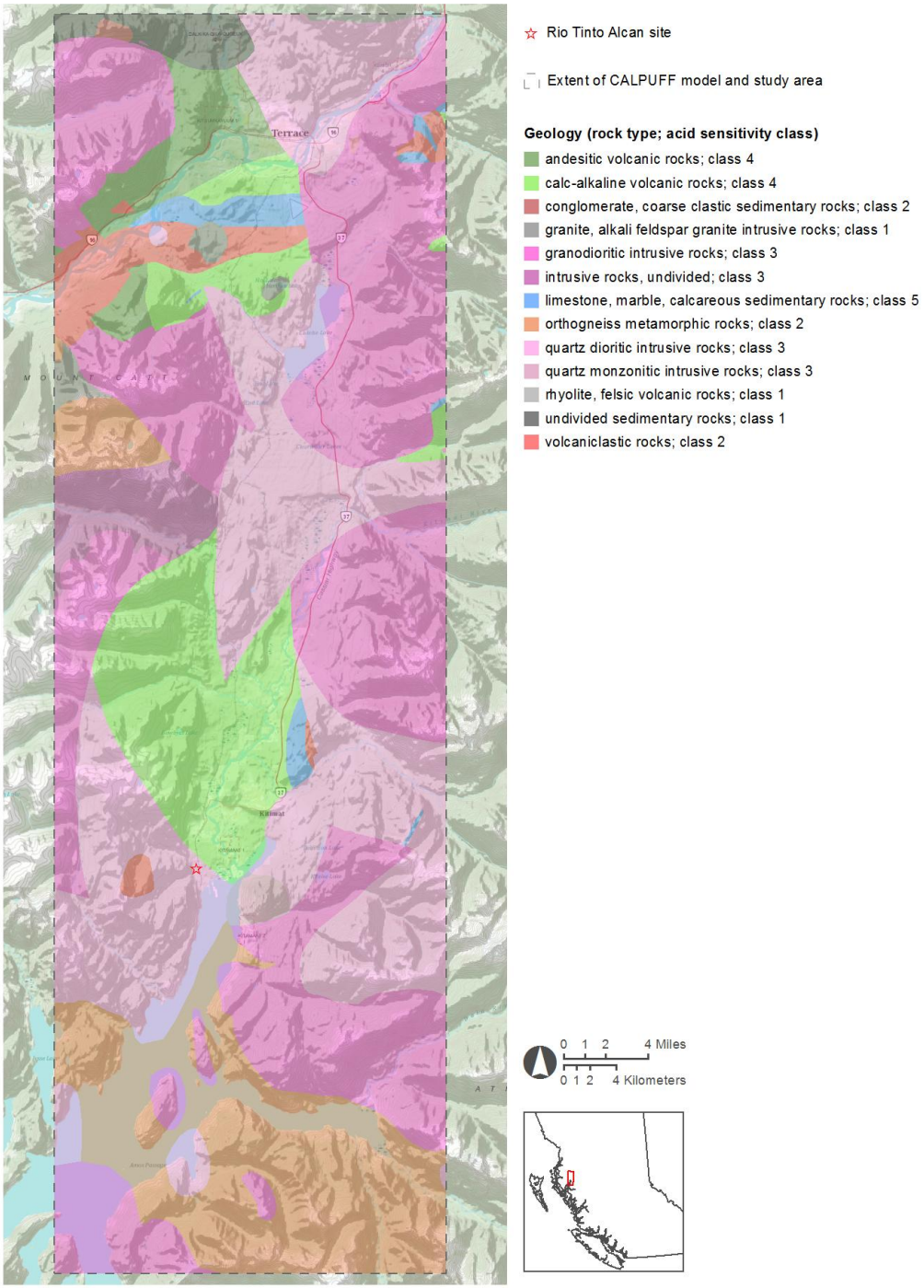


Figure 4.3-1: Geological rock type and acid sensitivity classes (with class 1 indicating the most acid sensitive regions) based on the reclassification of bedrock geology (1:25,000) according to the Skokloster Classification (see Table 4.3-1).

4.4 FLORA AND FAUNA

4.4.1 Flora – vegetation communities

The Kitimat Valley lies within the Coastal Western Hemlock Biogeoclimatic Ecosystem Classification zone of British Columbia. Mountain and ocean influences dominate, creating one of the wettest climates in Canada (B.C. Ministry of Forests 1999). Coniferous forests predominate in this zone and, because of the mild, wet climate in which they grow, these forests are complex and often highly productive ecosystems.

Within the context of the National Ecological Framework of Canada, the Kitimat Valley is part of the Coastal Gap Ecoregion of Canada, which in turn is part of the Pacific Maritime Ecozone (ESWG 1995). Vegetation in the Coastal Gap Ecoregion is described as ranging from coastal and valley-bottom wetlands, to floodplain shrubs and deciduous forest, to thick coniferous forests with understories that include blueberries (*Vaccinium* sp.) and dense mosses, and finally to subalpine shrublands. Rock, snow and ice predominate at the highest elevations (Figure 4.4-1).

Coastal wetlands range from open bogs to scrubby muskeg forests of cedar, hemlock, and spruce. These communities typically feature extensive development of sedges, Labrador tea (*Ledum* sp.), crowberry (*Empetrum* sp.), and thick mats of *Sphagnum* sp. (Demarchi 2010). Tufted hairgrass (*Deschampsia caespitosa*), sedges, rushes, glasswort, and silverweed (*Argentina* sp.) are characteristic of estuarine habitats at the mouths of the many rivers and streams.

Trees are important to the people of the Kitimat Valley. Communities in the region have a long history of involvement with the forest sector and, despite a general decline in forestry operations throughout the area (LSM & RM 2003), forestry continues to be a significant economic driver in the region. In 2001, 11.5% of Kitimat's experienced labour force was engaged in logging and forestry manufacturing, ranking third in importance behind mining/oil/gas industries (28.9%) and education/health/public administration services (19.7%) (LSM & RM 2003). In Kitamaat Village, commercial fishing is the largest industry, but forest-related employment in the form of fire suppression and forestry contracting is also important (Government of British Columbia 2002).

Many of the tree and shrub species in the Kitimat area are typical of mature, mid-seral and early coastal forests (GBC & GC 2006). The cool, moist climate of the Coastal Gap Ecoregion grows western hemlock (*Tsuga heterophylla*), balsam fir (*Abies balsamea*), western red cedar (*Thuja plicata*), yellow-cedar (*Callitropsis nootkatensis*), and spruce. A 500-year old Sitka spruce (*Picea sitchensis*) tree in Kitimat was registered in 1983 as the largest living spruce in British Columbia (District of Kitimat 2012). Occasional species include lodgepole pine (*Pinus contorta*), black cottonwood (*Populus balsamifera ssp. trichocarpa*), and red alder (*Alnus rubra*) (Government of British Columbia 2002).

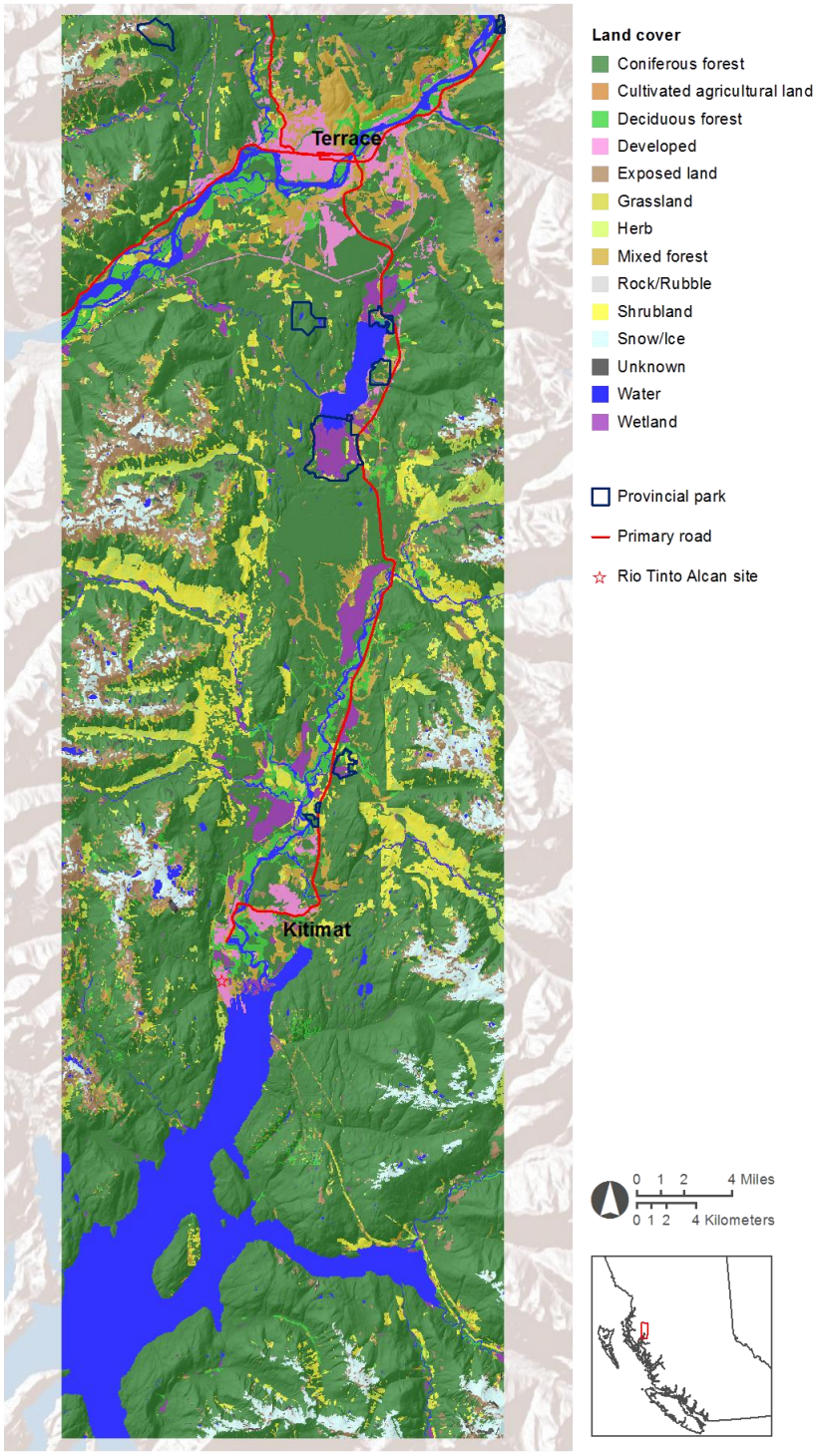


Figure 4.4-1: Land cover map showing vegetation, wetlands and waterbodies, cultivated agricultural land, developed land, protected areas, and primary roads.

Forest communities vary with elevation and moisture regime. In low-lying coastal areas of the ecoregion, vegetation tends to include open-growing western red cedar, yellow-cedar, and western hemlock, and some Sitka spruce (ESWG 1995). Floodplains feature dense shrub cover of red-osier dogwood (*Cornus sericea*), red elderberry (*Sambucus racemosa*), salmonberry (*Rubus spectabilis*), horsetails (*Equisetum* sp.), and ferns (Demarchi 2010). Coastal wetlands include sloping bogs, basin bogs, and occasional stream fens. Red alder is common in disturbed alluvial sites. Western hemlock occurs from tidewater to about 460 m elevation. Understories are shrub-dominated, with blueberries, false (mock) azalea (*Menziesia ferruginea*), salal (*Gaultheria shallon*), and devil's club (*Oplopanax horridus*) (Demarchi 2010). Beyond 460 m elevation, a subalpine zone of yellow-cedar and mountain hemlock (*Tsuga mertensiana*) predominates, with an understory of blueberries and dense mosses. Wet meadows are frequently found as part of the subalpine mosaic. As elevation increases, mountain hemlock and yellow-cedar give way to stunted clumps of trees known as "krummholz". Above 900 metres, mountain-heather heath and treeless alpine tundra take over (ESWG 1995). The alpine tundra zone is rock and ice dominated, with pockets of alpine vegetation. Small glaciers occur on the north sides of some mountain summits.

In the marine environment of the study area, the dominant vegetation is rockweed (*Fucus gardneri*). Blade kelp (*Laminaria* sp.), fringed sieve kelp (*Agarum fimbriatum*), sea sac (*Halosaccion glandiforme*), and several red algaes (*Rhodophyta* sp.) have also been reported as being present (Jacques Whitford Ltd. 2005a). In shallow areas, eelgrass (*Zostera marina*) and beachgrass commonly occur.

4.4.2 Fauna – fish and wildlife communities

4.4.2.1 The marine environment

Kitimat Arm, at the north end of Douglas Channel, is typical of other Pacific coastal fjords; it is characterized by steep rocky slopes and a U-shaped bottom profile. The depth of the Arm increases rapidly to over 110 m, 600 m south of the Kitimat estuary. Kitimat Arm joins the Douglas Channel at the south end of Coste Island, 22 km to the south. At this point, the depth of the Arm is approximately 350 m. The average width of the upper end of the Arm is 3 km.

Wild and hatchery salmonids contribute substantially to the recreational, First Nation (subsistence, cultural, and commercial), and commercial fisheries in the Douglas Channel (Jacques Whitford Ltd. 2005b). Other commercially harvested species include halibut (*Hippoglossus stenolepis*), cod, turbot (*Pleuronichthys coenosus*), skate (*Family Rajidae*), sole, starry flounder (*Platichthys stellatus*), shiner perch (*Cymatogaster aggregata*), prawns, and shrimp. Commercial crab harvesting also occurred in the Kitimat Arm until the fishery was closed in 1989. In Kitamaat Village, commercial fishing is the largest industry (Government of British Columbia 2002). Haisla fishers have recently and historically harvested coho, pink (*O. gorbuscha*), and chum salmon (*O. keta*), steelhead, halibut, red (*Pseudophycis* sp.) and gray cod

(*Gadus marcocephalus*), and Pacific herring (*Clupea harengus pallasi*) (Powell 2005, cited in Jacques Whitford Ltd. 2005b). There is also a limited subsistence harvest of blue mussels in Kitimat Arm. Other species harvested by the Haisla include crab, sea cucumber, octopus, and seals.

A compilation of the marine fish reported to occur in the Kitimat Arm and Douglas Channel is given in Table 1 of Appendix 4.4-1.

The intertidal zone of the Kitimat Arm, which includes the Kitimat River estuary, is a highly productive area utilized by migratory birds, shorebirds, marine mammals, and numerous fish species. Shallow, estuarine, brackish foreshore areas provide critical life stage habitat for most anadromous salmonid species present in Douglas Channel watersheds (Jacques Whitford Ltd. 2005b). For example, the estuary is a valuable rearing area for pink and chum salmon fry, and for Chinook (*O. tshawytsha*) smolts. The intertidal zone is also heavily used by shiner perch, starry flounder, and staghorn sculpin (*Leptocottus armatus*).

Invertebrates characteristic of rock substrates in the intertidal zone of Kitimat Arm include the acorn barnacle (*Balanus glanula*), the purple sea star (*Pisaster ochraceus*) (Acres 1986, cited in Jacques Whitford 2005b), sea urchins (*Strongylocentrotus* sp.), sea anemones (*Tealia* sp.), calcareous tube worms, and bryozoans (Hatfield Consultants Ltd. 1982, cited in Jacques Whitford Ltd. 2005b). Isopods, gastropods, brachyurans, and oligochaetes also occur on the steep and rocky shorelines of the Arm. Boulder and large cobble substrates also support mussels, barnacles and limpets (Jacques Whitford Ltd. 2005b).

In the intertidal sand community, bivalve species such as the butter clam (*Saxidomus giganteus*), heart cockle (*Clinocardium* sp.), and the bent nose clam (*Macoma* sp.) occur (Hatfield Consultants Ltd. 1982, cited in Jacques Whitford 2005b). Other invertebrates of the intertidal sand community include gammarid amphipods and polychaete worms (Levings 1976, cited in Jacques Whitford Ltd. 2005b).

In the subtidal zone of the Arm, benthic invertebrates include Dungeness crab (*Cancer* sp.), hermit crab (*Pagurus* sp.), several species of gastropod, snails (*Polinices* sp. and *Fusitriton* sp.), and nudibranchs (*Archidoris* sp. and *Triopha* sp.) (Hatfield Consultants Ltd. 1982, cited in Jacques Whitford Ltd. 2005b). The major marine invertebrates in the subtidal zone of Kitimat Arm (surveyed at Emsley Cove) include sponges, cnidarians, segmented worms, bryozoans, arthropods, molluscs, echinoderms, sea squirts, and brachiopods (Table 2, Appendix 4.4-1).

Marine mammals occur in the Kitimat Arm and Douglas Channel mainly during the summer months, following and feeding on anadromous fish spawning runs (Hatfield Consultants Ltd. 1982, cited in Jacques Whitford Ltd. 2005b). They include whales, porpoises, seals, the northern (Stellar) sea lion (*Eumetopias jubatus*), and the Pacific striped dolphin (*Stenella caeruleoalba*). Many of these species occur irregularly, while others migrate along traditional

routes. Species observed in the Kitimat Arm and Douglas Channel environment are listed in Table 3, Appendix 4.4-1.

Avifauna in the marine environment of the technical assessment study area includes both resident and non-resident species. Non-resident species are those that may breed in the area and then migrate elsewhere for winter, or they may breed somewhere else and migrate to the area for winter, or they may be transitory and occur only during spring and/or fall migration. For example, surf scoter (*Malanitla perspicillata*), common goldeneye (*Bucephala clangula*), and bufflehead (*Bucephala albeola*) are typically observed in higher numbers during their spring migration; they concentrate where there are spawning runs of herring. Fall movements tend to be less obvious, and they winter along the length of the British Columbia coastline. These species are not known to breed in the Kitimat area (Jacques Whitford Ltd. 2005e).

Surveys conducted during fall migration in 2004 recorded 18 species of waterfowl and seabirds in the Kitimat Arm and Douglas Channel (Jacques Whitford Ltd. 2005b). Observations included loons, grebes, great blue heron (*Ardea herodias*), Canada goose (*Branta canadensis*), a variety of dabbling ducks and seaducks, and several species of gull. Most species were observed in sheltered bays and inlets of the Arm; only the gull species were typically observed over deeper waters or on exposed rocky shorelines. Waterfowl species were most often observed in the shallower areas of bays and inlets, or in the Kitimat estuary (Jacques Whitford Ltd. 2005b). A complete list of the species observed during the 2004 surveys is given in Table 4 of Appendix 4.4-1.

4.4.2.2 The freshwater environment

Fish with life stages in freshwater include both resident freshwater and anadromous species. Salmonids that occur in the watersheds of the Kitimat Valley include coho, pink, chum, sockeye, and Chinook salmon, as well as coastal cutthroat trout, steelhead/rainbow trout, bull trout, Dolly Varden char, mountain whitefish (*Prosopium williamsoni*), and eulachon (*Thaleichthys pacificus*). Non-salmonids include coastrange sculpin (*Cottus aleuticus*), slimy sculpin (*C. cognatus*), Pacific lamprey (*Entosphenus tridentatu*), and threespine stickleback (*Gasterosteus aculeatus*). Freshwater fish species of special conservation status, as identified on provincial red and blue lists, include cutthroat trout, bull trout, and Dolly Varden char (Jacques Whitford Ltd. 2005c).

Little is known about the biota of the lakes in the technical assessment study area, with the exception of Lakelse Lake due to its commercial and recreational importance. The Lakelse system supports about 35% of the total Skeena River commercial fishery catch for all species (McKean 1986). Rainbow/steelhead trout, coho, and cutthroat trout support major sport fisheries. Resident species present in the system include rainbow/steelhead trout, cutthroat trout, Dolly Varden char, bull trout, mountain whitefish, and the following coarse fish: prickly sculpin (*Cottus asper*), largescale suckers (*Catostomus macrocheilus*), redside shiners (*Cyprinella*

lutrensis), northern pikeminnow (*Ptychocheilus oregonensis*), peamouth chub (*Mylcheilus caurinus*), and threespine stickleback (Skeena Fisheries Commission 2003). At the outlet for Lakelse Lake, the Lakelse River provides habitat for both anadromous and non-anadromous fish (Government of British Columbia 2002).

Salmonid spawning occurs in the lower reaches of many Lakelse Lake tributaries (Skeena Fisheries Commission 2003). The major tributaries flowing into Lakelse Lake are Williams Creek, Furlong Creek, Hatchery Creek, and Schulbuckhand (Scully) Creek. Williams Creek and Scully Creek are considered to be important spawning streams. Williams Creek and its lower tributaries (Sockeye Creek and Blackwater Creek) provide roughly 80% of the habitat used by Lakelse sockeye, which is a declining population that is thought to be limited by spawning and rearing habitat. Lakelse coho also spawn in the lower reaches of Williams Creek (Skeena Fisheries Commission 2003). The lower reaches of Furlong, Hatchery, and Scully Creeks support spawning coho, and pink salmon occasionally spawn in the lower reaches of Hatchery and Scully Creeks. Sockeye spawning also occurs in Hatchery Creek (Skeena Fisheries Commission 2003).

The Kitimat River is the largest river in the technical assessment study area, and its main tributaries are the Wedeene River, the Little Wedeene River, Hirsch Creek, and Humphreys Creek. The Kitimat River supports runs of all five species of Pacific salmon, anadromous steelhead, Dolly Varden char, and coastal cutthroat trout; the lower 10 km of the river is a major salmon migration route. Spawners use the entire mainstem to just above Davies Creek, and nearly all accessible tributaries (MacDonald and Shepard 1983). Almost all species of salmon returning to the Kitimat River watershed are declining in abundance, especially Chinook and coho. The Kitimat River also supports a number of resident salmonid and non-salmonid fish species. Table 5 in Appendix 4.4-1 lists the fish species present in the Kitimat River.

The Wedeene River supports Chinook, chum, coho and pink salmon, cutthroat trout, steelhead, rainbow trout, Dolly Varden char, and prickly sculpin (Lukuku and Stokes 2001). The same species are present in the Little Wedeene River, with the exception of cutthroat trout. Additionally, prickly and Aleutian sculpin (*Cottus aleuticus*) are present in the Little Wedeene River (Lukuku and Stokes 2001). Hirsch and Humpreys Creeks support the same salmonids as the Wedeene River, plus lamprey and several species of sculpin (Lukuku and Stokes 2001).

The species present in the Kitimat River (listed in Table 5 of Appendix 4.4-1) are also likely present in Anderson and Moore Creeks, which both discharge into the Kitimat estuary. Anderson Creek is known to support large runs of pink salmon that spawn from tidewater upstream to the weir. Coho and chum also spawn in Anderson Creek, and Dolly Varden char, rainbow trout, and cutthroat trout are also present. Moore Creek is not considered to be a productive salmon bearing stream, although coho spawning and rearing have been observed below the waterfall.

4.4.2.3 The terrestrial environment

The forests, wetlands, and waterways of the Kitimat Valley offer a wide range of habitats for a host of wildlife species. The Kitimat Valley supports a number of large mammal species, including deer (*Odocoileus hemionus*), moose (*Alces alces*), gray wolf (*Canis lupus*), coyote (*Canis latrans*), black bear (*Ursus americanus*), and grizzly bear (*Ursus arctos*). Additionally, a number of small mammal species (voles, mice, squirrels) and various fur-bearers, including marten (*Martes americana)*, weasel (*Mustela* sp.), and beaver (*Castor canadensis*), are also known to occur (Jacques Whitford Ltd. 2005d). Table 6 in Appendix 4.4-1 lists the mammalian wildlife species known to occur in the Kitimat Valley.

Avifauna in the technical assessment study area includes species typical of terrestrial and marine environments, including resident and non-resident species (Jacques Whitford Ltd. 2005e; GBC & GC 2006). In the Kitimat area, there are many species that only occur during spring and/or fall migration (GBC & GC 2006). Most noticeable are huge concentrations of spring migrants that feed on spawning runs of herring and eulachon (Municipality of Kitimat 2012). The British Columbia Breeding Bird Atlas (2008) provides evidence of breeding for 150 species in Region #34, a region that includes the technical assessment study area. Within the technical assessment study area, atlasers recorded a minimum of 42 and a maximum of 195 confirmed breeders (Figure 4.4-2). Additional information about the avifauna in the technical assessment study area comes from the Kitimat LNG Terminal environmental assessment (Jacques Whitford Ltd. 2005e). This work focused on the area between Kitimat and Emsley Cove, which is at the south end of the study area on the west side of Kitimat Arm (Figure 4.4-3). Surveyors reported that 222 species potentially occur there. Of these, 91 are possible breeders and the remainder are migrants or birds that winter in the area.

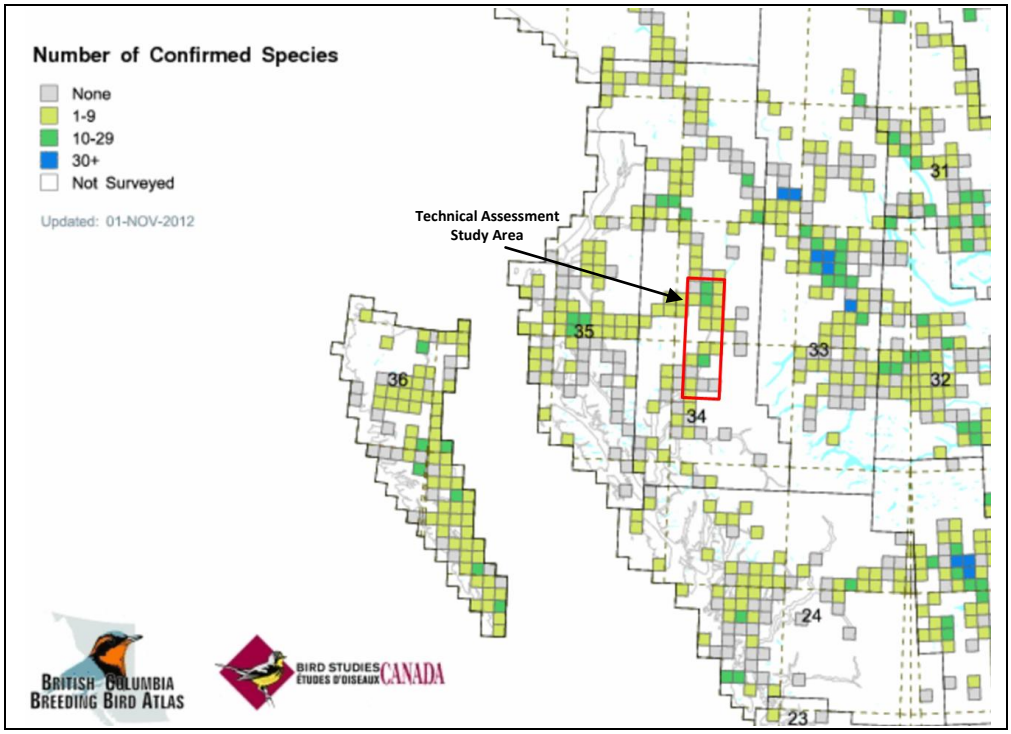


Figure 4.4-2: British Columbia Breeding Bird Atlas Region #34 (Terrace), showing outline of the technical assessment study area (from British Columbia Breeding Bird Atlas 2012).

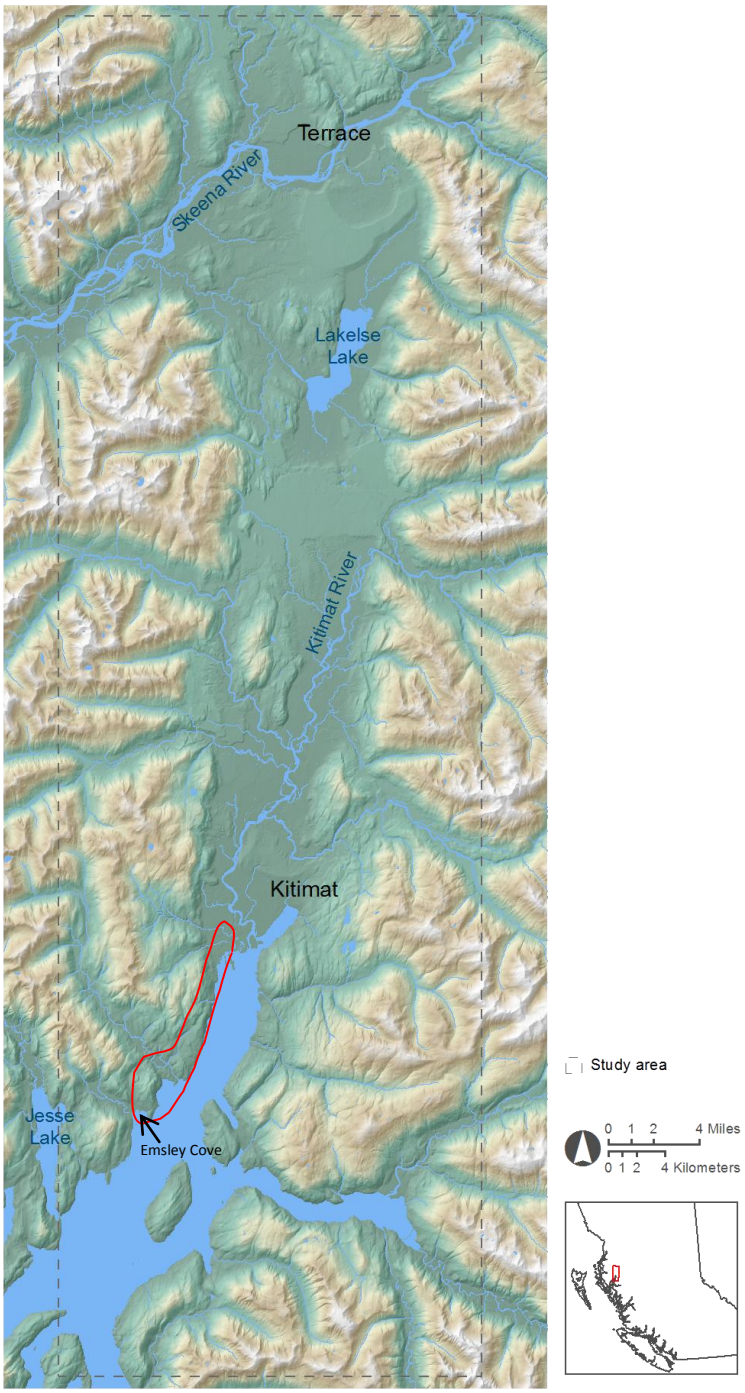


Figure 4.4-3: Technical assessment study area (dotted outline) showing assessment area for the Kitimat LNG Terminal avifauna surveys (solid red outline).

The terrestrial habitat for birds in the Kitimat Valley is relatively homogenous and somewhat fragmented by past forestry operations. Lowland forests provide breeding habitat for some migratory species. Bird use of the coniferous forest tends to become restricted with increasing elevation (GBC & GC 2006). Table 7 in Appendix 4.4-1 lists the bird species, resident and non-resident, most commonly observed within the Kitimat estuary and Valley.

4.4.3 Species of management concern

The technical assessment study area lies wholly within the Kalum Land and Resource Management Plan area (Government of British Columbia 2002). A total of 3 fish, 15 wildlife (mammals, birds, amphibians), and 13 vegetation species of federal, provincial and regional concern occur within the Kalum Forest District. Of these, 3 fish, 13 wildlife, and 6 vegetation species have distributions that include the technical assessment study area (IUCN 2012; UBC 2012). These species, along with brief descriptions of their habitat preferences, are listed in Table 8 of Appendix 4.4-1.

The B.C. Conservation Data Centre (B.C. Ministry of Environment 2013) designates 6 species from the Kalum Forest District as red-listed, and 30 as blue-listed (Table 9 in Appendix 4.4-1). At the national level, 231 species in British Columbia are legally designated under the federal *Species at Risk Act*. Of these, 15 are listed as occurring in the Kalum Forest District (Table 10 in Appendix 4.4-1), including 2 “special concern” lichens (B.C. Ministry of Environment 2013).

4.5 LAND USE

People of the Haisla Nation have inhabited area in and around the Kitimat Valley for over 8,000 years (LRM Consulting and Resource Matters! 2003). Fishing eulachon and salmon as well as hunting birds, deer, moose, bear, marten and mink are activities that have been undertaken by Haisla people for generations. Other Haisla activities on the land include harvesting plants for food and medicinal purposes, and cedar bark for shelter and spiritual sanctuaries.

Fur trading and gold prospecting brought Europeans to the area in the 1800s. By the early 1900s, the town of Terrace was established as a sawmill community. In the 1950s, the modern town of Kitimat was created with development of the Alcan aluminum smelter (District of Kitimat 2009). Since then, Terrace has grown to become the largest city in the area, and Kitimat’s economy has continued to be driven by industrial manufacturing (District of Kitimat 2009). Tourism and small business development have also added to the area economy, with forestry continuing to be a main activity on the landbase.

Kitimat Valley’s unique geography, being one of the only wide developable valleys along the British Columbia coastline, has brought various and often conflicting human activities (LRM Consulting and Resource Matters! 2003). In 1992, a planning process was initiated to address the complex use of land encompassing a large area which included the Kitimat Valley

(Government of B.C. 2002). The result was the Kalum Land and Resource Management Plan, which identifies management directions and objectives for designated areas and human activities (Government of B.C. 2002). The following sections of the report detail the designation of areas as well as activities occurring within and around the Kitimat Valley.

4.5.1 Settlement areas

The three main human settlement areas are Terrace (population 20,647), Kitimat (population 10,165) and Kitamaat (population 635) (B.C. Stats 2012).

Terrace was incorporated in 1927. A small sawmill community in the beginning, it now covers an area of 4,223 hectares and is a transportation hub and center for servicing other communities such as Prince Rupert and Kitimat (Government of B.C. 2002; City of Terrace 2012).

Kitimat began in the 1950s with the construction of the Alcan aluminum smelter (District of Kitimat 2009). It has since grown to encompass an area of 1,225 hectares, with the Rio Tinto Alcan aluminum smelter serving as the main economic driver (District of Kitimat 2009).

Kitamaat Village, located 11 km south of Kitimat, has been a community site for hundreds of years. It is currently the gathering place for the elected council of the Haisla Nation, whose traditional territory covers over 5,000 square miles.

4.5.2 Protected areas

Within the technical assessment study area (289,500 hectares) there are eight protected areas comprising 2,718 hectares (Figure 4.5-1) (B.C. Ministry of Environment 2012):

- Sleeping Beauty Mountain Provincial Park
- Kleanza Creek Provincial Park
- Hai Lake-Mount Herman Provincial Park
- Lakelse Lake Provincial Park
- Lakelse Lake Wetlands Provincial Park
- Nalbeelah Creek Wetlands Provincial Park
- Kitimat River Provincial Park
- Jessee Falls Protected Area

In accordance with the Provincial Protected Areas Strategy, protected areas have been designated for their natural, cultural heritage and/or recreational values, with logging, mining and hydroelectric development prohibited (Government of B.C. 2002). Most people attending the protected areas are local residents, using the areas for the outdoor recreation opportunities

(Government of B.C. 2002). Lakelse Lake is a particularly popular spot for day use and overnight excursions, attracting anglers and campers (Government of B.C. 2002).

Figure 4.5-1: Technical assessment area map displaying Timber Supply Areas (yellow), Timber Forest Licenses (green), and Protected Areas (blue).

4.5.3 Cultural heritage areas

In the Kalum Land and Resource Management Plan, a Cultural Heritage Resources is defined as:

> *"an object, a site, or the location of a traditional social practice of historical, cultural or archeological significance to the province, a community or an aboriginal people. Cultural heritage resources include archeological sites, structural features, heritage landscape features, and traditional use sites."* (Government of B.C. 2002:50).

Aboriginal people and the Ministry of Forests, Lands and Natural Resource Operations combine traditional use studies with operational level protocols to avoid or mitigate the impact of resource development in cultural heritage areas (Government of B.C. 2002).

4.5.4 Forestry

The technical assessment area lies within the Kalum Forest District and contains parts of the Kalum and Pacific Timber Supply Areas (TSA) as well as parts of Tree Farm Licenses (TFL) 1 and 41 (Figure 4.5-1). With a great deal of forest cover (Figure 4.4-1) and a climate that fosters western hemlock, balsam fir, western red cedar, and spruce trees, forestry has been a main activity in the area since the 1960s (Government of B.C. 2002; District of Kitimat 2009).

The Kalum TSA encompasses the Terrace and Kitimat municipalities as well as much of the Kitimat Valley. It is administered by the Kalum District office in Terrace. The Pacific TSA, which is mostly southeast of the technical assessment area, covers some land on the southeast part of the area. Within TSAs, land is managed for forestry as well as other land uses (Heidt 2007).

TFL 1, which is mostly north of the technical assessment area, covers some land on the northwest part of the area. The current licensee for TFL 1 is Coast Tsimshian Resources Limited Partnership (Ministry of Forests, Land and Natural Resource Operations 2012). TFL 41 came to be in 1978, when the Kitimat Valley area was designated a Provincial Forest. Since then, it has been reduced to 1/3 its original area, continuing to include the side valleys of the Kitimat Valley (Government of B.C. 2002). Currently, the licensee for TFL 41 is Skeena Sawmills Ltd. (Ministry of Forests, Land and Natural Resource Operations 2012).

Forestry in the technical assessment area operates in accordance with the Forest and Range Practices Act and follows objectives provided in the Kalum Sustainable Resource Management Plan (developed as part of the Kalum Land and Resource Management Plan process) (District of Kitimat 2009).

4.5.5 Agriculture

Containing much steep, rocky terrain, land capable of agriculture is limited (Government of B.C. 2002). The total cultivated land in the technical assessment area is 102 hectares, which is mostly in and around Terrace (Figure 4.4-1). The Kalum land and Resource Management Plan identifies current agriculture activity as an important resource for producing fresh products for the local community and for providing economic diversity (Government of B.C. 2002).

4.5.6 Hunting, trapping and botanical forest harvesting

Hunting birds, deer, moose, mountain goats, bear, marten and mink has been an important resource and cultural activity for people of the Haisla Nation for generations. Additionally, non-aboriginal hunters, both locally and from throughout the province, enjoy hunting within the area (Government of B.C. 2002).

Aboriginal and non-aboriginal trapping for marten, lynx, and beaver has long been economically and culturally important in the area. It is not a full-time occupation for anyone, yet many partake in the activity for recreational purposes and it does contribute to income for some people (Government of B.C. 2002).

First Nations people have harvested botanical forest products for generations, using plants for medicine, food, and cultural purposes (Government of B.C. 2002). Mushrooms, berries, bark, blossoms, and resins are some examples of the types of products harvested by Haisla people.

4.5.7 Outdoor recreation

Hiking, camping, fishing, hunting, and four-wheeling are some of the main outdoor activities that people enjoy in the area. Wintertime activities are also popular and include cross country skiing and snowmobiling (Government of B.C. 2002). The nearby access to alpine ridges and wilderness areas is a key value for people getting outdoors (Government of B.C. 2002). Much of the tourism centers around day hiking, with the alpine trails near Terrace and Kitimat highly used. Tourists also use provincial parks for their picnic and campground facilities (Government of B.C. 2002). Lakelse Lake is a particularly popular spot, especially for fishing and going on nature walks.

4.5.8 Wildlife and wildlife habitat

The Kalum Land and Resource Management Plan recognizes that certain wildlife species require special management such as maintaining favorable winter habitat for ungulates and monitoring local marmot and Kermode bear populations (Government of B.C. 2002).

One way in which the Plan manages for these values is through Special Resource Management Zones (SRMZ). For example, grizzly bear hunting is prohibited in Grizzly Bear Benchmark and

Linkages SRMZ (Government of B.C. 2002). Also, the Kowesas SRMZ is designated for special management of eulachon, marbled murrelets, as well as other Haisla cultural values (Government of B.C. 2002). All of the SRMZs involve land use regulation to manage for the particular value associated with the zone.

4.6 COMMUNITIES

Kitimat is a town of close to 9,000 inhabitants located 650 km north of Vancouver, in the Kitimat Valley. It is surrounded by mountains, and the Douglas Channel gives it direct access to the Pacific Ocean. Kitimat came into existence in the 1950s after the Provincial Government of British Columbia invited Alcan to develop hydroelectric facilities and an aluminum smelter, as described in the Introduction to this report. Kitimat was designed to keep industry well separated from the community, with large areas for expansion, looped streets surrounding an urban city centre, walkways connecting the community, and substantial greenspace areas. The Kitimat townsite currently occupies approximately 750 ha of land on the east side of the Kitimat River. Port and industrial areas cover an additional 475 ha on the west side of the river, downstream from the townsite. Educational advancement and skills training is supported by two post-secondary institutions in Kitimat: Northwest Community College and the Kitimat Valley Institute.

The last decade has seen the closure of two major industries in Kitimat: the Ocelot/Methanex plant, which operated from 1986 until 2005 manufacturing methanol and ammonia, and the Eurocan pulp and paper mill, which closed in 2010 after 40 years of operation (West Fraser Timber Co. Ltd. 2009). The Rio Tinto Alcan smelter is the largest provider of employment in Kitimat (with approximately 1,500 employees), and is located on Highway 37 southwest of the residential part of town. The proposed Kitimat Modernization Project would provide a sustained contribution to the local economy over a 50-year period. Other important contributors to the local economy include public administration, recreation, accommodation and food services, construction, professional services, retail trade and health care.

The City of Terrace is situated 63 km north of Kitimat, along the Skeena River between the Copper and Kitsumkalum Rivers, and is home to approximately 11,500 people. Terrace is a regional retail and service centre hub for northwestern British Columbia. Infrastructure and services include the administrative offices of the Kitimat-Stikine Regional District, the Mills Memorial Hospital, the Canadian National Railway, the Yellowhead Highway, and the Northwest Regional Airport (with connections to Prince George, Smithers, Victoria, Kelowna and Vancouver). The community opened its first sawmill in 1908, and is in the centre of the first Tree Farm Licence issued in British Columbia (TFL-1). From the 1950s to the late 1980s, a number of saw mills were constructed in the region, and a pulp mill in Prince Rupert processed lesser quality timber. When the forest industry began to decline in the 1990s, so too did the population of Terrace and surrounding communities. The community was affected in 2001 by the closure of the largest local employer, the former Skeena Cellulose Inc. sawmill. In 2005, the

Lax Kw ‘alaams-owned company, Coast Tsimshian Resources LP, purchased the licence for TFL-1.

The largest employers in Terrace are in the public sector, but there are some large private sector employers. Rio Tinto Alcan is the largest private sector employer, with 350 permanent employees living in Terrace. Efforts to diversify the economy include investments in tourism, recreation, mining, transmission line construction, education and skills training. Protection and sustainable management of natural resources is promoted by a number of active organizations, and like many communities in the area, the protection of salmon and watershed ecosystems is a high priority.

Lakelse Lake, about 20 km south of Terrace, is predominantly a summer recreational area that encompasses a seasonal provincial park, though a growing number of residents live there throughout the year.

4.7 FIRST NATIONS

The Haisla First Nation has occupied the Kitimat Valley for thousands of years. The Haisla’s main community today is Kitamaat Village, located across the Douglas Channel from the Kitimat smelter.

In 2010, Rio Tinto Alcan and Kitamaat Village Council (representing the Haisla First Nation) completed a Haisla Nation - Rio Tinto Alcan Legacy Agreement. This Agreement includes recognition of the impact on the Haisla Nation of Rio Tinto Alcan’s operations in what the Haisla see as their traditional territory. It also includes support of KMP by the Haisla Nation Council, and a fund to promote the sustainable economic, community, social, and educational advancement of the Haisla people.

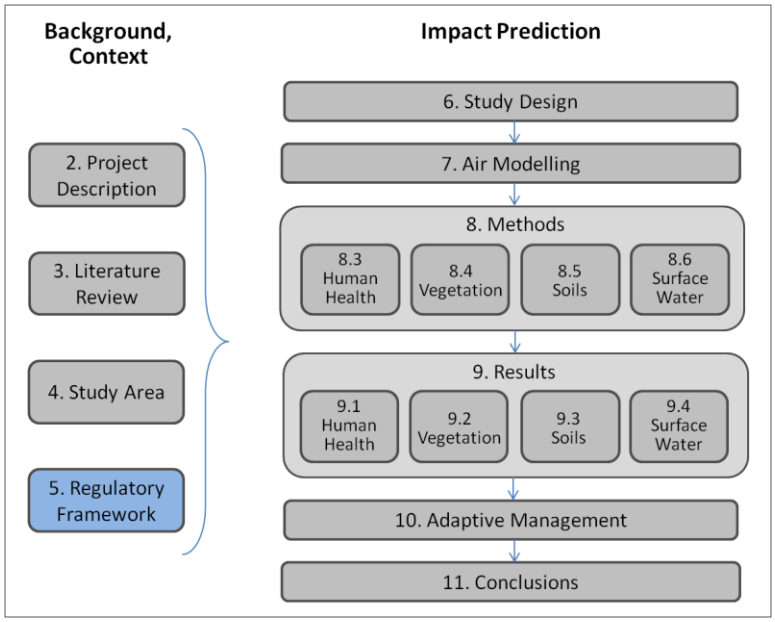
Two bands of the Tsimshian First Nation claim home to the Terrace area. The Kitselas Band primarily claim territory to the east and south of Terrace (east Skeena and Lakelse), while the Kitsumkalum Band is primarily resident to the west and north of Terrace along the Kalum and Skeena Rivers. Both of these First Nations bands are near completion of an agreement in principle on settling land claims to their traditional territories.

The Kitsumkalum Reserve is located west of Terrace, where the Kitsumkalum River flows into the Skeena River. Traditional Kitsumkalum territory encompassed the Kitsumkalum River watershed, although Kitsumkalum also claims the adjacent Zimacord River watershed, a part of which is traditionally the territory of the Gitlaan Tsimshians. The name Kitsumkalum, originally Gitsmgeelm, derives from the Tsimshian git- (people of) and -geelm, referring to riffles formed by shallow water running over rocks in the Kitsumkalum River.

The Kitselas website (http://www.kitselas.com/) indicates that people have occupied the Kitselas Canyon area for at least 5,000 years. The language used by the Kitselas Nation is

Tsimshian (or Symalgyax). There are four main clans: Gispudwada (Killerwhale), Laxgiboo (Wolf), Laxsgiik (Eagle), and Ganhada (Raven). Presently, the Kitselas Membership totals approximately 500. The Kitselas Territory is comprised of nine Reservations, three of which are occupied (the communities of Gitaus, Kulspai and Endudoon).

5.0 Regulatory Framework



Industrial air emissions are regulated by both Provincial and Federal Legislation and policies. The dominant legislation is Provincial, under which prescribed environmental waste discharges (that include air emissions) are regulated and authorized by permit.

5.1 B.C. Ministry of Environment Regulations

Under the British Columbia environmental Management Act, Industrial waste discharges are regulated under permit. RTA B.C. Operations Kitimat aluminum smelter has a Pollution Prevention (P2) Multimedia Permit, P2-00001 (issued December 7, 1999, with the last comprehensive amendment dated November 9, 2007), which authorizes the discharge of air emissions, effluent and refuse from the Kitimat aluminum smelter. RTA B.C. Operation's waste discharge P2 Multimedia Permit is unique in British Columbia. Section 4.2 of the permit allows for plant wide SO_2 emissions of 27 t/d from the electrolysis potrooms (fugitive roof emissions and dry scrubbers) and coke calciner. This section needs to be amended to increase SO_2 emissions to 42 t/d, remove emission sources from the old smelting process and add the new AP-40 pre-bake smelting processes that emit SO_2.

The requested SO_2 emission limit amendment to the P2-00001 Multimedia Permit is considered to be a significant amendment under the Public Notification Regulation of the Environmental Management Act. A change involving a 10% increase to waste discharges in either quantity or

quality is considered to be significant and requires due consideration of various lines of evidence to assess impacts to potential sensitive receptors and effects on environmental quality. Additionally, for a significant amendment, a public consultation process is required.

The process for completing a significant permit amendment varies depending on the complexity of the permit application. Small amendments can be completed within three months, while complex permit applications, such as for this application to increase SO_2 emissions, can take up to two years to complete the scientific studies on the various lines of evidence as well as completing the consultation process. Information describing the permit amendment process for waste discharges can be found in the Environment Protection section of the B.C. Ministry of Environment's web site.

Permit application details

The Proposed permit amendment to the P2-00001 Multimedia Permit is reproduced in the box below.[7]

Before:

4.2 SO_2 Emissions

4.2.1 This subsection applies to the plant wide emissions of sulphur dioxide discharged from the smelting and calcining processes. A portion of the sulphur contained in the green petroleum coke used for anode production is released as SO_2 during calcining from the pyroscrubber. The remainder of the sulphur is released as SO_2 as the anode is consumed during reduction operations as secondary emissions and primary emissions (i.e., via the dry scrubbers).

4.2.2 Total smelter emissions of SO_2 shall not exceed the following:

Parameter	Limit
SO_2	27 Mg/d

4.2.3 The works include, but are not limited to, the pyroscrubber, dry scrubber stacks, potline ventilators, anode paste plant stacks, and related appurtenances.

After:

4.2 SO_2 Emissions

4.2.1 This subsection applies to the plant wide emissions of sulphur dioxide discharged from the anode baking, smelting and calcining processes. A portion of the sulphur contained in the green petroleum coke used for anode production is released as SO_2 during calcining from the Pyroscrubber. Additional sulphur dioxide is released from the anode baking process. The

[7] The units used in the P2 permit for SO_2 emissions are mega grammes (Mg); 1 mega gramme = 1 metric tonne.

remainder of the sulphur is released as SO_2 as the anode is consumed during reduction operations as secondary emissions and primary emissions (i.e. via the gas treatment center).

4.2.2 Total smelter emissions of SO_2 shall not exceed the following:

Parameter	Limit
SO_2	42 Mg/d

4.2.3 The works include, but are not limited to, the pyroscrubber, gas treatment centres, potline ventilators, anode paste plant stacks, anode bake furnace, fume treatment centre, and related appurtenances.

SO_2 Memorandum of Understanding

As a condition for approval of the KMP project by RTA's Board of Directors, three environmental conditions had to be met before a Notice to Proceed would be issued. These conditions were:

- Confirmation that KMP could be constructed within the environmental context of the existing operation and not trigger the requirement for a statutory Environmental Impact Assessment that could take up to 2 years to complete.
- Confirmation that there would be no changes to water discharge requirements under the P2-00001 Multimedia Permit.
- Permitting of the key emissions for KMP (fluoride and SO_2).

All conditions except the completion of an SO_2 permit amendment could be met in time to obtain the Notice to Proceed from the Board of Directors. For the Board to be comfortable about approving the project, an SO_2 Memorandum of Understanding (MoU) was established between RTA and B.C. MOE. While the MoU did not grant authorization to increase the SO_2 emission limit, it established the application of logical and systematic adaptive management principles for developing the permit. Key elements of the program for adaptive management include:

1. completing science-based emissions modelling;
2. developing and implementing a science-based biophysical and ambient air monitoring program to measure ambient SO_2 concentrations and impacts;
3. regulating the SO_2 emissions from the Kitimat Modernization Project until the end of 2018 according to the policy entitled "Pollution Control Objectives for the Mining, Smelting and Related Industries of British Columbia, 1979 (Reprinted in 1989)", in its existing form on the effective date of this MoU; and
4. developing and implementing SO_2 mitigation strategies if the emissions modelling and monitoring show potential adverse impacts related to SO_2.

Additionally, the MoU emphasized the importance of taking a logical and systematic adaptive management approach to ensure the cost effective use of human and financial resources. While the scope of this technical assessment was above and beyond what is normal for industry in British Columbia, and the Aluminum Smelting Industry, the studies were designed to meet the intent of the principles of the MoU.

Under agreement in the MoU, the guidelines for ambient air quality in British Columbia established under the Provincial Pollution Control Objectives (PCOs) will be used to assess and regulate SO_2 emissions from KMP. The PCOs are specific to the Province's mining and metals sector and provide ambient air quality objectives for SO_2 emissions resulting from end-of-pipe mining and smelting activities. The PCOs set a range of acceptable ambient SO_2 concentrations with the application of the lower range targeted to protect sensitive receptors. Please refer to Appendix 5.1-1 for the table of ambient SO_2 concentrations under the PCOs. The PCOs are largely in agreement with the Canadian National Ambient Air Quality Objectives.

5.2 FEDERAL LEGISLATION

Presently, the Federal Government does not regulate SO_2 ambient air quality. The Canadian Council of the Ministers of Environment (CCME) has established Canada-wide SO_2 air quality standards. These standards will be replaced through upcoming Federal Regulation aimed at developing a Comprehensive Air Management System (CAMS).

The Canadian ambient air quality system (CAAQS) will be established under the Canadian Environmental Protection Act, replacing the current CCME Canada-wide air quality standards. The CAAQS will establish regional airsheds and a framework for air zone management. Additionally under the CAMS, industrial emission requirements will be established that set a base level of performance for major industries, including the aluminum sector.

The Baseline Industry Emission Requirements (BLIERS) set emission targets for industry to meet. Recommendations for BLIERS were developed through a collaborative working group with Environment Canada, provincial Ministries of Environment, Industry and NGOs. For the aluminum sector, a qualitative SO_2 BLIERS has been recommended for electrolysis, anode baking, and coke calcinations at existing and new facilities. The qualitative SO_2 BLIERS includes data collection and reporting to allow for the assessment of emission control and prevention, and will come into effect in 2013. Additionally, a working group of experts will be formed to develop a pollution prevention (P2) action plan. The P2 plan will identify initiatives applicable to aluminum smelting processes. Annual SO_2 data reporting will be required for coke calcination, electrolysis and anode baking processes. The reporting will be harmonized with Quebec's Air Quality Regulation and Quebec's Ministry of Environment reporting requirements. Reporting will include:

- sulphur concentration of green and calcined cokes;

- total quantity of coke used;
- SO_2 emissions released in processes;
- quantities of sulphur contained in material input for anode and aluminum production; and
- monthly data for the required reporting parameters.

5.3 SO_2 AND ACIDIC DEPOSITION PROTOCOLS

5.3.1 Canada

SO_2 regulations at the national level were established more than 25 years ago, specifying annual emissions caps (Federal/Provincial/Territorial Ministers of Energy and Environment 1998). In 1985, Canada signed the First Sulphur Protocol which specified a national cap on SO_2 emissions of 3.2 million tonnes per year starting in 1993.

In 1991, Canada and the United States signed an Air Quality Agreement to manage transboundary air pollution, starting with acid rain. The agreement set a lower annual emissions cap of 2.3 million tonnes for eastern Canada for the period 1994-1999, and upheld the 3.2 million tonne cap established in the First Sulphur Protocol for the rest of the country starting in 2000.

In 1994, Canada signed the Second Sulphur Protocol. This identified a Sulphur Oxide Management Area in southeastern Canada with an annual cap on emissions of 1.75 million tones starting in 2000.

In 1998, all provinces signed The Canada-Wide Acid Rain Strategy. This shifted the focus from emissions to critical loads, and specifies that SO_2 emissions in eastern Canada need to be reduced to a point where the resulting SO_4 deposition does not exceed critical loads, taking into account U.S. emission reductions as well as those in Canada. The strategy for the rest of Canada is to “keep clean areas clean” by managing SO_2 to ensure deposition levels do not approach the critical load. Critical loads for SO_4 deposition are defined as the amount that can be deposited on the area and still maintain 95% of the lakes in the region at or above a pH of 6. Critical loads for wet SO_4 deposition in eastern Canada range from 8 to over 20 kilograms of wet SO_4 per hectare per year.

5.3.2 Alberta

The province of Alberta has developed a framework for management of acid deposition based on critical loads and target loads (Alberta's Clean Air Strategic Alliance 1999). Target loads are defined as a level of deposition that considers the critical load; target loads are also practically and politically achievable. Under the framework, stakeholders have agreed that the target load will be below critical load.

Alberta also uses a 95% level of protection for establishing critical loads. The recommended **critical loads** are 0.25 keq/ha/yr for sensitive soils, 0.50 keq/ha/yr for moderately sensitive soils, and 1.00 keq/ha/yr for soils of low sensitivity. This is done by placing a grid measuring 1° latitude by 1° longitude (approximately 111 km by 60 km) on a receptor sensitivity map. If 5% or more of the area contained within a grid cell is rated as sensitive to acid deposition, then the entire grid cell is classified as sensitive. If less than 5% of the area is sensitive, but the total of sensitive and moderately sensitive areas equals or exceeds 5% of the grid cell area, the grid cell is classified as moderately sensitive. All remaining grid cells are of low sensitivity. The **target loads** are 0.22 keq/ha/yr in grid cells classified as sensitive, 0.45 keq/ha/yr in cells classified as moderately sensitive, and 0.90 keq/ha/yr in cells classified as having low sensitivity. These target loads are established at approximately 90% of the critical loads, and are subject to change as critical loads change.

The Alberta framework also includes the concept of "monitoring loads". Monitoring loads are levels of deposition predicted or estimated by a dispersion and deposition model that trigger monitoring and/or research actions. Monitoring loads are different from target loads in that the only action that occurs once deposition is at or above the monitoring load is the collection of additional data. Exceedance of a monitoring load does not trigger emission reduction actions. These monitoring loads are 0.17 keq/ha/yr for grid cells classified as sensitive, 0.35 keq/ha/yr for cells classified as moderately sensitive, and 0.70 keq/ha/yr in cells classified as having low sensitivity.

5.3.3 Europe

In Europe, according to a 2005 amendment of the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (EMEP 1999), countries within the geographic scope of the Cooperative Programme for Monitoring and Evaluation of Long-range Transmission of Air Pollutants in Europe have specific SO_2 emission ceilings for 2010. Emission limit values in mg/m^3 are also set for stationary sources of sulphur.

Emissions must be monitored to confirm compliance with these limit values. Measurements of emissions should be done continuously when emissions of SO_2 exceed 75 kg/h. In the case of continuous measurement for a new plant, compliance is achieved if the calculated daily mean values do not exceed the limit value and if no hourly value exceeds the limit value by 100%.

Where continuous measurements are needed for an existing plant, compliance is achieved if no monthly mean values exceed the limit values, and 97% of all of the 48-hour mean values do not exceed 110% of the limit values. If continuous measurements are not required, under discontinuous measurements compliance is achieved if the mean value based on an appropriate number of measurements under representative conditions does not exceed the value of the emission standard.

The objective of the Protocol is to control and reduce emissions of sulphur (and other compounds) from anthropogenic activities which are likely to cause adverse effects on human health, natural ecosystems, materials, and crops due to acidification (and other processes). Particular to the risk of acidification, the objective is to ensure that acidic deposition does not exceed critical levels and loads. The concepts of critical loads and exceedances are used to inform emission reduction strategies as shown in Figure 5.3-1, according to a detailed manual describing the methodologies and criteria for mapping critical levels/loads and geographical areas where they are exceeded (UNECE 2004).

This manual describes how the previous 1994 Sulphur Protocol uses the 5th percentile of the cumulative distribution function of critical loads in a grid cell as the critical load criterion (i.e., protecting 95% of the area or resources within a grid cell), with exceedance simply being the difference between the (current) S deposition and that 5th percentile critical load. An ecosystem area gap closure method was important for the 1999 Guthenberg Protocol, which considers both sulphur and nitrogen contributions to acidification.

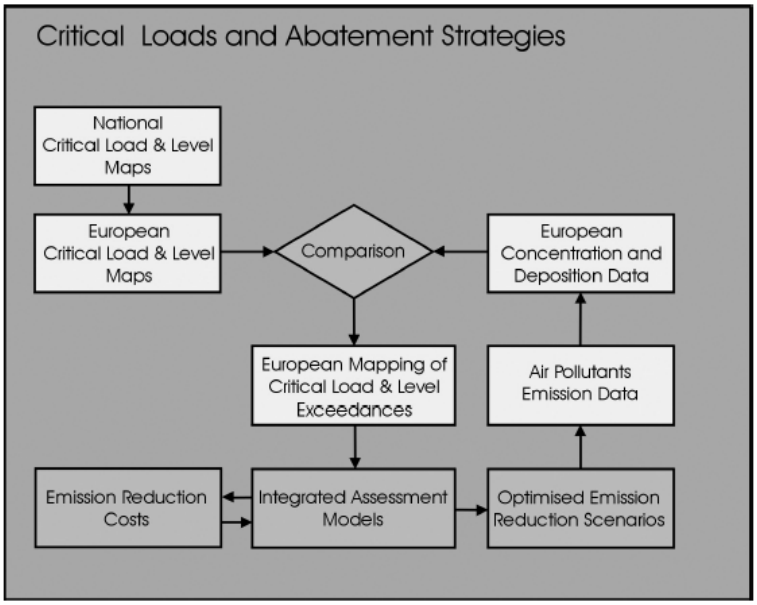
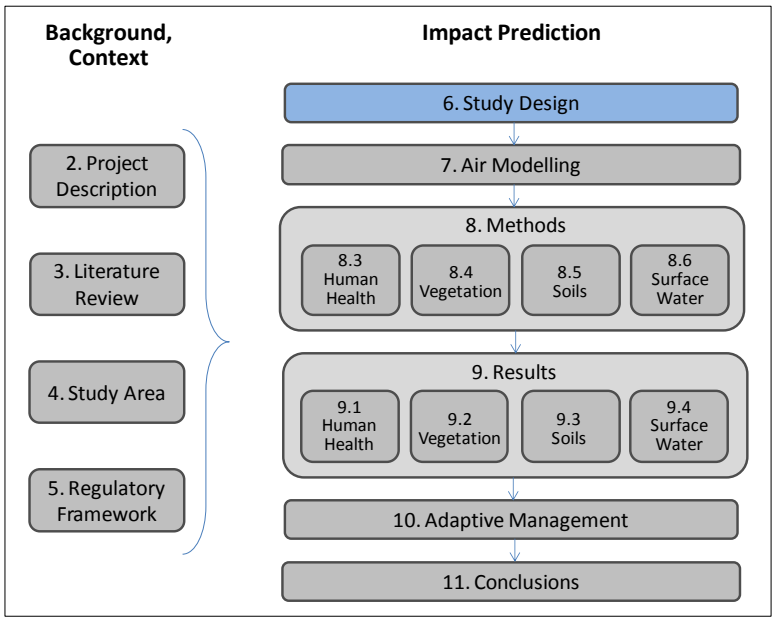


Figure 5.3-1: The role of critical loads maps for the development and implementation of air pollution control strategies. Source: Figure 3 from UNECE (2004).

6.0 Study Design



Five studies were conducted for this assessment. The first study focused on the air pathway in the source-pathway-receptor model, as this is the pathway that leads to both direct effects and indirect effects of SO_2 emissions on the receptors. The remaining four studies focused on the receptors: human health, vegetation, soils and water. Figure 6.0-1 illustrates how each of these studies fits in the source-pathway-receptor model presented in Section 3.1.1. The nature of these studies differed according to where they fit in the source-pathway-receptor model.

No specific assessment was done to determine the impacts of acidic deposition on materials (e.g., buildings, bridges, other aboveground infrastructure) because the SO_2 levels in population centres (Kitimat and Terrace) are predicted to be below published standards for the protection of materials. The European Commission's position paper on SO_2 (EC Working Group 1997:18) recommends an annual mean concentration standard of 10 $\mu g/m^3$ SO_2 for protecting bronze, limestone and sandstone, and 15 $\mu g/m^3$ for protecting zinc and steel. Post-KMP, the annual mean SO_2 concentration for residential and commercial areas of Kitimat (i.e., outside of the smelter property) is predicted to be <10 $\mu g/m^3$ for most locations in all three modelled years (see Volume 3, pages 257, 261 & 265), and only 4 $\mu g/m^3$ in Terrace (see Volume 3, page 270).

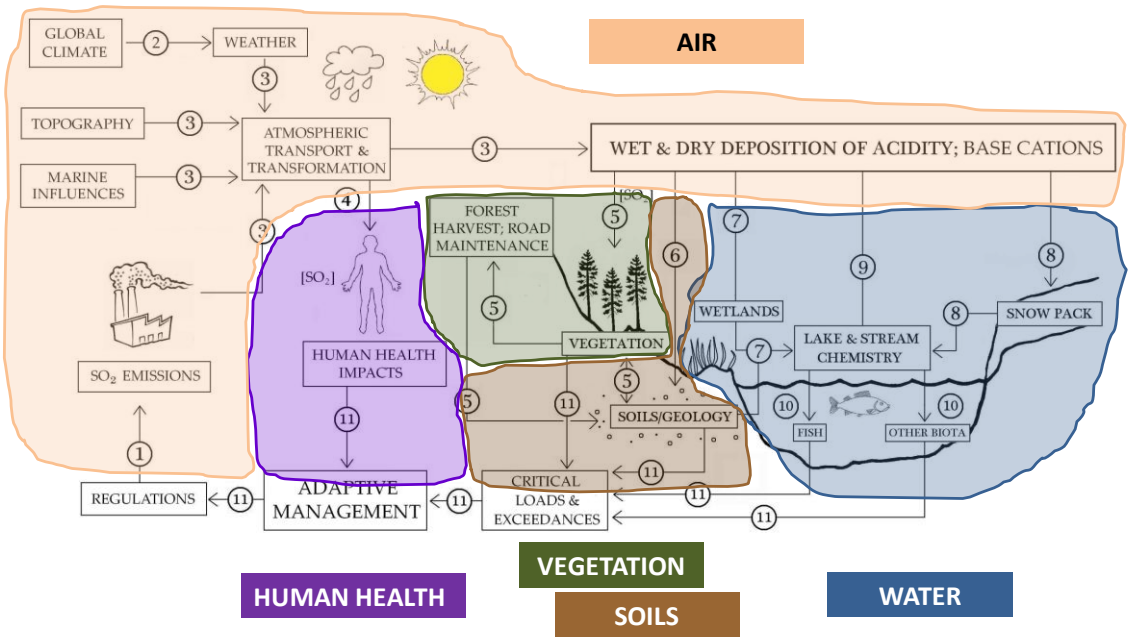


Figure 6.0-1: The study design overlaid on the source-pathway-receptor model.

The **air study** produced two important predictions: atmospheric concentrations of SO_2, and S deposition (expressed in units of kg/ha/yr of SO_4). Predictions of SO_2 concentrations were important inputs to studies of human health impacts and direct impacts on vegetation. Predictions of SO_4 deposition were used to assess indirect impacts on vegetation via soils, potential changes in soils, and the potential responses of lakes and streams. These predictions were made at two levels of spatial resolution: (1) a fine grid of points spaced 100 m apart (for residential areas); and (2) a coarse grid of points spaced 500 m apart (for the rest of the study area). See Appendix 7.6-1 for additional details.

Predictions of SO_2 concentrations and SO_4 deposition under KMP were generated using a computer model called CALPUFF. The results of applying CALPUFF to the four receptors depends on how conservative CALPUFF predictions are. In other words, does CALPUFF over-predict or under-predict SO_2 concentrations and SO_4 deposition? This was answered by testing the model against what we already know has occurred in the past. The air pathway study therefore had two temporal components. The first was retrospective modelling: running the model using estimates of historic emissions from the smelter, and comparing the modelled SO_2 concentration and S deposition results against historic data from instruments that have been monitoring actual SO_2 concentrations and SO_4 deposition. The second was prospective modelling of what is likely to happen in the future, to predict SO_2 concentrations and SO_4 deposition after KMP is fully operational. It is the results of this future modelling that drove the four receptor studies, though retrospective CALPUFF modelling results are also used in the

vegetation and surface water analyses for comparative purposes to assess historical conditions and impacts.

Figure 6.0-2 summarizes the high-level similarities and differences in the general approaches to the air study and the studies of the four receptors. The receptor studies followed two different approaches: the studies of human health and vegetation used the frequency and magnitude of exceedances of SO_2 concentration *thresholds* to predict impacts, whereas studies of soils and surface water used exceedances of *critical loads* of acidity to predict impacts on these receptors.

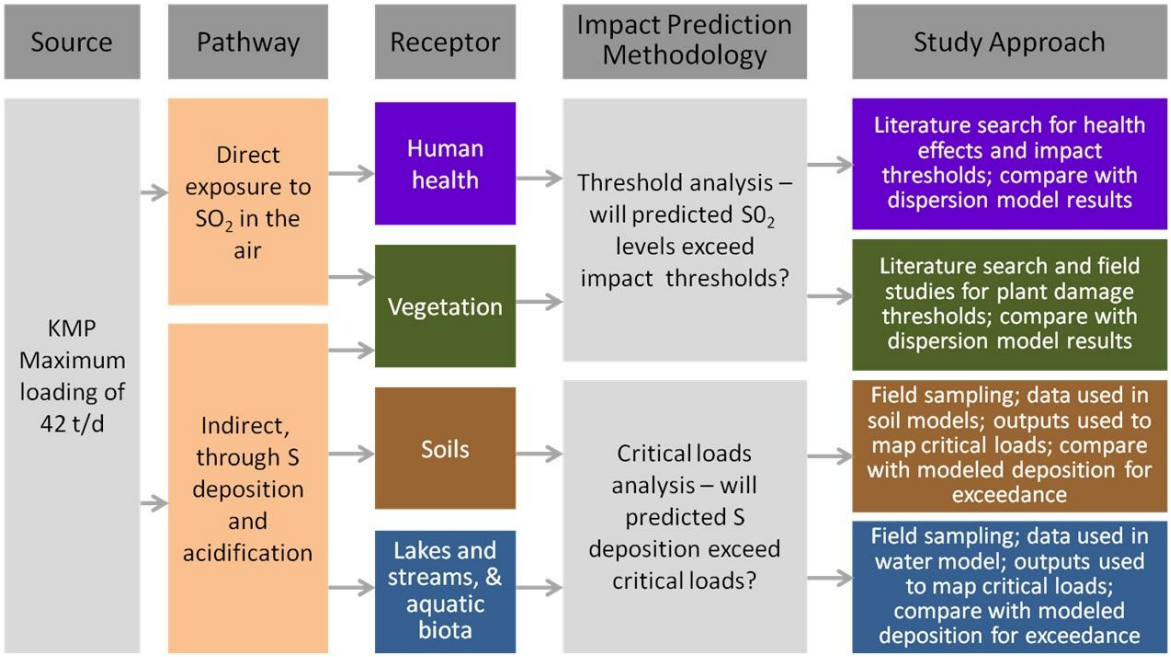


Figure 6.0-2: High-level study approaches for the four receptors.

The **human health study** investigated the potential for direct impacts on people in the study area from the expected SO_2 concentrations in the air after KMP. Potential health impacts from SO_2 and dose-response relationships were identified from the literature, and predicted SO_2 concentrations (from the air study) were transformed and analysed based on these dose-response relationships to assess the likely number of cases of respiratory impacts due to SO_2. Potential impacts on wildlife were investigated through a literature search (see Section 3.5.5) but not formally studied as part of our assessment; empirical evidence for direct impacts of SO_2 on wildlife is scarce and inconclusive.

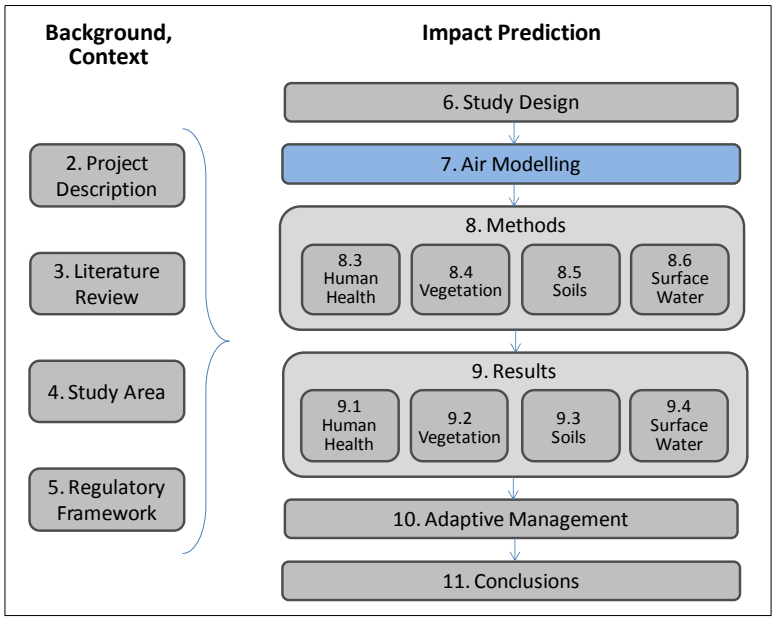
The **vegetation study** investigated the potential for impacts on plants from direct exposure to SO_2 concentrations in the air, as well as the potential for impacts on plants growing in soils where SO_4 deposition may exceed critical loads. The study identified potential vegetation

impacts from SO_2 and sensitivity thresholds from the literature, examined historic vegetation monitoring data in the study area for evidence of impact from previous exposure levels, and analysed predicted post-KMP SO_2 concentrations (from the air study) for exceedances of vegetation thresholds of concern.

The **soils study** and the **water study** both investigated the potential for SO_4 deposition in the study area to exceed critical loads. Exceeding soil critical loads poses a risk to vegetation. Exceeding lake and stream critical loads poses a risk for fish and other aquatic organisms, and any wildlife species that depend on those fish or other organisms for food. There are no regulatory thresholds for critical loads, as they depend on site-specific characteristics that govern the ability of the soil or water in any given area to neutralize acidity. Instead, these studies examined characteristics of the receptors to determine their critical loads, and then predicted whether post-KMP levels of SO_4 deposition would exceed these critical loads – and if so, where and by how much.

Further details on methodology for all five studies are presented in the next two sections.

7.0 Ambient Air Quality Monitoring and Air Dispersion Modelling



7.1 SULPHUR DIOXIDE (SO_2) IN THE ATMOSPHERE

Ambient air quality measurements in the Kitimat region include both measurements of sulphur dioxide (SO_2) gas as well as sulphate (SO_4^{2-}) ion species dissolved in rain and snow melt. Together, these species comprise atmospheric sulphur or "atmospheric S". As noted in Section 3.3, gaseous SO_2 can be quickly transformed by oxidation into particulate SO_4^{2-}, which can be incorporated into clouds and fall to earth as acidic rain, snow and fog. Aqueous phase conversion of SO_2 occurs in solution, in cloud droplets, in fog, on moist surfaces of plants and soil, and at the surface of water bodies. SO_2 gas and SO_4^{2-} aerosols also deposit directly to vegetation, soils, and structures as dry deposition, contributing an additional acid input to the environment. Further details are provided in Sections 3.2 and 3.3.

7.2 METHODS FOR MEASURING SULPHUR IN THE ATMOSPHERE

There are several accepted methods for the measurement of atmospheric S under routine atmospheric monitoring (see Table 7.2-1). The advantages and disadvantages of each method generally fall to capital cost for equipment and ongoing monitoring versus resolution of the monitoring data. Continuous SO_2 (active) monitors provide high resolution temporal observations of gaseous SO_2 and are generally used to evaluate air quality compliance against

legislated standard objectives. Passive diffusive sampler (PDS) networks are generally used to supplement information from active monitors as they are cost-effective, allowing the assessment of ambient levels over a wider area, and can be used to estimate SO_2 dry deposition. Continuous monitoring of particulate SO_4^{2-} bears high capital costs or very high uncertainty associated with measurements from passive particulate samplers. However, studies of particulate SO_4^{2-} formation in plumes of coal-fired plants with particulate control suggest that the oxidation rate of SO_2 is negligible in the region 15 to 30 km from the emissions source. Based on the results from other studies, rainout and washout are expected to be the most significant mechanisms for the removal of particulate SO_4^{2-} from the atmosphere as SO_4^{2-} aerosols readily serve as nuclei for the condensation of water.

Table 7.2-1: Methods for measuring atmospheric sulphur species, including gaseous, particulate and wet/dry deposition.

Method	Principle of Operation	Advantages	Disadvantages
Atmospheric Measurement of Sulphur Dioxide Gas			
Continuous Monitor	UV Fluorescence Monitor	Continuous data reporting	High capital cost, requires power, high technical ability
Active Monitor	Cation-coated denuder or diffusion tube with air sampler pump	Relatively low capital cost, good sensitivity	Requires power, integrated concentration, relatively high analytical cost
Passive Monitor	Cation-coated passive sampler	Low capital cost, no power, moderate technical ability	Integrated concentration, must be standardized to reference
Wet Deposition of Sulphate Ion			
Wet deposition collector	Laboratory analysis of SO_4^{2-}	Moderate capital cost, moderate technical ability	Weekly integrated concentration
Dry Deposition of Sulphur Dioxide Gas			
Flux measurement	Continuous monitoring	Continuous data reporting	High capital cost, requires power, high technical ability
Passive monitor	Inferred deposition using ambient concentration	Low cost estimate of dry deposition	Modeling uncertainty
Dry Deposition of Particulate Sulphate			
Active Monitor	Open-faced filter pack or $PM_{2.5}$ monitor with modelling	Reporting of weekly deposition	High capital cost, requires power, high technical ability, modelling uncertainty
Passive Monitor	'Sticky' pad in wet/dry collector	Estimate of SO_4^{2-} dry deposition flux	Very high uncertainty

7.3 AIR QUALITY MONITORING NETWORK

Rio Tinto Alan has established a comprehensive network in the Kitimat Valley to monitor concentrations of atmospheric pollutants, particularly atmospheric sulphur dioxide (SO_2), and air quality trends following KMP. Continuous SO_2 monitors evaluate air quality compliance with

standards established by the MOE, a PDS network monitors the air concentration of SO_2 over a wider area, supplementing the active monitors, and wet deposition monitoring sites have been established as part of the National Atmospheric Deposition Program (NADP; http://nadp.isws.illinois.edu). Additionally, model simulations have been performed using the CALPUFF model to predict future changes in air quality (see Section 7.6 for a description of the CALPUFF model).

The network comprises a broad range of sites; their locations and descriptions are provided in Table 7.3-1 and Figure 7.3-1. At each site, PDS (manufacturer Sigma-Aldrich model *Radiello*™) have been used to measure SO_2. Additionally, six stations have continuously measured SO_2 using UV fluorescence instruments. A seventh station, the British Columbia MOE's Mobile Air Monitoring Laboratory (MAML) operated from September to December 2010 and from May to November 2011 in Kitimat. A list of air quality parameters measured at each of the continuous stations is given in Table 7.3-2. More information about historic measurements is provided in Section 4.1.2. All stations follow strict protocols for observation and calibration; further information about the measurement methods is provided on the British Columbia MOE website at http://www.bcairquality.ca. Example photos of the continuous and passive monitoring sites are provided in Figure 7.3-2. Precipitation samples (rain and snow) are collected weekly at one station, Haul Road, to measure chemical concentrations and the wet deposition of the chemical species. An additional precipitation monitoring site at Lakelse Lake is proposed to begin operations in early 2013.

The continuous air quality monitoring stations provide hourly observations of SO_2, which is essential to assessing the potential health impacts of KMP. However, due to the complexity of the continuous instruments, it is not feasible to locate them in all critical monitoring areas in the Kitimat Valley. PDS are used to supplement the continuous monitors, and are located at strategic locations. The goal of the PDS network is to provide an efficient means to measure SO_2 in the air across a wide area, and to evaluate changes in SO_2 over time during KMP. The PDS measurements have also been used to evaluate CALPUFF-modelled concentrations predicted for current pre-KMP conditions, and could be used to evaluate CALPUFF predictions in the ramp-up to full KMP implementation and the post-KMP phase.

The passive diffusive samplers were initially deployed in a special study during the summers of 2011 and 2012 to establish the ability of PDS to measure current concentrations of SO_2 in the air, evaluate the quality of data provided by PDS, and compare PDS measurements to continuous SO_2 instruments. These short-term studies provided useful information on optimal deployment durations, locations, and sampler orientation as part of a longer-term measurement plan. Further detail on the study is provided in Appendix 7.3-1.

Table 7.3-1: Stations in the Kitimat Air Quality Monitoring Network.

Site Name	ID	Elevation m	Longitude decimal	Latitude degree	Sampling Type		
					PDS Air	Continuous Air	Precipitation
Bish Road Lookout	1	149	-128.72714	53.93800	×		
Bish Site (4.1 km)	2	31	-128.70338	53.96476	×		
Rifle Range	3	31	-128.70928	54.01699	×		
KMP Camp	4	13	-128.70257	54.01951	×	×	
Bend	5	18	-128.71261	54.02820	×		
Haul Road	6	8	-128.70192	54.02931	×	×	×
Sand Hill	7	161	-128.70968	54.05140	×		
PNG Station	8	14	-128.69109	54.06636	×		
Claque Mtn.	9	58	-128.69522	54.07867	×		
Kitamaat Village	10	4	-128.65096	53.97338	×	×	
Low Spot	11	3	-128.65237	54.02460	×		
Low Channel	12	5	-128.66375	54.04692	×		
Riverlodge	13	11	-128.67101	54.05396	×	×	
Kitimat MAML [a]	14	26	-128.65434	54.05586	×	×	
Colghlin Park	15	97	-128.62808	54.05209	×		
High School	16	87	-128.62698	54.06022	×		
Whitesail [b]	17	97	-128.63910	54.06695	×	×	
Cablecar	18	19	-128.62640	54.09957	×		
Williams Creek	19		-128.44657	54.42764	×		
Lakelse Lake [c]	*20*	*82*	*-128.58495*	*54.37481*	×	×	×
Onion Lake [d]	21		-128.66849	54.09502	×		
Power Line [d]	22		-128.61583	54.30348	×		
Railsite [e]	23		-128.68723	54.06115		×	

[a] Continuous monitoring operated September 2010 to November 2011.
[b] Continuous monitoring ended May 2011.
[c] Proposed.
[d] Established August 2012.
[e] Continuous monitoring ended June 2010.

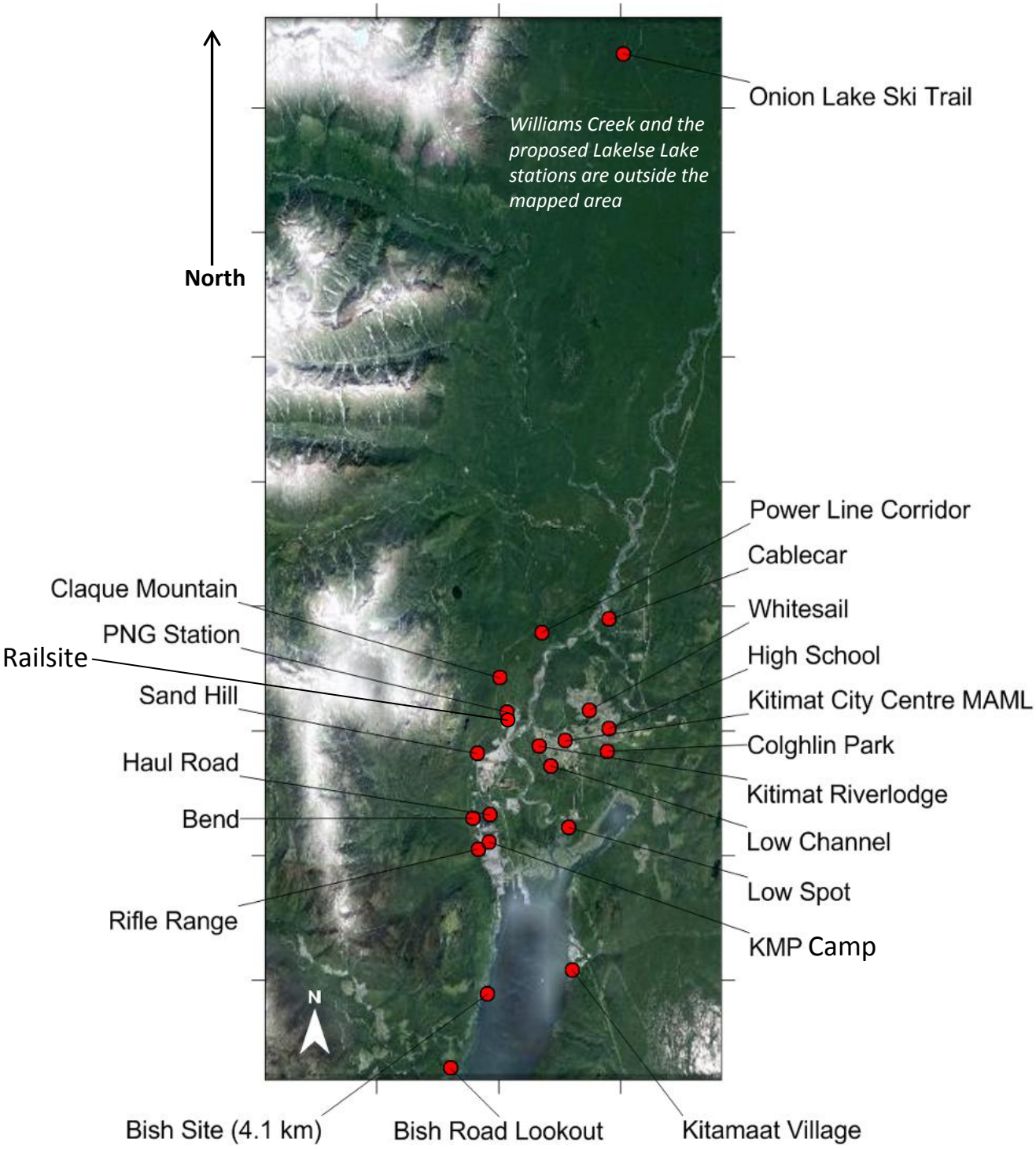


Figure 7.3-1: Location of passive and continuous air quality monitoring stations in the Kitimat Valley, British Columbia.

Table 7.3-2: Air quality parameters measured at continuous monitoring stations in the Kitimat Valley.

Site Name	Sulphur Dioxide	Fine Particulate Matter		Hydrogen Fluoride	Nitrogen Oxides	Ozone
		<2.5 µm	<10 µm			
KMP Camp	×		×	×		
Haul Road	×	×				
Kitamaat Village	×	×				
Riverlodge	×	×	×	×		
Whitesail	×	×				
Kitimat MAML[a]	×	×	×	×	×	×
Railsite	×					

[a] MAML (Mobile Air Monitoring Laboratory) operated from September to December 2010 and from May to November 2011.

Figure 7.3-2: Example photos of continuous and passive monitoring for air quality at (left) Kitamaat Village continuous monitoring station, and (right) Low Spot passive monitor.

7.4 KITIMAT AIR QUALITY SUMMARY AND AMBIENT SO_2 LEVELS

As reported by the B.C. Lung Association, ambient levels of SO_2 in the Kitimat region currently meet British Columbia MOE objectives, defined as an annual arithmetic mean of less than 25 micrograms of SO_2 per cubic meter of air (µg SO_2/m^3). This is equivalent to 9.4 ppb SO_2 at an ambient temperature of 20°C (http://www.bcairquality.ca/reports/pdfs/aqotable.pdf, accessed 30 Nov 2012). Health risks from acute and chronic exposure to SO_2 are described in Section 9.1

Facilities reporting SO_2 emissions to the Canadian National Pollutant Release Inventory (NPRI) in the Kitimat region include RTA and Eurocan Pulp and Paper Company. Eurocan ceased

operations in January 2010. Facility emissions reported in the NPRI are summarized in Table 7.4-1.

Table 7.4-1: On-site air emissions of SO_2 in the Kitimat Region reported by the Canadian National Pollutant Release Inventory [a].

Year	SO_2 Emissions [tonnes/year]	
	Pre-KMP	Eurocan
2002	6,421	720
2003	7,046	430
2004	7,583	647
2005	7,417	669
2006	7,883	664
2007	6,877	618
2008	7,115	661
2009	6,277	606
2010 [b]	5,489	
2011	5,257	

[a] Source: http://www.ec.gc.ca/inrp-npri/.

[b] Eurocan ceased operation January 2010, 2011 data considered "preliminary and unreviewed" by Environment Canada.

Figure 7.4-1 compares data from monitoring stations across British Columbia, as reported by the B.C. Lung Association. Air quality in the Kitimat region is generally good as compared to other locations in B.C., with concentrations at Kitamaat Village representing some of the lowest concentrations routinely measured in B.C. The highest concentrations in Kitimat are measured at the RTA KMP Construction Camp, yet these concentrations fell within MOE objectives during 2011.

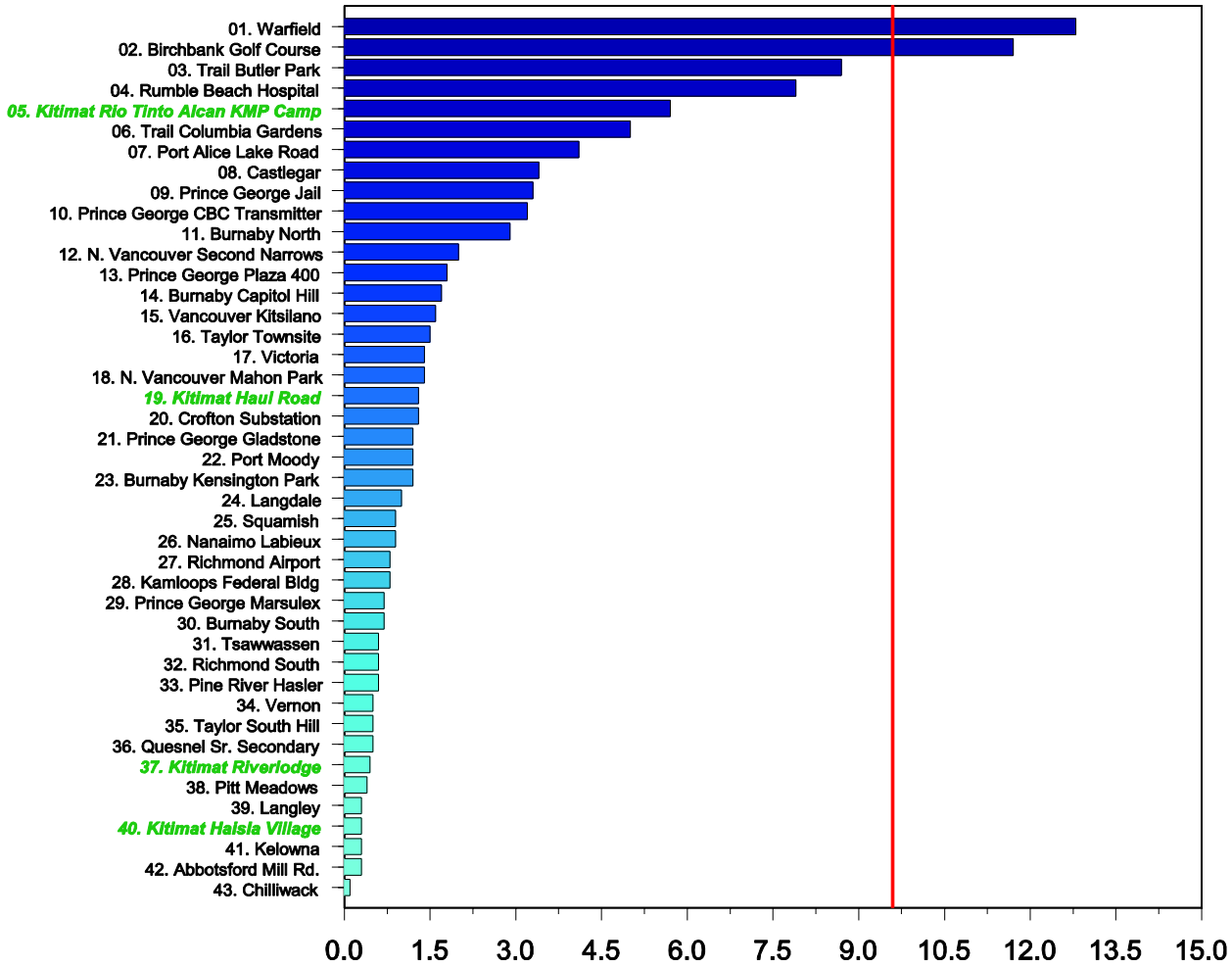


Figure 7.4-1: Comparison of annual mean SO_2 concentrations (ppb) across British Columbia from 2011, highlighting (in green) stations in the Kitimat region. Red line is 9.4 ppb SO_2, the B.C. MOE objective. Source: B.C. Lung Association.

Concentrations of SO_2 in the ambient air show a long-term trend consistent with SO_2 emissions from the RTA facility. Monthly mean SO_2 concentration data from continuous monitoring stations at Haul Road, Kitamaat Village, Riverlodge, and Railsite are shown in Figure 7.4-2 with monthly SO_2 emissions from the RTA facility. The long-term trend is notable after the financial crisis of 2008, and in particular after the closure of Eurocan in January 2010 (Table 7.4-1).

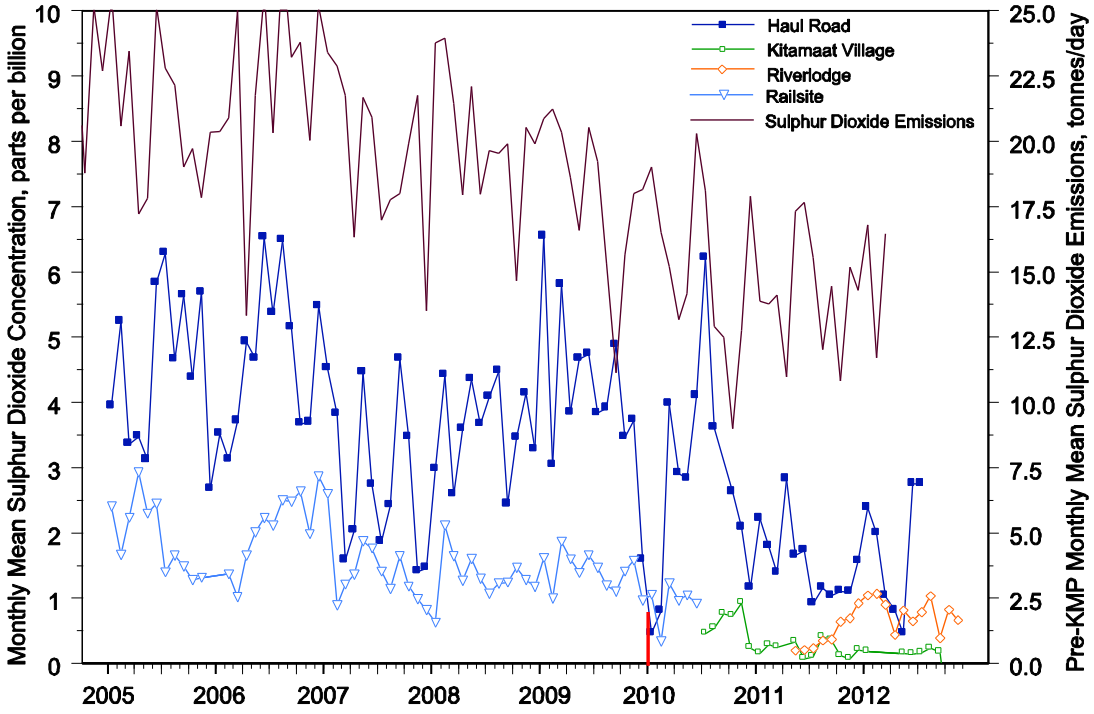
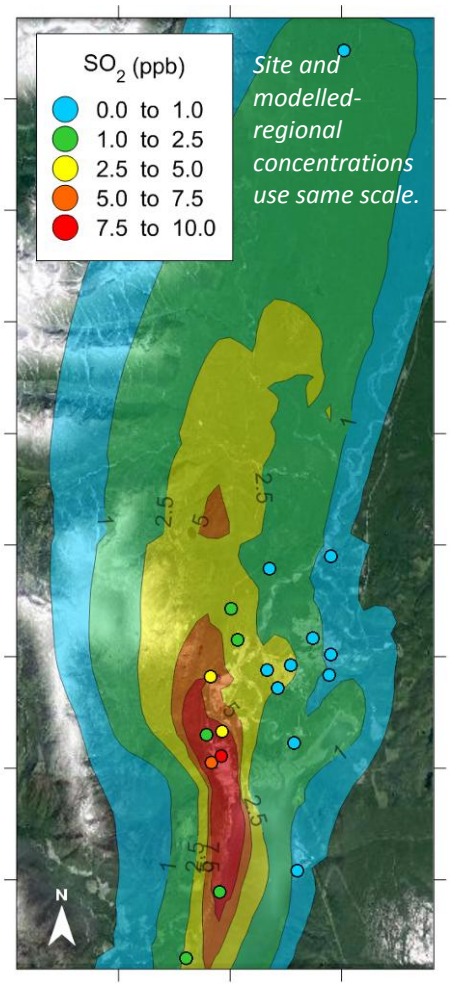


Figure 7.4-2: Monthly mean SO_2 concentrations at Haul Road, Kitamaat Village, Riverlodge and Railsite based on continuous monitoring data, as compared to monthly mean SO_2 air emissions from the RTA facility. The red line indicates closure of Eurocan facility in January 2010 (see Table 7.4-1).

Weekly measured concentrations in the Kitimat PDS network had concentrations ranging from 0 to 9 ppb during the period from June to September 2012. The median concentration for each station is shown in Figure 7.4-3 and compared with pre-KMP modeled SO_2 air concentrations (Section 7.6 provides further details on the pre-KMP model scenario). The higher concentrations generally follow the modelled plume pattern, with the highest concentrations at the KMP station. The PDS network measurements confirm that elevated SO_2 levels are localized to the vicinity of the facility, consistent with CALPUFF model predictions.



Atmospheric SO_2 (ppb)

KMP Camp	9.94
Rifle Range	5.51
Haul Road	3.84
Sand Hill	2.69
Bend	2.33
Bish Site (4.1 km)	2.03
Claque Mountain	1.43
Bish Road Lookout	1.41
PNG Station	1.25
Onion Lake Ski Trail	0.86
Power Line	0.60
Kitimat Riverlodge	0.19
Low Channel	0.11
Whitesail	0.06
Cablecar	0.05
City Centre MAML	0.03
Kitamaat Village	0.02
Low Spot	0.02
Williams Creek	0
Colghlin Park	0
High School	0

Figure 7.4-3: Median ambient SO_2 concentrations from PDS network during June to October 2012 (coloured dots), as compared with CALPUFF-modelled pre-KMP annual average air concentrations (coloured zones on map).

Kitimat area deposition estimates

The rate of removal of SO_2 via dry deposition is proportional to the ambient levels of SO_2 in the atmosphere, although it is affected by ambient weather conditions and surface conditions. For example, forested lands will more effectively remove SO_2 from the atmosphere than open areas. Atmospheric chemistry inferential models are typically used to estimate the rate of SO_2 dry deposition; such methods are used by the Canadian Air and Precipitation Monitoring Network for measurements across Canada (Zhang et al. 2003). The method employed in this study utilized dry deposition fluxes provided by Environment Canada (see Appendix 7.3-1 for details). Wet deposition of sulphur is measured by collecting samples of precipitation, including

both rain and snow. Evaluation of the wet and dry deposition data provides an estimate of total sulphur deposition.

There is an existing wet deposition monitoring station in the Kitimat region at Haul Road, operating since July of 2000 (Figure 7.4-4). This station was upgraded with new equipment in September of 2012 and incorporated into the National Atmospheric Deposition Program (NADP) as NADP site BC22 in September 2012. An additional monitoring location is planned for Lakelse Lake in early 2013, which will operate as NADP station BC23.

Figure 7.4-4: Haul Road wet deposition monitoring location (Station #6, NADP ID BC22), showing electronic recording rain gauge (shown at left) and a wet deposition collector (at right).

As of November 2012, available data from the NADP station were found to compare well with historic data from the Haul Road station. See Figure 7.4-5 for a comparison of historic Haul Road wet SO_4^{2-} ion concentration, continuous SO_2 concentration, and NADP wet SO_4^{2-} ion concentration.

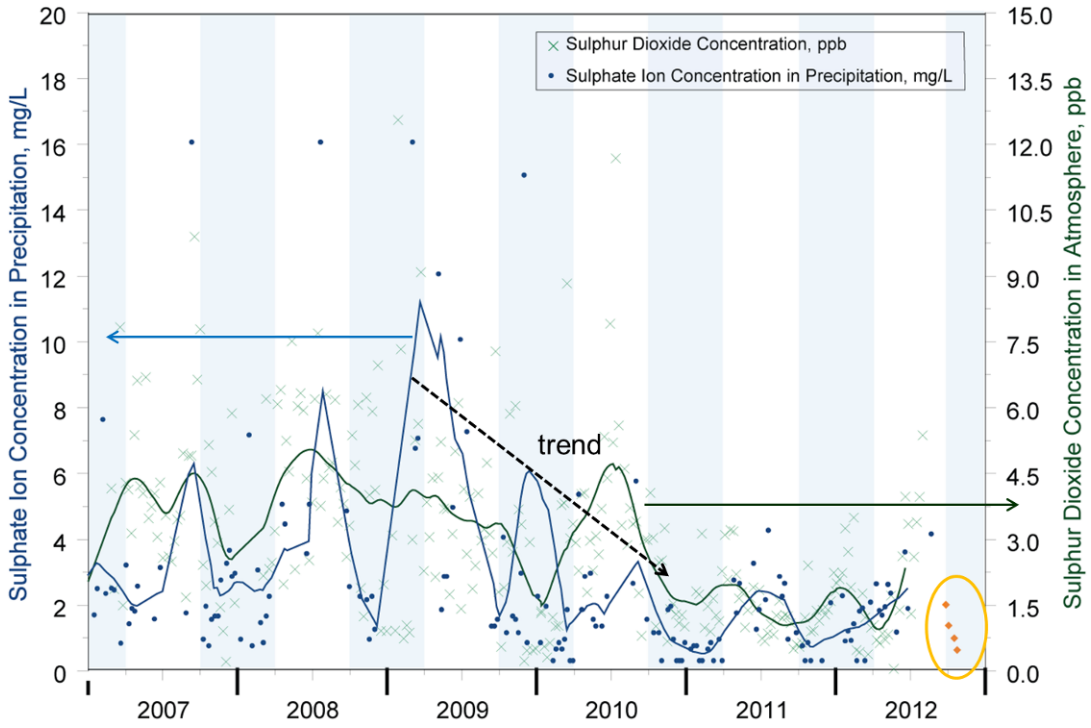


Figure 7.4-5: Comparison of Haul Road concentration of sulphate ion in wet deposition (blue line, left axis) and ambient sulphur dioxide concentration (green line, right axis) from 2007-2012; orange dots represent data from NADP station established in September 2012, and shaded blue bars represent cold seasons.

Monthly wet, dry, and total deposition of sulphur for 2005 to the present are compared with monthly average SO_2 emissions for the Haul Road station in Figure 7.4-6. The data indicate that deposition of sulphur varies throughout the year due to ambient weather conditions, and not necessarily coincident with SO_2 emissions. Overall sulphur deposition indicates a decreasing trend, particularly after the financial crisis of 2008 and the closure of the Eurocan facility in January 2010 (Table 7.4-1).

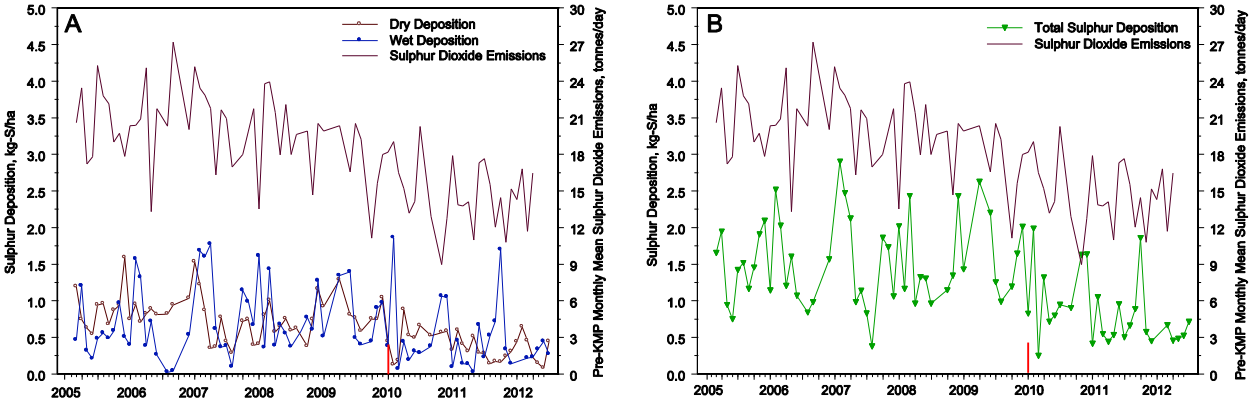


Figure 7.4-6: A. monthly wet and dry deposition of sulphur at Haul Road station, 2005 to the present. B. total sulpur deposition as compared to monthly SO_2 emissions from the RTA facility, 2005 to the present. See footnote at bottom of page.

CALPUFF-modelled total sulphur deposition at Haul Road under pre-KMP conditions (averaged over 2006, 2008 and 2009) is estimated to be 26 kg of sulphur per hectare per year (Table 7.4-2). In comparison, total sulphur deposition averaged over the same period was estimated to be 18.2 kg S/ha, based on the wet deposition measurements and dry deposition inferred from continuous SO_2 monitoring data.[8] Ambient measurements were 30% less than the predicted sulphur deposition. The relative ratio of dry deposition to total deposition compared reasonably well, representing 54% of estimated deposition versus 42% predicted by the CALPUFF model (Table 7.4-2). The comparison at Haul Road suggests that the CALPUFF simulations may overestimate pre-KMP total sulphur deposition; however, both show approximately the same proportion of dry deposition. It is notable, however, that estimated dry deposition exceeded wet deposition, while CALPUFF predicts that wet deposition should be greater than dry deposition. There are uncertainties inherent in both procedures: for the dry deposition estimate, the monthly dry deposition velocity is inferred from Saturna, B.C., and for CALPUFF, ambient meterology is limited to reduced data sets. That noted, the modelled and observed total deposition estimates show reasonable agreement for a near-field location (i.e., close to emission sources). Lakelse Lake deposition results are not currently available, but the establishment of the station is pending.

[8] Deposition expressed in units of kg S /ha/yr is about one third the value of deposition expressed in units of kg SO_4 /ha/yr, since the atomic weight of S (~32 g) is about one third of the molecular weight of SO_4 (~96 g).

Table 7.4-2: Wet and dry deposition of sulphur, comparing estimated annual mean values at Haul Road during 2006, 2008, and 2009 and modelled values for Haul Road and Lakelse Lake stations averaged over 2006, 2008 and 2009.

Site Name	Estimate kg S /ha/yr 2006, 2008, 2009		Modelled Pre-KMP, kg S /ha/yr 2006, 2008, 2009	
	Wet Deposition	Dry Deposition	Wet Deposition	Dry Deposition
Haul Road	8.3 (46%)	9.9 (54%)	15 (58%)	11 (42%)
Lakelse Lake	N/A	N/A	1.7 (56%)	1.3 (44%)

Based on predictions by the CALPUFF air quality model, atmospheric deposition of sulphur is expected to range from ~1 to 50 kg S /ha/yr across the Kitimat region. A plot showing the relative deposition across stations is provided in Figure 7.4-7. Stations in the figure are plotted by increasing latitude (e.g., South to North); consistent with the general direction of the plume emitted from KMP. The Haul Road and Lakelse Lake stations bracket the expected range of sulphur deposition.

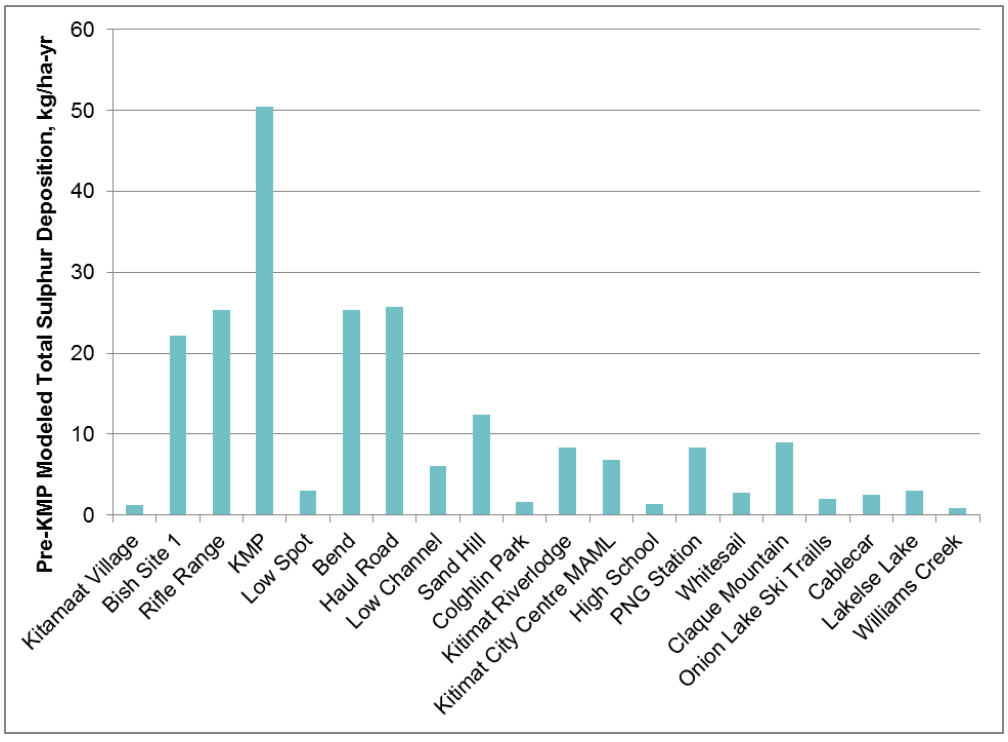


Figure 7.4-7: Pre-KMP modelled sulphur deposition for select locations in the Kitimat region, plotted by increasing latitude (left to right).

7.5 DESCRIPTION OF EMISSION SCENARIOS

Trinity Consultants conducted modelling to predict ambient air concentrations of SO_2 and total sulphur deposition for worst-case meteorological conditions at the requested permit level after the proposed project is implemented (post-KMP scenario). Trinity also conducted modelling to estimate the ambient air concentrations under current conditions (pre-KMP scenario) at actual annual average SO_2 emissions levels for the years modelled. The post-KMP scenario represents emission rates from the smelter assuming 36.4 kg SO_2/tonne of aluminum and a production rate of 420,600 tonnes of aluminum per year.

The pre-KMP modelling analysis serves a twofold purpose. First, the pre-KMP modelling results provide a baseline against which the post-KMP predicted concentrations can be compared. Second, the pre-KMP SO_2 modelling results can be compared to the SO_2 monitoring data available for the same meteorological years. This comparison provides understanding of the level of conservatism of the CALPUFF model. The pre-KMP modelling scenario uses RTA's historic emissions data to determine actual emission rates, on an annual average basis, which can be found in Table 7.6-3 and Table 7.6-4. These emission rates are used to estimate actual SO_2 concentrations in the atmosphere. The post-KMP modelling scenario uses RTA's requested permit limit of 42 tonnes per day.

Table 7.5-1 and Table 7.5-2 describe the modelled emission sources, as affected by the project. The sources listed in Table 7.5-1 as "Source to be removed" are not included in the post-KMP modelling scenario, but they are included in the pre-KMP modelling scenario. The sources listed as "Existing" in Table 7.5-2 are included in both the pre-KMP and post-KMP modelling scenarios. The sources listed as "New Source" are included in the post-KMP modelling scenario, and they are not included in the pre-KMP modelling scenario.

Table 7.5-1: Sources to be removed with KMP project.

Emission Source	Description	Status for Proposed Project	Source Type [a]	Contaminants [b]
DS1	Dry Scrubber #1	Source to be removed	P	SO_2, HF
DS2	Dry Scrubber #2	Source to be removed	P	SO_2, HF
DS3	Dry Scrubber #3	Source to be removed	P	SO_2, HF
DS4	Dry Scrubber #4	Source to be removed	P	SO_2, HF
DS5	Dry Scrubber #5	Source to be removed	P	SO_2, HF
DS6	Dry Scrubber #6	Source to be removed	P	SO_2, HF
DS7	Dry Scrubber #7	Source to be removed	P	SO_2, HF
DS8	Dry Scrubber #8	Source to be removed	P	SO_2, HF
L1C	Potroom 1c	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L2A	Potroom 2a	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L2B	Potroom 2b	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L2C	Potroom 2c	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L3A	Potroom 3a	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L3B	Potroom 3b	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L4A	Potroom 4a	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L4B	Potroom 4b	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L5A	Potroom 5a	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L5B	Potroom 5b	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L7B	Potroom 7b	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L8A	Potroom 8a	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
L8B	Potroom 8b	Source to be removed	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
F1	Casting DC 1 Furnace 1	Source to be removed	P	HF, PM_{10}, and $PM_{2.5}$
F2	Casting DC 1 Furnace 2	Source to be removed	P	HF, PM_{10}, and $PM_{2.5}$
F5	Casting DC 3 Furnace 5	Source to be removed	P	HF, PM_{10}, and $PM_{2.5}$
F6	Casting DC 3 Furnace 6	Source to be removed	P	HF, PM_{10}, and $PM_{2.5}$

[a] P = point source. L = Buoyant line source.

[b] All pre-KMP modelled emission rates for sources to be removed are based on past actual emission rates, on an annual average basis, corresponding to the meteorological year modelled.

Table 7.5-2: New and existing sources.

Emission Source	Description	Status for Proposed Project	Point Type [a]	Contaminants [b]
PYRO	Pyro Scrubber	Existing source	P	SO_2, NO_x, PM_{10}, and $PM_{2.5}$
COOLER [c]	Calciner Cooler	Existing source	P	SO_2, PM_{10}, and $PM_{2.5}$
F41	Casting DC 4 Furnace 41	Existing source	P	NO_x, HF, PM_{10}, and $PM_{2.5}$
F42	Casting DC 4 Furnace 42	Existing source	P	NO_x, HF, PM_{10}, and $PM_{2.5}$
FC1	Casting C Furnace 1	New source	P	NO_x, HF, PM_{10}, and $PM_{2.5}$
FC2	Casting C Furnace 2	New source	P	NO_x, HF, PM_{10}, and $PM_{2.5}$
FC3	Casting C Furnace 3	New source	P	NO_x, HF, PM_{10}, and $PM_{2.5}$
GTC1	Gas Treatment Center Stack 1	New source	P	SO_2, HF, PM_{10}, and $PM_{2.5}$
GTC2	Gas Treatment Center Stack 2	New source	P	SO_2, HF, PM_{10}, and $PM_{2.5}$
FTC	Fume Treatment Center (Baking Furnace)	New source	P	SO_2, NO_x, HF, PM_{10}, and $PM_{2.5}$
PASTE	Paste Plant Stack	New source	P	PM_{10}, and $PM_{2.5}$
Bath	Bath Treatment	New source	L	PM_{10}, and $PM_{2.5}$
PS	Pallet Storage	New source	L	HF
PotA_N	Potroom A North Vent	New source	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
PotA_S	Potroom A South Vent	New source	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
PotB_N	Potroom B North Vent	New source	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
PotB_S	Potroom B South Vent	New source	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
PotC_S	Potroom C North Vent	New source	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
PotC_S	Potroom C South Vent	New source	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
PotD_S	Potroom D North Vent	New source	L	SO_2, HF, PM_{10}, and $PM_{2.5}$
PotD_S	Potroom D South Vent	New source	L	SO_2, HF, PM_{10}, and $PM_{2.5}$

[a] P = point source. L = Buoyant line source.

[b] All emissions used for post-KMP modelling scenario are based on proposed emissions levels. Therefore, a single emission value is assumed to apply for the entire simulation period. All pre-KMP modelled emission rates for existing sources are based on past actual emission rates, on an annual average basis, corresponding to the meteorological year modelled.

[c] The calciner cooler emission factor is determined based on a 345 day production year, but the emission rate is assumed to occur continuously for modelling purposes. This assumption results in a conservative (i.e., higher than expected) maximum short-term emission rate.

7.6 SO_2 FROM SOURCE TO ATMOSPHERE

This section describes the method, technical background, and results of the CALPUFF dispersion modelling analysis of SO_2 emissions from the Kitimat smelter. Trinity Consultants conducted modelling to predict ambient air concentrations of SO_2 and total sulphur deposition for worst-case meteorological conditions at the requested permit level after the proposed project is implemented (post-KMP). Trinity also conducted modelling to estimate the ambient air concentrations under current conditions (pre-KMP) at actual annual average SO_2 emissions levels for the years modelled.

7.6.1 Methods

The CALPUFF dispersion modelling analysis follows the modelling methods and procedures detailed in a modelling protocol developed for the project in cooperation with and approved by the Ministry of Environment (MOE).[9]

The technical challenges of applying the CALPUFF model to predict local SO_2 concentrations, as well as long range concentrations and total sulphur deposition were addressed through several years of discussions with MOE, beginning in 2007. The major outcomes of the process included:

- establishing an accepted CALPUFF modelling protocol for modelling conducted for a previous design of KMP using a single year of meteorological data (2006);
- discussing and implementing improvements over the historic modelling protocol, including use of three years of meteorological data, use of refined terrain and coastline options, and use of the latest version of CALPUFF to incorporate more refined building downwash estimates, important for estimating near field concentrations;
- completing a robust quality assurance review of the key CALMET control parameters by comparing the wind fields and wind rose output of several sample periods using various control settings;
- completing sensitivity studies for background ozone concentrations and the use of 5th generation mesoscale model meteorological data (MM5 data) to determine the effect of these parameters on the CALPUFF model output; and
- establishing an improved CALPUFF modelling protocol based on the outcomes of the discussions and studies discussed above.

[9] Trinity Consultants submitted a final modelling protocol on September 4, 2012 for approval by the B.C. Ministry of Environment. As documented in the response letter provided by Mr. Ben Weinstein, MOE, to Ms. Anna Henson, Trinity Consultants (email communication, November 4, 2012), the Ministry accepted and agreed to the approach outlined in the September modelling protocol, with consideration of sensitivity study results presented on November 1, 2012.

7.6.1.1 Summary of what a dispersion model is and how a dispersion model is used

Dispersion models serve as a tool to predict or estimate ambient air concentrations 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 changes in emissions 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 four times.

Once a project is in operation, air monitoring programs are often implemented to verify that the ambient concentrations are below levels of concern. However, more and more often in the recent past, dispersion models are also used to estimate air concentrations from existing sources, as a reliable and more cost effective option. Most notably, the United States Environmental Protection Agency (U.S. EPA) recently proposed using dispersion modelling to determine the attainment status of regions within each state in comparison to a new SO_2 ambient air quality standard. The most commonly used dispersion models for predicting air concentrations from industrial sources are AERMOD, AERSCREEN, and CALPUFF. While the CALPUFF model is more complex and technically challenging, it offers several advantages. The modelling analysis presented in this report applies the CALPUFF dispersion model for several reasons, including:

- the need to determine long range impacts (AERMOD is not recommended for distances over 50 kilometres);
- the need to represent the complex terrain conditions in the Kitimat area (AERMOD assumes winds do not change direction across the entire domain for each time step); and
- the need to represent the buoyant plume rise typical of aluminum smelter potroom roof vents (AERMOD does not include a buoyant source type, while CALPUFF does).

7.6.1.2 What is dry and wet deposition?

As described in detail in Section 3.1, deposition of SO_2 occurs when SO_2 emissions get directly deposited on the land in gaseous form and as sulphur particles (dry deposition), and additional amounts get transformed in the atmosphere, into sulphuric acid which falls to the earth in rain, snow and fog (wet deposition) (Saski et al. 1988; Hicks et al. 1993).

Total sulphur deposition (from both dry and wet deposition and from deposition of SO_2 and SO_4) determines acidic deposition from SO_2 emissions, which may have indirect effects on soils, lakes and streams via changes in soil and water chemistry that occur over time.

7.6.1.3 Dispersion model 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 each specified receptor in a modelling domain. CALPOST is the post-processor for CALPUFF that computes impacts from a source based on the pollutant concentrations that are output by CALPUFF.

7.6.1.3.1 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 grid points at which meteorological fields are developed with CALMET. The computational grid determines the computational area for a CALPUFF run, and is defined identically to the meteorological grid. The sampling grid defines the locations where the ground level concentration and/or deposition results are determined and stored within the CALPUFF output files.

The modelling protocol found in Appendix 7.6-1 presents a plot of the meteorological and computational modelling domain in Figure 2-1, and Figures 4-2, 4-3, and 4-4 of the protocol present plots of the discrete receptors.[10] Figures 4-3 and 4-4 in Appendix 7.6-1 show receptors located at specific points of interest, identified by MOE. The meteorological and CALPUFF computational grid spacing is 4 kilometres (km) across the entire domain for long range modelling. For local scale modelling, the analysis applies a more refined meteorological and CALPUFF computational grid of 500 metres.

7.6.1.3.2 CALMET meteorological processor

Trinity used the CALMET meteorological processor to generate the meteorological data for CALPUFF. CALMET is the meteorological processor that compiles meteorological data from raw observations of surface and upper air conditions, precipitation measurements, mesoscale model output, and geophysical parameters into a single hourly, gridded data set for input into CALPUFF. Full details regarding the CALMET meteorological processor are provided in the modelling protocol in Appendix 7.6-1.

[10] Note that the gridded receptor network presented in Figure 4-2 of the protocol (Appendix 7.6-1) shows the originally proposed receptor grid. The gridded receptor network was expanded to the south to capture the entire zone of sulphur deposition impact, defined as 10 kilograms of SO_4 per hectare per year (kg/ha/yr).

7.6.1.3.2.1 Geographical 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 analysis presented in this report uses the same geophysical datasets and processing methods that were used for the KMP modelling for meteorological year 2006, approved by MOE in 2008. The terrain and landuse data, as well as the processing methods used for the 2006, 2008, and 2009 CALMET analyses, are described in more detail in the modelling protocol in Appendix 7.6-1.

7.6.1.3.2.2 Meteorological data

CALMET was used to assimilate data for years 2006, 2008, and 2009 using 5th generation mesoscale model output (MM5 data), surface station observations, upper air station observations, and National Oceanic and Atmosphere Administration buoy station observations to develop the meteorological field.[11] Full details regarding the meteorological data are provided in the modelling protocol provided in Appendix 7.6-1.

At the request of MOE, Trinity conducted a sensitivity study in order to provide a comparison between using only surface station observations (no MM5 data) and using the CALMET dataset developed by Trinity as described above (MM5 data combined with surface station data). The methodology and results of this MM5 sensitivity study are presented in Section 7.6.1.3.3.5.

7.6.1.3.2.3 Control parameters

The CALMET processing applied the recommended CALMET control parameters presented in Table 9.6 of the "Guidelines for Air Quality Dispersion Modelling in British Columbia" (B.C. Air Quality 2008). For switch settings that have multiple or variable recommended settings, the appropriate settings were based on expert judgment, discussed and agreed upon between Trinity Consultants and MOE. The CALMET switch settings used in this CALMET modelling analysis are provided in Table 3-3 of the modelling protocol (Appendix 7.6-1).

7.6.1.3.2.4 QA/QC procedures

The Quality Assurance (QA) procedures for the CALMET processing were performed as specified in Sections 10.2.1 of the B.C. Dispersion Modelling Guidelines. Further details regarding the QA/QC procedure are provided in the modelling protocol in Appendix 7.6-1.

[11] Note that precipitation data are not available on an hourly scale in the meteorological domain. Therefore, the MM5 dataset is used for precipitation information.

7.6.1.3.3 CALPUFF dispersion model

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

7.6.1.3.3.1 Emissions source rates for the scenarios modelled

This report focuses only on SO_2. However, the modelling analysis included emissions of particulate matter less than 10 micrometres (µm) in diameter (PM_{10}), particulate matter less than 2.5 µm in diameter ($PM_{2.5}$), SO_2, nitrogen oxides (NO_X), and hydrogen fluoride (HF) from the sources affected by the modernization project at the Kitimat smelter.

The post-KMP SO_2 emission rates assume 36.4 kg SO_2/tonne aluminum and a production rate of 420,600 t/yr (tonnes/year) aluminum. Table 7.6-1 details the point source parameters for pre-KMP modelling. Table 7.6-2 details the line source parameters for pre-KMP modelling. Table 7.6-3 and Table 7.6-4 detail the SO_2 emission rates applied to each pre-KMP source in the modelling year.

Table 7.6-5 and Table 7.6-6 detail the source parameters for the post-KMP sources.

Table 7.6-7 details the SO_2 emission rates applied to each post-KMP source for all modelling years. The CALPUFF dispersion model allows emission units to be represented as point, line, area, or volume sources. The source types modelled at the Kitimat smelter include point sources and buoyant line sources. For point sources (e.g., dry scrubber stacks) with unobstructed vertical releases, the modelling analysis uses actual stack parameters (i.e., height, diameter, exhaust gas temperature, and gas exit velocity).

In addition to the source parameters provided below, the CALPUFF model includes buildings in order to determine the affects of "building downwash," when plumes from sources become caught in the turbulent wakes of structures. Wind blowing around a building creates zones of turbulence that are greater than if the building were absent. The CALPUFF dispersion model provides for treatment of building wake effects that, for certain emissions units (point sources), uses wind direction-specific building dimensions following the algorithms developed by Schulman and Hanna (1986). Full details describing downwash effects are provided in the modelling protocol in Appendix 7.6-1.

Table 7.6-1: Pre-KMP point source parameters.

Source and Source Type		UTM Easting (km)	UTM Northing (km)	Stack Height (m)	Base Elevation (m)	Stack Diameter (m)	Exit Velocity (m/s)	Temperature (K)
DS1	P	519.824	5983.902	22.68	13.7	1.23	26.5	365
DS2	P	519.812	5983.972	22.68	13.7	1.23	23.9	365
DS3	P	519.739	5984.204	23.74	14.36	1.4	18.2	365
DS4	P	519.755	5984.279	23.74	14.36	1.22	18.2	365
DS5	P	519.759	5984.327	23.74	14.36	1.22	18.2	365
DS6	P	519.636	5984.854	25.68	14	1.22	16.4	357
DS7	P	519.564	5984.878	23.47	14.3	1.53	16.4	357
DS8	P	519.561	5984.91	26.4	14.3	1.73	12.8	357
PYRO	P	519.89	5983.391	45.7	9.4	2.59	22.6	1207
COOLER	P	519.834	5983.434	15.2	9.4	0.71	21	370

Table 7.6-2: Pre-KMP line source parameters.

Source and Source Type		UTM Easting (km)	UTM Northing (km)	UTM Easting (km)	UTM Northing (km)	Stack Height (m)	Base Elevation (m)	Average Buoyancy (m^4/s^3)
L1C	L	519.728	5983.891	520.073	5983.954	14	13.7	571
L2A	L	519.721	5983.93	520.065	5983.993	14	13.7	571
L2B	L	519.716	5983.963	520.059	5984.025	14	13.7	571
L2C	L	519.709	5983.996	520.053	5984.058	14	13.7	571
L3A	L	519.677	5984.177	520.031	5984.241	18	14.2	1411
L3B	L	519.671	5984.211	520.025	5984.275	18	14.2	1411
L4A	L	519.665	5984.245	520.019	5984.309	18	14.2	1411
L4B	L	519.659	5984.279	520.012	5984.344	18	14.2	1411
L5A	L	519.652	5984.313	520.006	5984.378	18	14.2	1411
L5B	L	519.646	5984.348	520.000	5984.411	18	14.2	1411
L7B	L	519.489	5984.861	519.893	5984.935	18	14	1411
L8A	L	519.483	5984.895	519.887	5984.968	18	14	1411
L8B	L	519.477	5984.929	519.881	5985.002	18	14	1411

Table 7.6-3: Pre-KMP point source SO_2 emission rates.

Emission Source	2006 SO_2 (g/s)	2008 SO_2 (g/s)	2009 SO_2 (g/s)	2006 SO_2 (t/d)	2008 SO_2 (t/d)	2009 SO_2 (t/d)
DS1	1.70E+01	1.71E+01	1.54E+01	1.471	1.475	1.328
DS2	1.73E+01	1.72E+01	1.60E+01	1.499	1.483	1.379
DS3	2.17E+01	2.13E+01	1.74E+01	1.873	1.841	1.503
DS4	2.20E+01	2.14E+01	1.87E+01	1.904	1.849	1.620
DS5	2.12E+01	2.12E+01	1.85E+01	1.829	1.834	1.599
DS6	1.20E+01	1.19E+01	8.96E+00	1.037	1.027	0.774
DS7	1.24E+01	1.19E+01	1.01E+01	1.075	1.031	0.871
DS8	1.24E+01	1.19E+01	1.01E+01	1.075	1.031	0.871
PYRO	9.47E+01	7.32E+01	7.06E+01	8.180	6.325	6.097
COOLER	2.53E+00	1.95E+00	1.88E+00	0.218	0.169	0.163

Table 7.6-4: Pre-KMP line source SO_2 emission rates.

Emission Source	2006 SO_2 (g/s)	2008 SO_2 (g/s)	2009 SO_2 (g/s)	2006 SO_2 (t/d)	2008 SO_2 (t/d)	2009 SO_2 (t/d)
L1C	1.53E+00	1.52E+00	1.42E+00	0.132	0.132	0.123
L2A	1.48E+00	1.49E+00	1.29E+00	0.128	0.129	0.111
L2B	1.54E+00	1.50E+00	1.41E+00	0.133	0.130	0.122
L2C	1.52E+00	1.53E+00	1.40E+00	0.132	0.132	0.121
L3A	1.92E+00	1.92E+00	1.49E+00	0.166	0.166	0.128
L3B	1.91E+00	1.84E+00	1.58E+00	0.165	0.159	0.137
L4A	1.94E+00	1.86E+00	1.66E+00	0.168	0.161	0.144
L4B	1.95E+00	1.91E+00	1.65E+00	0.168	0.165	0.142
L5A	1.89E+00	1.87E+00	1.72E+00	0.163	0.162	0.149
L5B	1.85E+00	1.87E+00	1.54E+00	0.160	0.162	0.133
L7B	2.12E+00	2.10E+00	1.58E+00	0.183	0.181	0.137
L8A	2.20E+00	2.10E+00	1.78E+00	0.190	0.182	0.154
L8B	2.20E+00	2.10E+00	1.78E+00	0.190	0.182	0.154

Table 7.6-5: Post-KMP point source parameters for SO_2 emission sources.

Source and Source Type		UTM Easting (km)	UTM Northing (km)	Stack Height (m)	Base Elevation (m)	Stack Diameter (m)	Exit Velocity (m/s)	Summer Temp (K)	Winter Temp (K)
PYRO	P	519.886	5983.375	46.5	5.8	2.57	21.96	1208	1208
COOLER	P	519.828	5983.417	15.2	6.2	0.71	20.36	374	374
GTC1	P	519.667	5985.05	60	10.1	7	17	373	373
GTC2	P	519.549	5985.028	60	10.1	7	17	373	373
FTC	P	519.349	5985.196	50	15.42	2	14	373	373

Table 7.6-6: Post-KMP line source parameters for SO_2 emission sources.

Source and Source Type		UTM Easting (km)	UTM Northing (km)	UTM Easting (km)	UTM Northing (km)	Stack Height (m)	Base Elevation (m)	Average Buoyancy (m^4/s^3)
PotA_N	L	519.729	5984.93	519.673	5985.212	23.5	10.1	595.58
PotA_S	L	519.785	5984.62	519.733	5984.908	23.5	10.1	595.58
PotB_N	L	519.66	5984.918	519.605	5985.2	23.5	10.1	595.58
PotB_S	L	519.716	5984.608	519.664	5984.896	23.5	10.1	595.58
PotC_N	L	519.611	5984.909	519.555	5985.191	23.5	10.1	595.58
PotC_S	L	519.667	5984.599	519.615	5984.887	23.5	10.1	595.58
PotD_N	L	519.542	5984.897	519.487	5985.179	23.5	10.1	595.58
PotD_S	L	519.598	5984.587	519.546	5984.875	23.5	10.1	595.58

Table 7.6-7: Post-KMP emission rates for SO_2.

Emission Source	SO_2 (g/s)	SO_2 (t/yr)
PYRO	8.70E+01	2,745
COOLER	2.32E+00	73
GTC1	1.84E+02	5,791
GTC2	1.84E+02	5,791
FTC	2.00E+01	631
PotA_N	9.37E-01	30
PotA_S	9.37E-01	30
PotB_N	9.37E-01	30
PotB_S	9.37E-01	30
PotC_N	9.37E-01	30
PotC_S	9.37E-01	30
PotD_N	9.37E-01	30
PotD_S	9.37E-01	30

7.6.1.3.3.2 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". The only CALPUFF switch setting for which a required or recommended setting was not provided was the "dispersion coefficients switch setting" (MDISP). As the goal of this CALPUFF analysis is to determine near-field impacts of the modernization project, the dispersion coefficients switch setting was set to MDISP 2, as recommended for near-field impacts.[12] Chemical transformation, wet removal, and dry deposition pollutant removal were modelled, as recommended in the "Guidelines for Air Quality Dispersion Modelling in British Columbia". The mass of a pollutant in a given puff decreases as the puff travels through time and space as 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 "Guidelines for Air Quality Dispersion Modelling in British Columbia," CALPUFF Version 6.42 includes several new control parameters (not included in CALPUFF Version 5.8) that must be specified. These new control parameters and the corresponding values used in this analysis are presented in Table 4-8 of the modelling protocol in Appendix 7.6-1.

[12] Note that for the MDISP 3 switch setting, CALPUFF uses Pasquill-Gifford coefficients for rural areas and McElroy-Pooler for urban areas automatically based on land use in the CALMET data.

7.6.1.3.3.3 QA/QC procedures

The Quality Assurance (QA) procedures for the CALMET processing were performed as specified in Section 10.2.1 of the B.C. Dispersion Modelling Guidelines. Further details regarding the QA/QC procedure are provided in the modelling protocol in Appendix 7.6-1.

7.6.1.3.3.4 Atmospheric transformation and transport

This CALPUFF modelling analysis applied the MESOPUFF-II chemical transformation algorithms, where the concentrations of NO_2, SO_2, ammonium sulfate, ammonium nitrate, nitric acid, and PM_{10} may be tracked.[13] There are two user-selected input parameters that affect the MESOPUFF II chemical transformation: ammonia and ozone background concentrations. We applied a constant background ammonia concentration of 0.5 ppb, based on the recommended background for forest. A constant background ozone concentration was also applied, using the CALPUFF default of 80 ppb.

The high default ozone concentration of 80 ppb is recommended as a conservative assumption to avoid the situation where limited ozone results in a slower reaction rate of SO_2 to SO_4. 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 may not be conservative when considering SO_2 air concentrations. Because the purpose of this analysis is to predict sulphur deposition and SO_2 air concentrations, MOE requested that Trinity perform a sensitivity study to determine if using lower background ozone values more typical for the Kitimat region could result in noticeably higher SO_2 concentrations. The results of the ozone sensitivity study are summarized in the following section.

7.6.1.3.3.5 Impact of CALPUFF selected parameters on predicted results

Trinity conducted two sensitivity studies to predict the effect of key model inputs on the SO_2 concentrations predicted by CALPUFF. The two input parameters evaluated were background ozone concentrations (ozone study) and the use of MM5 data (MM5 study).

As detailed in Appendix 7.6-2, the results of the ozone sensitivity study demonstrated that the CALPUFF SO_2 air concentrations would not be noticeably affected if a site-specific regional ozone background concentration were used. Specifically, 0% change in SO_2 concentrations and a 2% to 5% change in SO_4 concentrations were detected between the study results and the original CALPUFF results. Therefore, the use of the default ozone background of 80 ppb was maintained in this analysis.

MOE also requested that Trinity perform a sensitivity study to determine the effect of using only surface and upper air station meteorological data (as opposed to surface/upper air station

[13] This report focuses on the results of SO_2 modelling.

and MM5 data, as used in the modelling analysis, i.e., “Full CALMET”). The study was conducted for a single month from each meteorological year, selected to correspond to the month when the maximum modelled SO_2 concentration occurred at the Whitesail monitoring station. For the full CALMET CALPUFF modelling results to be directly comparable, the CALPUFF results using the original "Full CALMET" dataset are extracted for the study month only.

As detailed in Appendix 7.6-2, the study results using only surface and upper air observations compared closer to the monitoring data in the majority of comparisons (i.e., using only surface/upper air station meteorological data results over-predicted by less than the Full CALMET results). However, the primary goal of conducting the study using only surface and upper air observations was to confirm that no serious concerns exist related to the MM5 data conflicting with the surface and upper air station data, causing artificial stagnant zones with unrealistically high impacts. The results of the sensitivity study demonstrated that the difference between the study results using only surface and upper air observations and the Full CALMET study results are within the acceptable range to alleviate concerns. The study results using only surface and upper air observations were on average 17% lower than the Full CALMET results in residential areas and 12% higher in offsite areas. As presented in the concentration contour plots in Appendix 7.6-2, the overall spatial distribution is similar between the study results using only surface and upper air observations and the Full CALMET results. Additionally, overall, the Full CALMET results are more conservative, particularly in residential areas. For all of these reasons, the use of the Full CALMET dataset was maintained in this analysis, and approved by MOE.

7.6.2 SO_2 ambient concentration modelling results

7.6.2.1 Pre-KMP SO_2 results

The pre-KMP modelling analysis serves a twofold purpose. First, the pre-KMP modelling results provide a baseline against which the post-KMP predicted concentrations can be compared. Second, the pre-KMP SO_2 modelling results can be compared to the SO_2 monitoring data available for the same meteorological years (monitoring data study).

7.6.2.1.1 Pre-KMP SO_2 monitoring study results

Trinity compared the pre-KMP modelling results to the SO_2 monitoring data available for the modelled meteorological years (2006, 2008, and 2009). This comparison provided an understanding of the level of conservatism of the CALPUFF model.

The monitoring data study included the three SO_2 monitoring stations in operation in 2006 through 2009, Whitesail, Railsite, and Haul Road. Modelled concentrations at the location of each monitor were compared to measured SO_2 concentrations at each monitor. As detailed in Appendix 7.6-3, the monitoring data study demonstrated that the CALPUFF model predicts concentrations approximately double measured concentrations (227%), averaged over the

three years, three sites, and averaging periods of interest (1-hour, 3-hour, 24-hour, and annual).

The results of this study provide a level of confidence that the CALPUFF model is not under predicting, because the station, averaging period, and yearly average CALPUFF estimates were all greater than the monitoring data. Additionally, the study provides a check on the model: first, the 227% over estimate is well within the range of expectations of 150% to 400%; and, secondly, the comparison of modelled concentrations to monitored concentrations does not vary substantially from site to site, year to year, or averaging period to averaging period. For these reasons, the SO_2 monitoring study affirms that the CALPUFF model performs well and meets the needs of the other studies included in this SO_2 technical assessment study.

7.6.2.1.2 Pre-KMP SO_2 modelling results

Table 7.6-8 summarizes the maximum SO_2 concentration modelled over the three meteorological years (2006, 2008, and 2009). Modelled emission rates used in the pre-KMP modelling analysis represent the annual average emissions for the corresponding meteorological year (as opposed to the smelter's permitted SO_2 limit of 27 t/d. The modelled emissions are also compared to the British Columbia MOE Pollution Control Objectives (PCOs) and the World Health Organization (WHO) standards. The PCOs are nonstatutory limits typically used to: (1) assess current or historical air quality; (2) guide decisions on the permitting of new or modified facilities; (3) develop long-term air-management strategies and evaluate progress; and (4) aid regulatory development.[14,15] WHO air quality guidelines are designed to offer quidance in reducing the health impacts of air pollution. They are intended to provide appropriate targets for a broad range of policy options for air quality management in different parts of the world.

Using the actual emission rates, the estimated SO_2 concentrations exceed the 1-hour, 3-hour, and 24-hour averaging period PCOs for discharges into air.[16] Within the residential areas, the estimated SO_2 concentrations exceed only the 1-hour averaging period maximum PCO. All maximum estimated SO_2 concentrations exceed the WHO standards. Comparisons to the PCOs and to WHO do not provide conclusions related to impacts on the environment or human health. Section 9.0 describes how the predicted air concentrations of SO_2 could affect human

[14] Information on PCO uses was obtained from the British Columbia Air Quality website.

[15] National Ambient Air Quality Objectives (NAAQO) are determined by the Canadian government and used in Section 9.2 for vegetation considerations. The objectives indicate maximum desirable levels and maximum acceptable levels (indicated as #/#). The 1-hour averaging period is 158 ppb (413 $\mu g/m^3$)/315 ppb (823 $\mu g/m^3$), the 24-hour averaging period is 53 ppb (139 $\mu g/m^3$)/105 ppb (274 $\mu g/m^3$), and the annual averaging period is 11 ppb (29 $\mu g/m^3$)/21 ppb (55 $\mu g/m^3$). Comparison to these standards has not been done in this section. Values listed in units of $\mu g/m^3$ are converted from units of ppb using standard atmospheric conditions of 25°C and 1 atm (101.325 kPa).

[16] The Pollution Control Objectives for discharges to air are provided in Table I, Ambient Air Control Objectives, of the 1979 publication by the British Columbia MOE pollution control board, titled "Pollution Control Objectives for The Mining, Smelting, and Related Industries of British Columbia" (reproduced in Appendix 5.5-1).

health and vegetation, and how the predicted levels of sulphur deposition could affect soils and water.

Table 7.6-8: Pre-KMP maximum SO_2 results modelled over 2006, 2008, and 2009.

Averaging Period	Year [a]	Maximum Concentration Offsite [b] ($\mu g/m^3$)	Maximum Concentration Residential [b] ($\mu g/m^3$)	Pollution Control Objectives [c] ($\mu g/m^3$) Minimum	Pollution Control Objectives [c] ($\mu g/m^3$) Maximum	World Health Organization ($\mu g/m^3$) [d]
1-hour	2006	2,296	939	450	900	300
3-hour	2006	1,227	561	375	665	N/A
24-hour	2006	526	228	160	260	20
Annual	2008	53	21	25	75	N/A

[a] The year corresponds to the maximum concentration in the residential area; the offsite maximum concentration does not necessarily correspond to the same year.

[b] Modelled concentrations represent the maximum of the three meteorological years modelled, and include background concentrations corresponding to the appropriate averaging period. Background concentrations are based on monitoring data at the nearby Kitamaat Village monitoring station, as follows: 1.5 ppb (3.9 $\mu g/m^3$) for the 1-hour and 3-hour averaging periods, 1.2 ppb (3.1 $\mu g/m^3$) for the 24-hour averaging period, and 0.4 ppb (1.0 $\mu g/m^3$) for the annual averaging period. Background values listed in units of $\mu g/m^3$ are converted from measured units of ppb using standard atmospheric conditions of 25°C and 1 atm.

[c] Comparisons to the PCO do not provide conclusions related to impacts on the environment or human health. Section 9.0 describes how the SO_2 air concentration results predicted by the air dispersion modelling analysis impact human health and vegetation, and how the sulphur deposition results impact soils and water.

[d] The WHO Guidelines include a 500 $\mu g/m^3$ SO_2 objective based on a 10-minute mean. This objective is adjusted to 300 $\mu g/m^3$ for the 1-hour averaging period based on a peak to mean ratio of 1.7, as determined from SO_2 monitoring data collected at the Haul Road station.

The United States Environmental Protection Agency (U.S. EPA) has National Ambient Air Quality Standards (NAAQS) for SO_2. The form of these standards is different from the PCO and WHO. Though the same model inputs are used, the modelled concentrations shown in Table 7.6-8 and Table 7.6-9 are different as determined by the standards form. The U.S. EPA NAAQS SO_2 1-hour standard is based on a 3-year average of the 99th percentile of the annual distribution of daily maximum 1-hour concentrations. For comparison to this standard, the concentration at the receptor with the highest 3-year average (over 2006, 2008 and 2009) of the 4th high values for each year is considered. The U.S.EPA NAAQS SO_2 3-hour and 24-hour standard is based on the maximum of the second high values over three years. The annual U.S. EPA NAAQS SO_2 standard is based on the maximum of the annual arithmetic mean concentrations over three years. The annual concentrations for both tables are the same. The estimated SO_2 concentrations exceed the U.S. EPA NAAQS for the 1-hour averaging period in both residential

and offsite locations. For the 24-hour averaging period, SO_2 concentrations exceed the U.S. EPA NAAQS in offsite locations, however, not within the residential areas.

Table 7.6-9: Pre KMP SO_2 modelled results compared to U.S. EPA NAAQS.

Averaging Period	Year[a]	SO_2 Concentration - Offsite Receptors (ug/m^3) [b]	SO_2 Concentration - Residential Receptors (ug/m^3) [b]	U.S. EPA NAAQS SO_2 Standard (ug/m^3)
1-hour [c]	All	1,117	424	196
3-hour [d]	2006	1,089	480	1300
24-hour [d]	2006	465	189	365
Annual [e]	2008	53	21	80

[a] The year corresponds to the maximum concentration in the residential area; the offsite maximum concentration does not necessarily correspond to the same year.

[b] Modelled concentrations include background concentrations corresponding to the appropriate averaging period. Background concentrations are based on monitoring data at the nearby Kitamaat Village monitoring station, as follows: 1.5 ppb (3.9 $\mu g/m^3$) for the 1-hour and 3-hour averaging periods, 1.2 ppb (3.1 $\mu g/m^3$) for the 24-hour averaging period, and 0.4 ppb (1.0 $\mu g/m^3$) for the annual averaging period. Background values listed in units of $\mu g/m^3$ are converted from measured units of ppb using standard atmospheric conditions of 25°C and 1 atm.

[c] The U.S.EPA NAAQS SO_2 1-hour standard is based on a 3-year average of the 99th percentile of the annual distribution of daily maximum 1-hour concentrations. For comparison to this standard, the concentration at the receptor with the highest 3-year average (over 2006, 2008 and 2009) of the 4th high values for each year is considered.

[d] The U.S.EPA NAAQS SO_2 3-hour and 24-hour standard is based on the maximum of the second high values over three years.

[e] The annual U.S. EPA NAAQS SO_2 standard is based on the maximum of the annual arithmetic mean concentrations over three years.

Figure 7.6-1 and Figure 7.6-2 present the number of times pre-KMP modelled concentrations exceed the maximum and minimum range of the 1-hour PCO, respectively, at each modelled location. The numbers of exceedances shown in the figures represent the maximum number of exceedances for the three meteorological years (2006, 2008, and 2009). Figure 7.6-1 provides a comparison for the maximum PCO for the 1-hour averaging period (thus, results are compared to 900 $\mu g/m^3$), and Figure 7.6-2 provides a comparison to the minimum PCO for the 1-hour averaging period (thus, results are compared to 450 $\mu g/m^3$). Figures for other averaging periods may be found in Appendix 7.6-4. Section 7.6.2.2 includes Table 7.6-12 detailing the number of exceedances for each modelled year compared to the minimum and maximum PCOs.

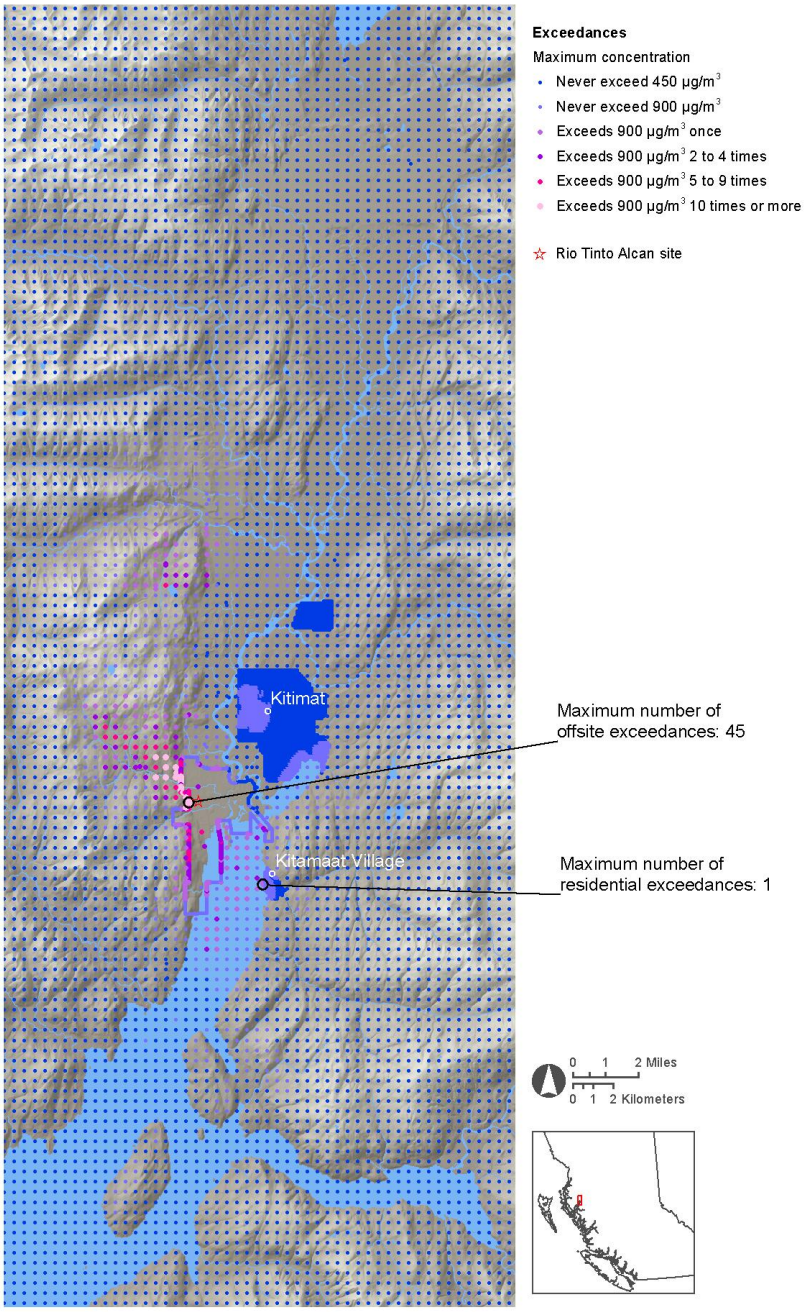


Figure 7.6-1: Maximum number of exceedances per year over 900 µg/m^3, 1-hour averaging period, pre-KMP SO_2 emissions.

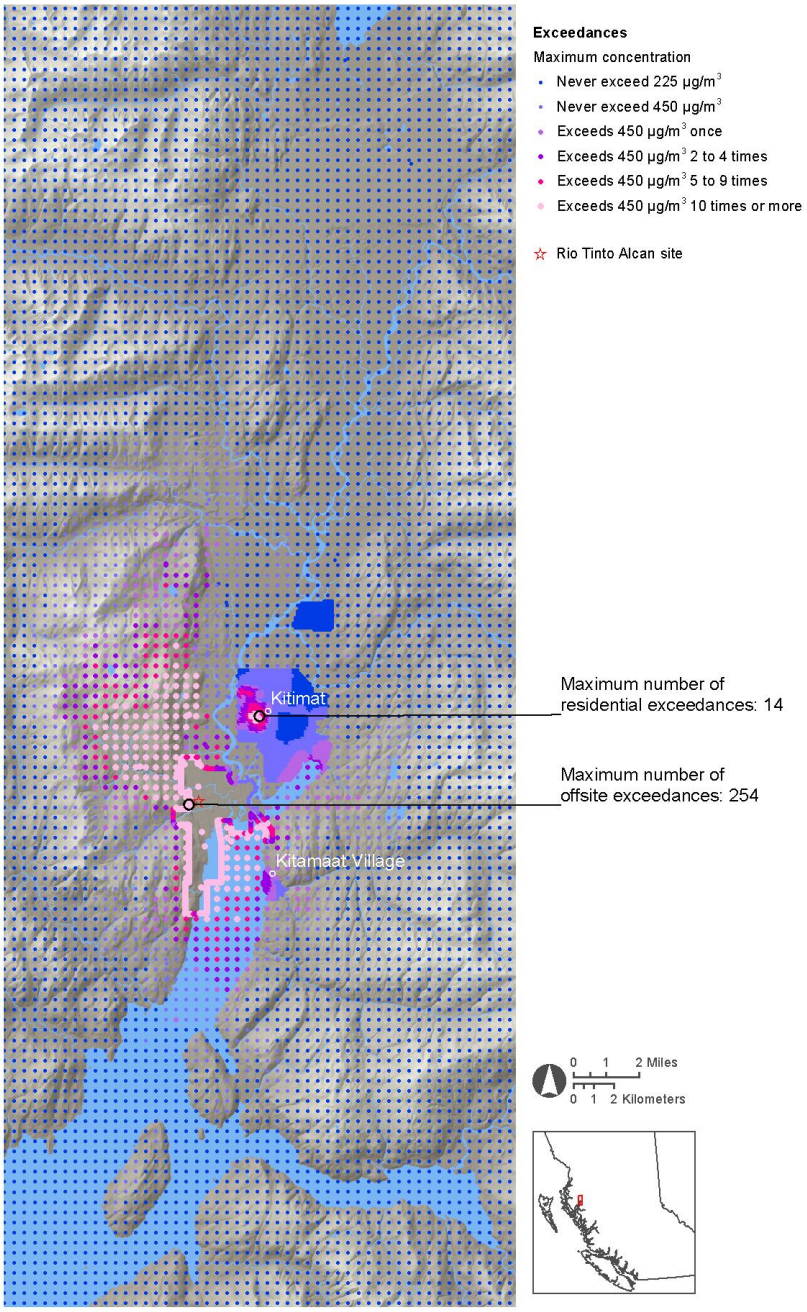


Figure 7.6-2: Maximum number of exceedances per year over 450 µg/m^3, 1-hour averaging period, pre-KMP SO_2 emissions.

Additional modelling results may be found in Appendix 7.6-4, Pre-KMP Modelling Results, including the following information:

- tabulated SO_2 concentration results for each averaging period and meteorological year compared to the PCOs and compared to the World Health Organization guidelines and the U.S. EPA National Ambient Air Quality Standards for SO_2;
- tabulated SO_2 concentrations at each point of interest for each averaging period and meteorological year;
- tabulated results presenting the maximum SO_2 concentration attributable to each source group;
- contour plots of modelled SO_2 ambient concentration at 1-hour, 3-hour, 24-hour, and annual averaging periods for each year;
- long range contour plots of modelled SO_2 ambient concentration at 1-hour, 3-hour, 24-hour, and annual averaging periods for the year corresponding to the maximum concentration at the Terrace Access Centre;
- frequency plots showing the SO_2 concentration for each averaging period at the maximum receptor throughout the year; and
- exceedance plots indicating the maximum number of times the point exceeds the minimum PCOs over the three meteorological years for 3-hour, 24-hour, and annual averaging periods (the 1-hour exceedance plot is included above).

7.6.2.2 Post-KMP SO_2 results

Modelled emission rates used in the project model represent the requested permitted SO_2 limit of 42 t/d. Table 7.6-10 outlines the maximum SO_2 concentration modelled over the three meteorological years (2006, 2008, and 2009). The modelled emissions are also compared to the PCOs. At the requested SO_2 limit, predicted concentrations exceed the 1-hour, 3-hour, and 24-hour averaging period PCO maximum concentration. Within the residential areas, the predicted concentrations exceed the 1-hour and 3-hour averaging period maximum PCOs. All maximum estimated SO_2 concentrations exceed the WHO standards.

Table 7.6-10: Post-KMP maximum SO_2 results modelled over 2006, 2008, and 2009.

Averaging Period	Year [a]	Maximum Concentration Offsite [b] ($\mu g/m^3$)	Maximum Concentration Residential [b] ($\mu g/m^3$)	Pollution Control Objectives [c] ($\mu g/m^3$)		World Health Organization ($\mu g/m^3$) [d]
				Minimum	Maximum	
1-hour	2009	2,630	1,918	450	900	300
3-hour	2006	1,122	874	375	665	N/A
24-hour	2006	261	191	160	260	20
Annual	2006	35	16	25	75	N/A

[a] The year corresponds to the maximum concentration in the residential area; the offsite maximum concentration does not necessarily correspond to the same year.

[b] Modelled concentrations include a background concentration appropriate to the averaging period.

[c] Comparisons to the PCO do not provide conclusions related to impacts on the environment or human health. Section 9.0 describes how the SO_2 air concentration results predicted by the air dispersion modelling analysis impact human health and vegetation, and how the sulphur deposition results impact soils and water.

[d] The WHO Guidelines include a 500 $\mu g/m^3$ SO_2 objective based on a 10-minute mean. This objective is adjusted to 300 $\mu g/m^3$ for the 1-hour averaging period based on a peak to mean ratio of 1.7, as determined from SO_2 monitoring data collected at the Haul Road station.

As mentioned in the pre-KMP section (Section 7.6.2.1.2), the modelled concentrations are compared to the U.S. EPA NAAQS for SO_2. The form of these standards is different from the PCO and WHO. Though the same model inputs are used, the modelled concentrations shown in Table 7.6-10 and Table 7.6-11 are different as determined by the standards form. The estimated SO_2 concentrations exceed the U.S. EPA NAAQS for the 1-hour averaging period in both residential and offsite locations.

Table 7.6-11: Post-KMP SO_2 modelled results compared to U.S. EPA NAAQS.

Averaging Period	Year [a]	SO_2 Concentration - Offsite Receptors (ug/m^3) [b]	SO_2 Concentration - Residential Receptors (ug/m^3) [b]	U.S. EPA NAAQS SO_2 Standard (ug/m^3)
1-hour [c]	All	1,093	666	196
3-hour [d]	2006	1,003	661	1300
24-hour [d]	2006	241	153	365
Annual [e]	2008	35	16	80

[a] The year corresponds to the maximum concentration in the residential area; the offsite maximum concentration does not necessarily correspond to the same year.

[b] Modelled concentrations include background concentrations corresponding to the appropriate averaging period. Background concentrations are based on monitoring data at the nearby Kitamaat Village monitoring station, as follows: 1.5 ppb (3.9 $\mu g/m^3$) for the 1-hour and 3-hour averaging periods, 1.2 ppb (3.1 $\mu g/m^3$) for the 24-hour averaging period, and 0.4 ppb (1.0 $\mu g/m^3$) for the annual averaging period. Background values listed in units of $\mu g/m^3$ are converted from measured units of ppb using standard atmospheric conditions of 25°C and 1 atm.

[c] The U.S.EPA NAAQS SO_2 1-hour standard is based on a 3-year average of the 99th percentile of the annual distribution of daily maximum 1-hour concentrations. For comparison to this standard, the concentration at the receptor with the highest 3-year average (over 2006, 2008 and 2009) of the 4th high values for each year is considered.

[d] The U.S.EPA NAAQS SO_2 3-hour and 24-hour standard is based on the maximum of the second high values over three years.

[e] The annual U.S. EPA NAAQS SO_2 standard is based on the maximum of the annual arithmetic mean concentrations over three years.

Table 7.6-12 details the occurrences of the SO_2 concentrations exceeding the minimum and maximum range of the PCOs. The number of exceedances presented in the table represents the greatest number of exceedances at a single receptor for the given year and scenario. The modelling analysis predicts that the maximum number of offsite exceedances will decrease as a result of the project, from 254 to 53 for the 1-hour PCO minimum and from 45 to 7 for the 1-hour PCO maximum. Conversely, the model predicts that the number of exceedances in the residential areas will increase as a result of the project, from 14 to 30 for the 1-hour PCO minimum and from 1 to 3 for the 1-hour PCO maximum.

Table 7.6-12: Pollution Control Objectives exceedance table.

Averaging Period	Threshold (µg/m³)	Year	Pre-KMP # of Exceedances [a] Residential	Pre-KMP # of Exceedances [a] Offsite	Post-KMP # of Exceedances [a] Residential	Post-KMP # of Exceedances [a] Offsite
1-hour	Pollution Control Objective Minimum: 450	2006	14	254	30	34
		2008	1	190	9	37
		2009	4	119	8	53
1-hour	Pollution Control Objective Maximum: 900	2006	1	45	3	7
		2008	0	22	1	7
		2009	0	14	3	6
3-hour	Pollution Control Objective Minimum: 375	2006	5	79	12	10
		2008	1	48	3	12
		2009	1	36	3	16
3-hour	Pollution Control Objective Maximum: 665	2006	0	18	1	2
		2008	0	7	1	1
		2009	0	4	0	3
24-hour	Pollution Control Objective Minimum: 160	2006	4	27	1	4
		2008	0	54	0	4
		2009	0	29	0	5
24-hour	Pollution Control Objective Maximum: 260	2006	0	11	0	0
		2008	0	3	0	1
		2009	0	3	0	1

Averaging Period	Threshold (µg/m³)	Year	Pre-KMP # of Exceedances [a] Residential	Pre-KMP # of Exceedances [a] Offsite	Post-KMP # of Exceedances [a] Residential	Post-KMP # of Exceedances [a] Offsite
Annual	Pollution Control Objective Minimum: 25	2006	0	1	0	1
		2008	0	1	0	1
		2009	0	1	0	1
Annual	Pollution Control Objective Maximum: 75	2006	0	0	0	0
		2008	0	1	0	0
		2009	0	0	0	0

[a] The value for each scenario location is the greatest number of exceedances at a single receptor for the given year.

Table 7.6-13 details the occurrences of the SO_2 concentrations exceeding the values of the WHO SO_2 standards. The number of times that a single receptor exceeds the value of each respective limit is shown. The modelling analysis predicts that the maximum number of offsite exceedances will decrease as a result of the project for the 1-hour and 24-hour averaging periods. Conversely, the model predicts that the number of exceedances in the residential areas will increase as a result of the project for the 1-hour averaging period.

Table 7.6-13: WHO exceedance table.

Averaging Period	Threshold (µg/m^3)	Year	Pre-KMP # of Exceedances [a] Residential	Pre-KMP # of Exceedances [a] Offsite	Post-KMP # of Exceedances [a] Residential	Post-KMP # of Exceedances [a] Offsite
1-hour	WHO Limit [b]: 300	2006	90	512	83	142
		2008	7	637	17	251
		2009	7	459	13	176
24-hour	WHO Limit: 20	2006	139	241	94	166
		2008	41	277	43	206
		2009	42	228	39	160

[a] The value for each scenario location is the greatest number of exceedances at a single receptor for the given year.

[b] The WHO Guidelines include a 500 µg/m^3 SO_2 objective based on a 10-minute mean. This objective is adjusted to 300 µg/m^3 for the 1-hour averaging period based on a peak to mean ratio of 1.7, as determined from SO_2 monitoring data collected at the Haul Road station.

Table 7.6-14 details the occurrences of the SO_2 concentrations exceeding the values of the U.S. EPA NAAQS SO_2 standards. The number of times that a single receptor exceeds the value of each respective limit is shown. The modelling analysis predicts that there will be only a small number of exceedances for the 3-hour, 24-hour and annual averaging periods for pre-KMP modelling; while there are no exceedances for the post-KMP modelling using these averaging periods. The 1-hour averaging period shows a decrease in offsite exceedances between the pre-KMP modelling and post-KMP modelling. The 1-hour averaging period for residential receptors does not show a general trend between pre- and post-KMP models. However, the highest number of exceedances is shown in 2006, where the number decreases between pre-KMP and post-KMP.

Table 7.6-14: EPA exceedance table.

Averaging Period	Threshold (µg/m^3)	Year	Pre KMP # of Exceedances [a]		Post KMP # of Exceedances [a]	
			Residential	Off Site	Residential	Off Site
1-hour	U.S. EPA NAAQS Limit [b]: 196	2006	269	1038	169	398
		2008	27	1405	27	522
		2009	21	974	25	488
3-hour	U.S. EPA NAAQS Limit [c]: 1,300	2006	0	0	0	0
		2008	0	0	0	0
		2009	0	0	0	0
24-hour	U.S. EPA NAAQS Limit [c]: 365	2006	0	4	0	0
		2008	0	1	0	0
		2009	0	1	0	0
Annual	U.S. EPA NAAQS Limit [d]: 80	2006	0	0	0	0
		2008	0	1	0	0
		2009	0	0	0	0

[a] The value for each scenario location is the greatest number of exceedances at a single receptor for the given year.

[b] The 1-hour SO_2 standard for U.S. EPA is based on a 3-year average of the 99th percentile of the annual distribution of daily maximum 1-hour concentrations. Therefore, the exceedances presented here are greater than the number of exceedances required to be reported to U.S. EPA within the United States.

[c] The 3-hour and 24-hour SO_2 standards for U.S. EPA are based on the maximum of the second high values over three years. Therefore, the exceedances presented here are greater than the number of exceedances required to be reported to U.S. EPA within the United States.

[d] The annual SO_2 standard for U.S. EPA is based on the maximum of the annual arithmetic mean concentrations over three years. Therefore, the exceedances presented here are greater than the number of exceedances required to be reported to U.S. EPA within the United States.

Figure 7.6-3 and Figure 7.6-4 present the number of times post-KMP modelled concentrations exceed the maximum and minimum range of the 1-hour PCO, respectively, at each modelled location. The numbers of exceedances shown in the figures represent the maximum number of exceedances for the three meteorological years (2006, 2008, and 2009). Figure 7.6-3 presents a comparison for the maximum PCO for the 1-hour averaging period (thus, results are compared to 900 µg/m^3), and Figure 7.6-4 presents a comparison to the minimum PCO for the 1-hour averaging period (thus, results are compared to 450 µg/m^3). Figures for other averaging periods may be found in Appendix 7.6-4.

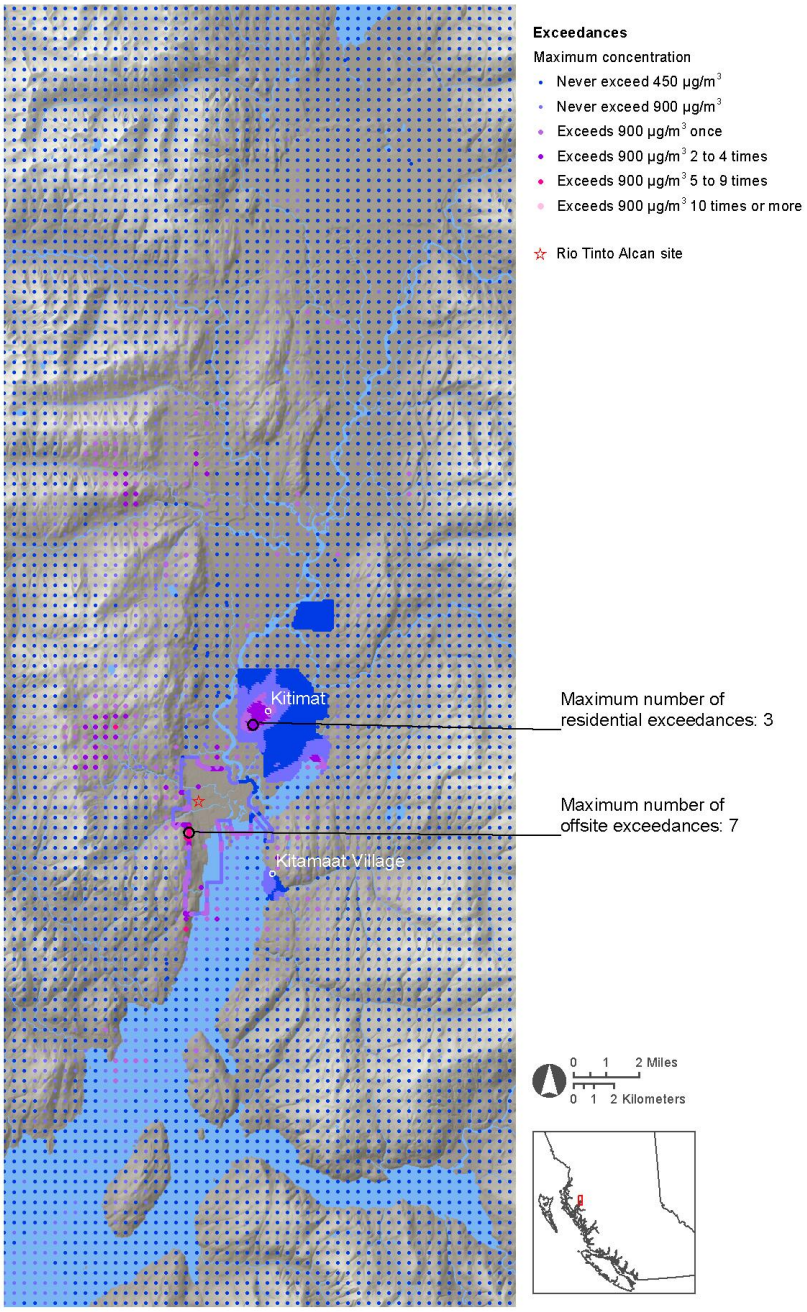


Figure 7.6-3: Maximum number of exceedances per year over 900 µg/m^3, 1-hour averaging period, post-KMP SO_2 emissions.

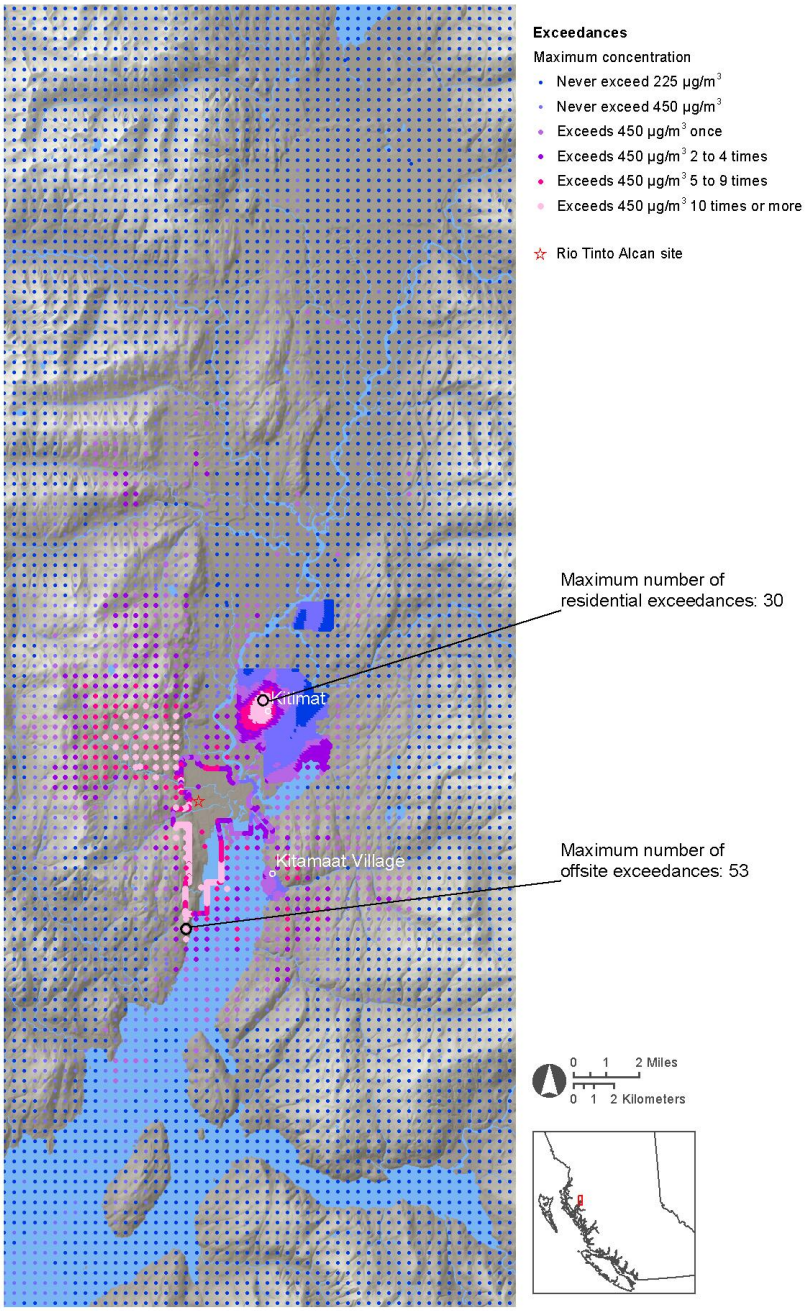


Figure 7.6-4: Maximum number of exceedances per year over 450 µg/m^3, 1-hour averaging period, post-KMP SO_2 emissions.

Additional modelling results may be found in Appendix 7.6-5, including the following information:

- tabulated SO_2 concentration results for each averaging period and meteorological year compared to the PCOs and compared to the World Health Organization guidelines and the U.S. EPA National Ambient Air Quality Standards for SO_2;
- tabulated SO_2 concentrations at each point of interest for each averaging period and meteorological year;
- tabulated results presenting the maximum SO_2 concentration attributable to each source group;
- contour plots of modelled SO_2 ambient concentration at 1-hour, 3-hour, 24-hour, and annual averaging periods for each year;
- long range contour plots of modelled SO_2 ambient concentration at 1-hour, 3-hour, 24-hour, and annual averaging periods for the year corresponding to the maximum concentration at the Terrace Access Centre;
- frequency plots showing the SO_2 concentration for each averaging period at the maximum receptor throughout the year; and
- exceedance plots indicating the maximum number of times the point exceeds the minimum PCOs over the three meteorological years for 3-hour, 24-hour, and annual averaging periods (the 1-hour exceedance plot is included above).

7.6.2.3 Comparing pre- and post-KMP modelling results

The maximum modelled SO_2 concentrations in Table 7.6-8 and Table 7.6-10 show that post-KMP results are greater than pre-KMP results for the 1-hour averaging period. However, all other averaging periods show that the maximum modelled SO_2 concentrations for pre-KMP are higher. As indicated by the exceedance plots shown in Figure 7.6-1 through Figure 7.6-4, the pre-KMP scenario shows a large number of exceedances of the 1-hour standard located relatively close to the facility. The post-KMP 1-hour averaging period shows a number of exceedances at the same locations near the facility, only a lower number; it also shows exceedances at a greater distance from the facility. The same observations are true for all other averaging periods. A third type of result presentation, contained within the appendices, shows contour plots of modelled SO_2 concentrations. These figures show most obviously how the highest SO_2 concentrations occur near the facility in both the pre-KMP and post-KMP scenarios. The maximum concentrations near the facility are less in the post-KMP scenario compared with the pre-KMP scenario; however, concentrations exceeding the standards are seen at distances further from the facility in the post-KMP scenario.

The aforementioned changes to the distribution of SO_2 concentrations are most likely due to changes to stack parameters planned as part of the proposed KMP. Several factors contribute to modelling results, most obviously the magnitude of emission rate; however, changes in stack parameters and building configurations may also have a large impact on the magnitude and

distribution of model predicted concentrations. As indicated in Section 7.6.1.3.3.1, the stack parameters, emission rates, building configurations, and number of sources have changed as a result of the proposed KMP. Plume rise is increased when a given point source increases the velocity, temperature, or height of its exhaust. The height of the stack indicates the starting point for the plume, increased temperature contributes to plume rise due to buoyant forces, and increased exit velocity contributes to plume rise due to mechanical forces. Ultimately, all three stack changes will result in the plume reaching a greater height above ground level, which will result in the plume being more dilute before reaching ground level, where concentrations are recorded in dispersion modelling studies, but will also result in impacts from the plume reaching further from the stack.

Plume rise can also be impacted by the presence of buildings located near stacks through a phenomenon called building downwash. Depending on the relative size (i.e., height, length, and width) of buildings located near stacks included in the modelling studies, the exhaust from the stack can be mixed toward ground level more rapidly and over shorter distances from the stack than if no building were present. Changes in building and stack configurations can change the degree of building downwash considered in the model, resulting in changes to the magnitude and distribution of concentrations in a similar manner to the stack changes discussed above. Building downwash effects may be another explanation for differences between the pre-KMP and post-KMP SO_2 concentrations presented here.[17]

7.6.2.4 KMP deposition results

Trinity analysed deposition results for the pre-KMP and post-KMP modelling scenarios. Figure 7.6-5 presents the maximum modelled total sulphur deposition, averaged over the three meteorological years 2006, 2008, and 2009 for the post-KMP modelling scenario. Post-KMP modelled emission rates used in the project model represent RTA's requested permitted SO_2 limit of 42 t/d. The deposition results are provided on a three year average basis, because acidification of soils or water from sulphur deposition has the potential to occur after many years of exposure, rather than from exposure over a single year, day, or hour.

[17] The ideas presented here to explain why the different magnitudes and distributions of SO_2 concentrations have not been scientifically proven via modelling trials for the pre-KMP and post-KMP modelling studies. These explanations are hypothesized based on dispersion and modelling knowledge.

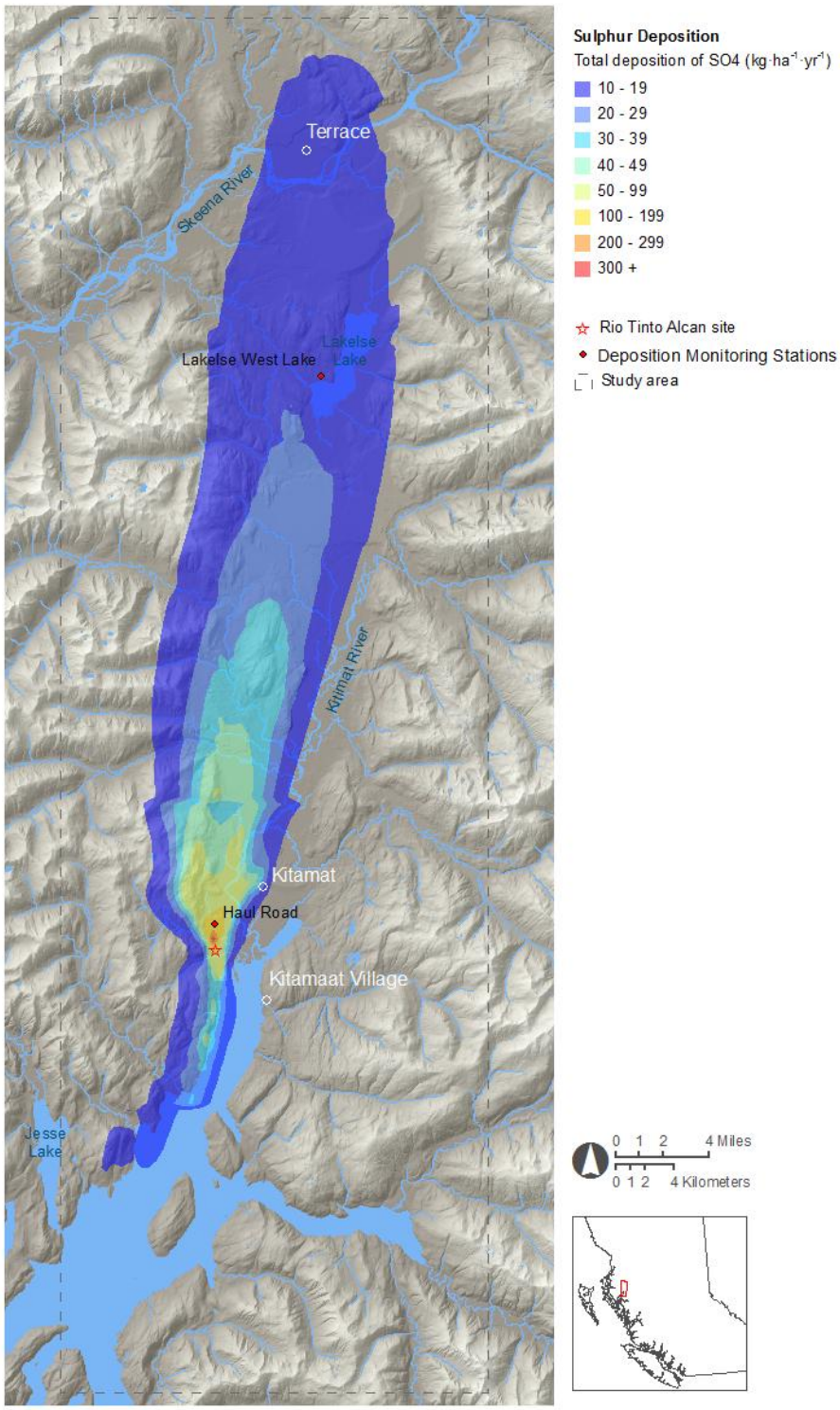


Figure 7.6-5: Post-KMP total sulphur deposition in kg SO_4 /ha/yr.

7.6.3 Discussion

The comparison of the modelled SO_2 concentrations to the established MOE PCOs presented in the previous sections provides a first indication of how KMP will affect SO_2 concentrations compared to ambient air objectives established in British Columbia. However, these comparisons do not provide conclusions related to impacts on the environment or human health. Section 9.0 describes how the SO_2 air concentration results predicted by the air dispersion modelling analysis could affect human health and vegetation, and how the predicted levels of sulphur deposition could affect soils and water (which in turn can affect vegetation and animal life).

7.6.3.1 SO_2 air concentration results

Sections 9.1 and 9.2 discuss the risk to human health and vegetation from the predicted SO_2 concentrations, respectively. As both human health and vegetation are affected by high, short-term SO_2 concentrations, the following paragraphs discuss the highest 1-hour SO_2 concentration events.

The maximum predicted residential concentration of SO_2 (1-hour averaging period) occurs in January 2009, and is 1,918 µg/m^3. This 2009 maximum 1-hour residential concentration is considered an outlier. As illustrated in the post-KMP residential 1-hour frequency plot, found in Appendix 7.6-5, the maximum modelled residential value in 2009 is almost double that of the second highest value and over four times higher than any other value at that receptor.

Additionally, the results of a post-KMP sensitivity study for the time period when the 2009 maximum residential concentration occurred (January 2009) showed that when only MM5 data or only surface station data are used, the maximum residential results for January 2009 are considerably lower. Observation-only results were 9% of the full CALMET results, and MM5-only results were 52% of the full CALMET results for the maximum 1-hour concentration during the month of January at any residential receptor. With this outlier removed, the maximum predicted residential SO_2 concentration during the 1-hour averaging period is 1,546 µg/m^3. This maximum concentration occurred in October 2006.

Frequency plots at the locations where the maximum 1-hour offsite and residential SO_2 concentrations occur for 2006 and 2008 show similar relationships between the peak value at the receptor, and the typical values and the second and third highest values. For example, the maximum modelled offsite value in 2006 is over four times that of the second highest value and over ten times higher than any other value at that receptor.

Potential causes of the highest short term SO_2 air concentrations include:

- calm winds directed toward terrain, causing the plume from the tall gas treatment center stacks to remain concentrated (experiencing little dispersion) until impinging upon a hillside;

- stagnant air inversion conditions causing emissions to remain in the general vicinity of the smelter; and
- conflicting MM5 and surface station conditions causing artificial stagnant conditions (as demonstrated for the January 2009 MM5 sensitivity study).

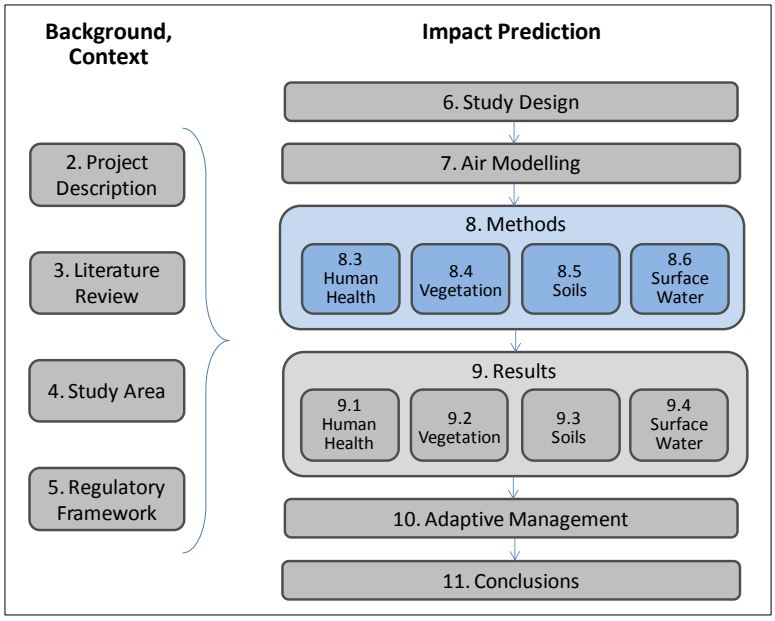
7.6.3.2 Total sulphur deposition

There are no established objectives in British Columbia or Canada for sulphur deposition. Therefore, the sulphur deposition results are not compared to a set deposition threshold. Rather, Sections 8.5.1, 8.6.1, 9.3, and 9.4 discuss soil and water thresholds and impacts. Total sulphur deposition modelling results are used to define the soil and water study areas and to compare predicted deposition levels to critical loads.

As discussed in detail in Section 8.6.1, data from other parts of North America indicate that it is very unlikely to find any acidic lakes and streams (i.e., Acid Neutralizing Capacity (ANC) <0) in regions with less than 10 kg/ha/yr of total SO_4 deposition (i.e., dry plus wet deposition). Figure 7.6-5 presents the zone of impact defined by the 10 kg/ha/yr of total SO_4 deposition, based on post-KMP model results. Figure 7.6-5 shows impacts extending north approximately 60 km (including portions of Terrace) and south approximately 15 km (short of extending to impact Jesse Lake).[18] The soil and water sampling study areas considered the entire modelled zone with 10 kg/ha/yr or more of total SO_4 deposition and included some potentially sensitive areas beyond this zone.

[18] At the time of initial soil and water study design, the full extent of the 10 kg/ha/yr as SO_4 deposition contour was unknown, because the initial modelling receptor grid did not extend far enough south (i.e., initial deposition modelling results showed the contour ending at the edge of the receptor grid, rather than showing a closed contour). Due to the initially unknown extent of the 10 kg/ha/yr deposition contour to the south, additional lake sampling was conducted at a conservative distance beyond the extent of the receptor grid. Subsequent modelling with the receptor grid extended to the south resulted in a fully defined contour of 10 kg/ha/yr of total SO_4 deposition.

8.0 Methods of Assessing Impacts on Receptors



8.1 RISK ASSESSMENT FRAMEWORK USE TO EVALUATE IMPACTS

The technical assessment conclusions are described in this report using a structured and transparent framework. The framework is based on a risk assessment approach comprising two dimensions commonly used in risk assessment matrices: the probability or likelihood of an impact, and the consequence of such an impact. Each dimension has five levels, to allow sufficient resolution for meaningfully distinguishing and classifying impacts. There are four possible impact categories ranging from low (green) or moderate (yellow) to high (orange) or critical (red), depending on the combined levels of both dimensions. Impact category is a function of likelihood and consequence, as illustrated in Figure 8.1-1. For example, impacts considered very unlikely, and of minor consequence, would be classified as “low”. Conversely, impacts considered almost certain, and of catastrophic consequence, would be classified as “critical”. Each likelihood–consequence combination is assigned one of the four impact categories.

The framework was informed by considerations of significance used in the British Columbia and federal environmental assessment processes, as well as the risk framework used by Fisheries and Oceans Canada (DFO), all of which combine elements of impact probability, impact consequence, and uncertainty. The criteria commonly used to determine significance in applications for a British Columbia Environmental Assessment Certificate include frequency and

probability, which align with the likelihood dimension in the KMP assessment framework; magnitude, spatial extent, duration, reversibility and receptor importance, which align with the consequence dimension in the KMP assessment framework; as well the level of confidence and certainty in the significance determination, which is addressed in the KMP adaptive management framework. Impact determinations under the Canadian Environmental Assessment Act[19] are based on adversity of impact, significance of impact, and likelihood of impact, with significance factors including extent, duration, intensity, and receptor sensitivity (FEARO 1994). Significance under the DFO risk assessment framework is based on magnitude, geographic extent, duration and frequency, degree of reversibility and ecological context; likelihood is based on probability and scientific uncertainty.

With these factors in mind, all five levels in both dimensions in the assessment framework have been defined for each receptor (human health, vegetation, soil, surface water). Any potential impact can therefore be classified in the matrix, depending on its likelihood and consequence as determined by the assessment results. Explicit definitions for each dimension for each receptor are presented later in this section, and again in the presentation of the assessment results in Section 9.0.

[19] The new act, CEAA 2012, does not formally define significance, nor is there any new guidance on significance determination. In response to a question we raised about this at a Forum to introduce the new Act in Vancouver on October 17th, 2012, the CEAA representative advised the continued use of the existing guidance (FEARO 1994).

Likelihood	Consequence				
	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**

Legend	*What each impact category means*
Low	No impact or acceptable impact; routine monitoring
Moderate	Acceptable impact but in need of closer scrutiny; moderate monitoring
High	Unacceptable impact; contingency/response action; intensive monitoring
Critical	Extremely unacceptable impact; critical response action; very intensive monitoring

Figure 8.1-1: Risk Assessment Framework, showing the two dimensions, the five levels under each, and the four impact categories. This shows an *example* of how impact categories might be assigned across the cells. The pattern varies slightly across the matrices used for each of the four receptors, according to their respective definitions of the levels for each dimension.

While the definitions of each dimension are explicit, determining the differences between each level, such as what distinguishes a 'serious' from a 'major' consequence, is somewhat subjective. The Qualified Professionals (QPs) working on this technical assessment study, under the direction of ESSA, have used established targets and evidence-based thresholds as well as their experience and professional judgment to guide them in defining these boundaries between levels. Determining whether an impact would be **green**, **yellow**, **orange** or **red** is also subjective: one reader may consider a particular impact 'moderate' and another may consider the same impact' high' depending on the value each places on the receptor. The QPs have used benchmark conventions in their areas of expertise to classify their impact predictions in this framework. The transparency of the assessment framework allows readers to see what assumptions have been made in the impact predictions, and to draw alternative conclusions about the importance of the impacts according to their own values. Ultimately the acceptability of any particular impact is a policy decision.

8.2 ADAPTIVE MANAGEMENT

Uncertainties are inherent in any prediction of impacts. Despite the rigorous assessments described in the subsequent sections of this report, some **critical uncertainties** remain with respect to the impact predictions. Critical uncertainties are those which when resolved *may*

result in a predicted impact shifting up or down one or more levels in either of the dimensions in the risk assessment framework, which could result in a different impact category (**green**, **yellow**, **orange** or **red**). Resolving critical uncertainties could also result in a change in decisions about mitigative actions. Other uncertainties which exist in this technical assessment, but if resolved are not expected to change either the impact category or appropriate mitigative actions, may be 'nice to know' but are not considered critical.

The critical uncertainties from the technical assessment are very explicitly identified for each receptor in the results sections of this report. Most of these uncertainties cannot be resolved prior to the Kitimat Modernization Project, and will require monitoring data once the modernized smelter is operational. Adaptive management, implemented in a very rigorous manner, provides a framework for learning what is needed to reduce these uncertainties post-KMP and then implementing the appropriate mitigations if unacceptable impacts occur, or are expected.

The team of QPs has designed an adaptive management plan for resolving critical uncertainties, which is described in Section 10.0. (Section 10.0 also provides a brief introduction to adaptive management for readers unfamiliar with the approach.)

8.3 HUMAN HEALTH STUDY

As discussed in Section 3.4, the scientific evidence for health effects "sufficient to infer a causal relationship" is for short-term exposure to SO_2 and respiratory morbidity. Respiratory responses in individuals with existing restrictive airway diseases are most closely linked to short-term peaks of SO_2 exposure.

Selection of dose response relationship

The assessment of potential health risks associated with SO_2 releases in Kitimat was performed on the basis of a short-term concentration-response relationship developed by the U.S. EPA (U.S. EPA 2009) for peak 5-minute exposures and lung function changes in exercising individuals with asthma (Figure 8.3-1). The U.S. EPA report included concentration-response relationships using both log-logistic and probit functions. We have chosen to perform the calculations using the log-logistic concentration response curve, which is the more conservative of the two. By conservative, we mean that the choice is more likely to overestimate rather than underestimate health risk. Additionally, we have chosen the dose-response curve associated with an increase in specific airway resistance of 100% (the EPA also included a dose-response relationship for an increase of 200% (the same effect, but a greater increase in airway resistance, and occurring less often)). Note that both outcomes (100% or 200% increase in specific airway resistance) would be considered *medium* severity outcomes within the risk assessment framework, so the choice is not expected to affect the overall results. The selected dose-response relationship is described in the EPA report as Equation 9.2 and illustrated in that report's Figure 9-2 (U.S. EPA 2009).

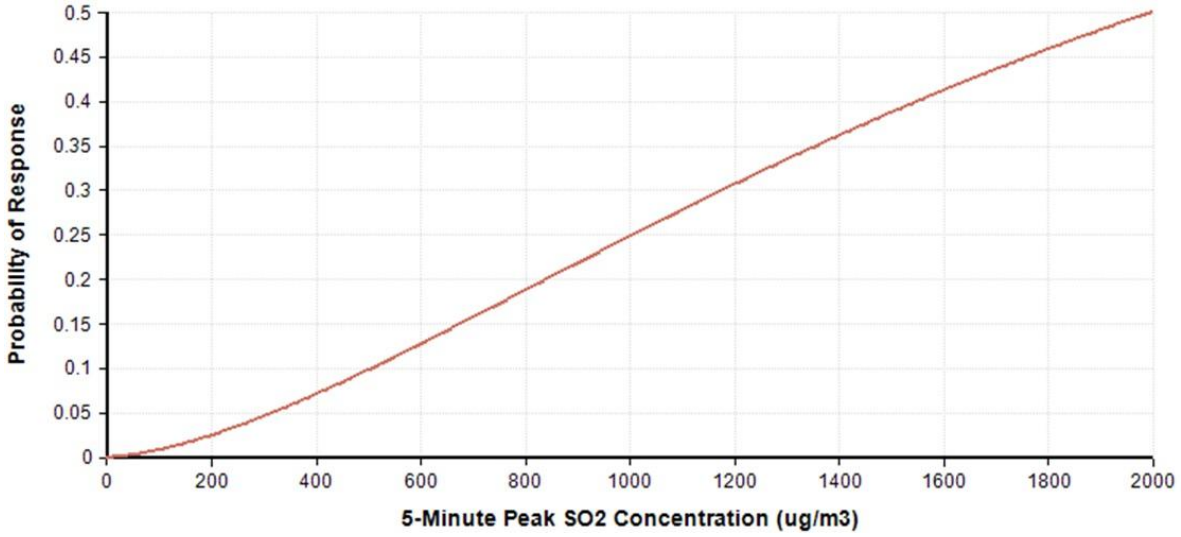


Figure 8.3-1: Concentration-response function (U.S. EPA 2009).

8.3.1 Definition of a respiratory response

The U.S. EPA defined a respiratory response based on two measures of lung function, forced expiratory volume in 1 second (FEV1) and specific airway resistance (sRaw), and on two levels of change in these measures. Four definitions of a respiratory response by the U.S. EPA were: (1) an increase in sRaw ≥100%; (2) an increase in sRaw ≥200%; (3) a decrease in FEV1 ≥15%; and (4) a decrease in FEV1 ≥20%.

FEV1 and sRaw are considered to be interchangeable indices of airway obstruction (Mahut et al. 2011), and can also be used as complementary measures for evaluation of lung function. FEV1 and sRaw measurements generally agree (Piatti et al. 2012). Some studies (e.g., Simon et al. 2012) suggest that sRaw may be a more sensitive indicator of bronchial obstruction than FEV1. Our definition of a respiratory response is an increase in sRaw ≥100%. An increase in sRaw ≥100% is defined by the U.S. EPA as an indicator of "moderate or greater bronchoconstriction" (U.S. EPA 2008). It is important to note that sRaw is a physical measurement of airway resistance, and does not indicate necessarily that a person experiencing this increase in airway resistance would be aware of it. As such, it is considered to be a very mild health effect, or a precursor to the development of symptoms. This respiratory effect is reversible and common among individuals with restrictive airway diseases; it can also be caused by allergens, exercise and cold temperatures, or combinations of these.

8.3.2 Exposure data

Modelled data were provided by Trinity Consultants as 1-hour averaged outdoor SO_2 concentrations. The model results were provided for a variety of residential locations and other

locations of interest (see Section 7.0 for a description of the modelling approach and results). To use these data for concentration-response analysis, the following methodology was used:

1. Modelled 1-hour data were analysed, and histograms of 1-hour average SO_2 concentrations were computed by location of interest, month and hour of day.
2. 1-hour average SO_2 concentrations were converted into 5-minute peak concentrations.
3. A conversion factor was used from measured data to calculate indoor SO_2 concentrations from outdoor concentrations.

1-hour average SO_2 concentration histograms

Source Data Format

Modelled SO_2 concentration values were provided for a period of three years (2006, 2008 and 2009). These were provided as hourly average concentration values ($\mu g/m^3$) for different receptors located in and around Kitimat. Values were provided for each hour of the day, for a period of 364 days, for each receptor. For example, Table 8.3-1 provides values for one receptor for the last 12 hours of January 1, 2006.

Table 8.3-1: Sample hourly averaged data for one receptor.

Year	Day	Hour	SO_2 ($\mu g/m^3$)
2006	1	1200	149.76
2006	1	1300	36.20
2006	1	1400	50.72
2006	1	1500	25.18
2006	1	1600	37.33
2006	1	1700	40.67
2006	1	1800	13.24
2006	1	1900	35.43
2006	1	2000	33.31
2006	1	2100	32.55
2006	1	2200	36.00
2006	1	2300	47.55

Data Analysis

The following method was used to convert the hourly SO_2 concentration into histograms for use in the model:

1. Four regions were selected and the receptors located in each of those areas were identified.
2. Histogram bins were established to capture the full range of SO_2 concentration values.
3. The concentration values were grouped by location, month, hour of day and concentration bin to establish histograms of the concentration values.

Step 1: Region selection

Four regions were selected for analysis: Service Centre, Lower Kitimat, Upper Kitimat, and Kitamaat Village (Figure 8.3-2). Each receptor is associated with a specific Universal Transverse Mercator (UTM) location. The UTM boundaries were established for each of the four regions of interest. These boundaries were then used to establish which receptors were located within each region.

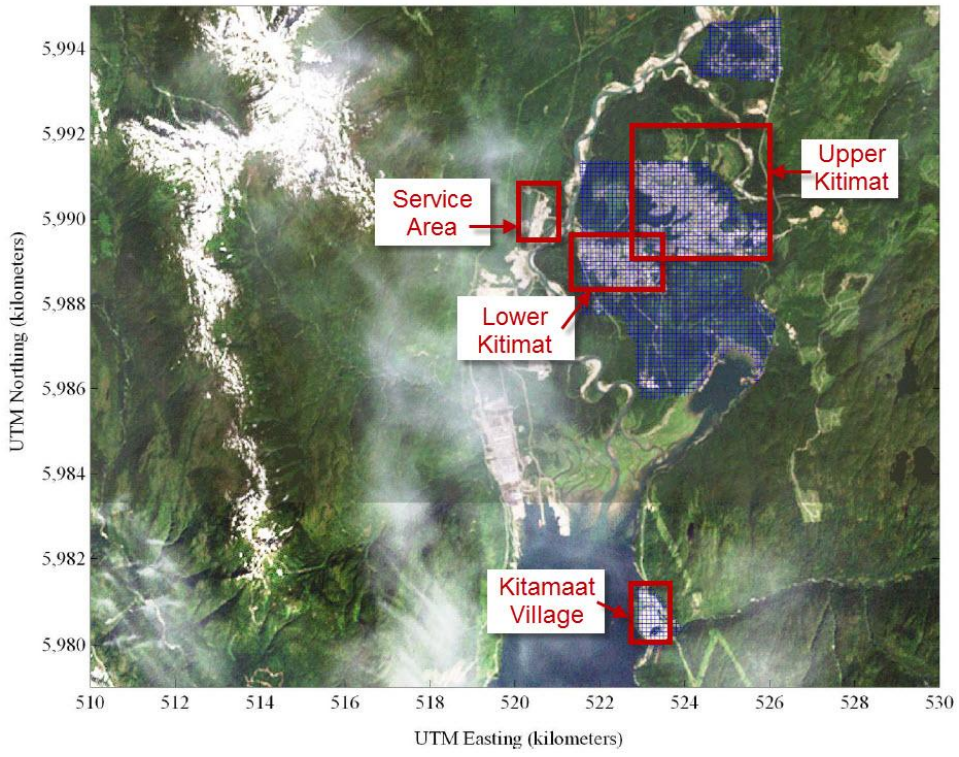


Figure 8.3-2: Location of four residential and business locations in the Kitimat area defined for use in the human health risk assessment.

Step 2: Concentration histogram bins

Thirty-six concentration bins were established to capture the range of SO_2 concentration values. Smaller ranges were used at the lower end of the concentration values to provide greater resolution for these values, given their higher frequency. Table 8.3-2 provides a description of the histogram bins.

Table 8.3-2: Description of histogram bins for hourly-averaged SO_2 concentration.

Bin	Minimum Value (µg/m^3)	Maximum Value (µg/m^3)
0	0	1
1	1	10
2	10	20
3	20	30
4	30	40
5	40	50
6	50	60
7	60	70
8	70	80
9	80	90
10	90	100
11	100	125
12	125	150
13	150	175
14	175	200
15	200	250
16	250	300
17	300	350
18	350	400
19	400	450
20	450	500
21	500	600
22	600	700
23	700	800
24	800	900
25	900	1000
26	1000	1100
27	1100	1200
28	1200	1300
29	1300	1400

Bin	Minimum Value ($\mu g/m^3$)	Maximum Value ($\mu g/m^3$)
30	1400	1500
31	1500	1600
32	1600	1700
33	1700	1800
34	1800	1900
35	1900	2000

Step 3: Generating histograms

The modelled concentration values were grouped by region, month and hour of day, combining data for all receptor gridpoints in that region and for all three years. Each data point associated with a specific region, month and hour of day was assigned to a specific concentration bin. It was then possible to establish both the frequency of data points in each bin and the mean concentration value for each bin for each region, month and hour of day. Due to the focus on exposures while exercising, the hours from 10 pm through to 6 am (i.e., overnight) were excluded from the analysis.

For example, Table 8.3-3 shows the values established for the frequency and mean concentration of each bin for noon for all days in September in the region of Lower Kitimat. Row 2 indicates that for 19% of the days in September at 12 noon, the 1 hour average concentration will be between 1 and 10 $\mu g/m^3$ with a mean concentration of 3.81 $\mu g/m^3$. Also, the concentration will be 20 $\mu g/m^3$ or less (the first three bins) 95% of the time. For this particular histogram, no values exceeded 350 $\mu g/m^3$.

These histograms are used by the health assessment model to establish the likelihood of exposure to a given concentration value over the course of a year, by region, month and time of day.

Table 8.3-3: Sample histogram data of the relative frequency of SO_2 concentrations.

Concentration ($\mu g/m^3$)	Frequency	Cumulative Frequency	Mean Concentration
0-1	0.75	0.75	0.06
1-10	0.19	0.94	3.81
10-20	0.01	0.95	13.57
20-30	4.60E-03	0.96	24.60
30-40	4.30E-03	0.96	35.16
40-50	7.38E-03	0.97	45.69
50-60	8.90E-03	0.98	54.26
60-70	3.77E-03	0.98	64.69

70-80	2.66E-03	0.98	74.79
80-90	2.05E-03	0.98	84.71
90-100	1.71E-03	0.99	94.34
100-125	2.82E-03	0.99	111.11
125-150	2.25E-03	0.99	137.04
150-175	2.05E-03	0.99	162.56
175-200	1.75E-03	1.00	186.97
200-250	3.27E-03	1.00	221.36
250-300	1.37E-03	1.00	275.30
300-350	3.42E-04	1.00	310.42
350-400	0	1	N/A
400-450	0	1	N/A
450-500	0	1	N/A

Five-minute peak SO_2 concentrations

Five-minute peaks were estimated by applying a peak-to mean ratio (a multiplier greater than 1.0) to the 1-hour average SO_2 concentrations.

There are three possible ways to estimate the peak-to-mean ratios:

- from past observations of the relationship between peak and mean SO_2 concentrations from air monitoring sites in Kitimat;
- by modelling post-KMP SO_2 concentrations at a higher temporal resolution (5-minute timesteps as opposed to 1 hour timesteps); and
- by using measured peak-to-mean ratios in other areas that are available in the literature.

We chose the first of these ways given that: (1) the peak-to-mean ratios are expected to be highly location specific due to topography and meteorological effects; (2) increasing the air modelling temporal resolution to 5-minute time steps is highly computationally intensive; and (3) local monitoring data were available for both 1-hour and 5-minute averaging periods.

Peak-to-mean ratios were computed by Trinity Consultants on the basis of existing data on 1-hour average and 5-minute peak SO_2 concentrations from the Kitimat Haul Road air monitoring station (Figure 8.3-3). The observed peak-to-mean ratios are illustrated below in the form of a frequency distribution (Figure 8.3-4). As shown in Figure 8.3-4, the peak-to-mean ratio frequency distribution is stable across seasons. The values range from 1 to 21 with a mean of approximately 2.

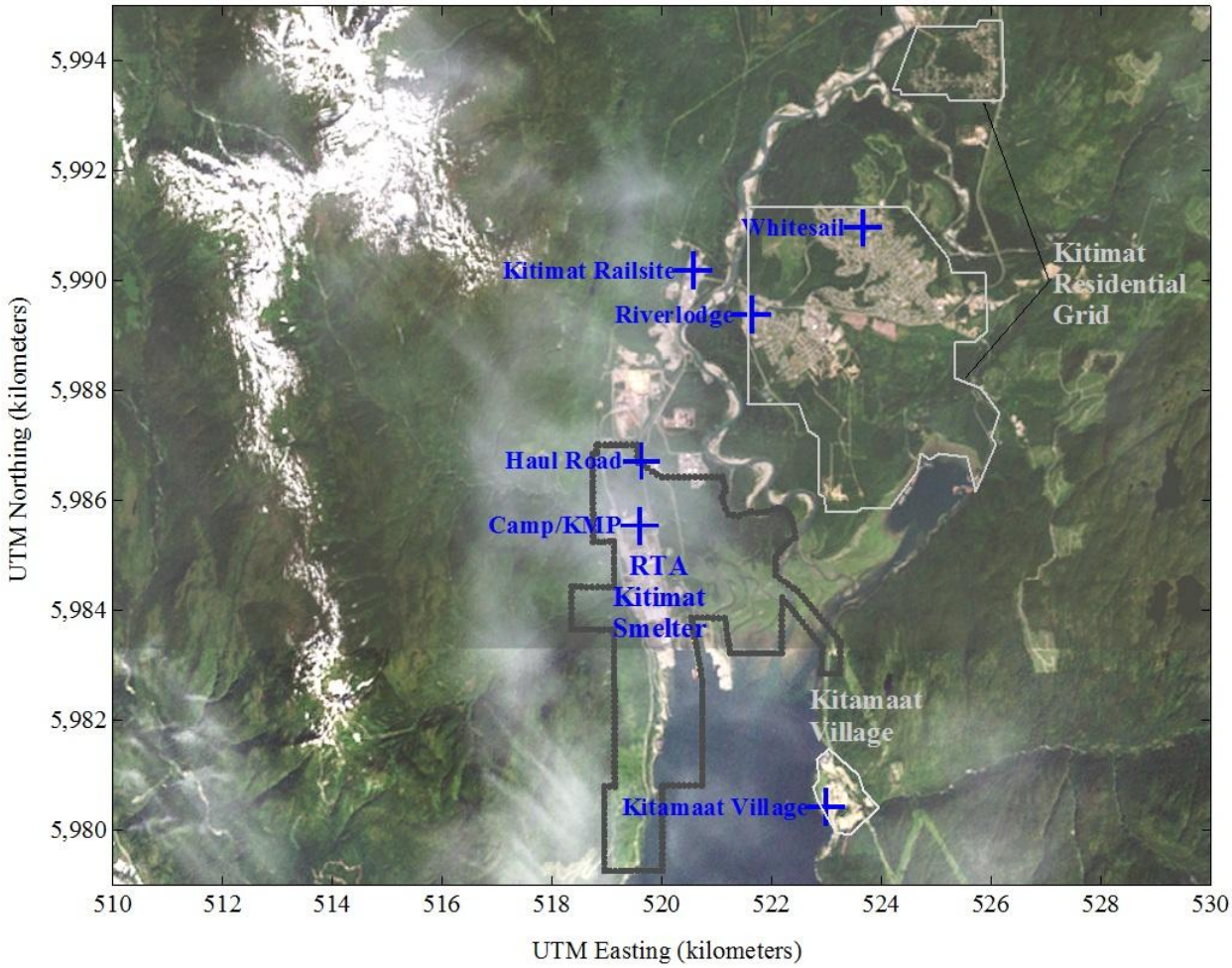


Figure 8.3-3: Location of air monitoring stations in the Kitimat area (from Trinity Consultants 2012, Figure 4-1: Kitimat Smelter Area Map, reproduced in Appendix 7.6-1 of this report). Data from the Haul Road monitoring site was selected as the basis for estimating peak-to-mean ratios.

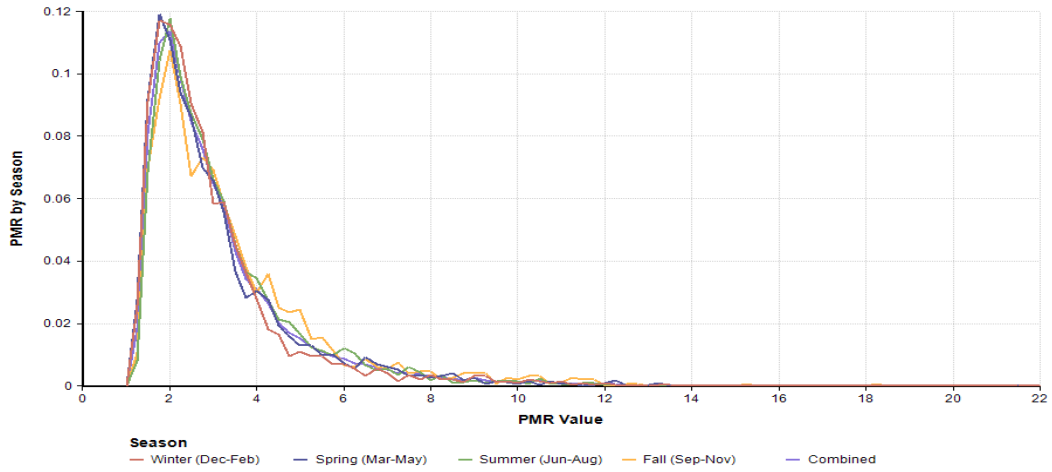


Figure 8.3-4: Frequency distribution of peak-to-mean ratios by season.

The concentration-response modelling employed the full peak-to-mean ratio distribution by multiplying hourly-averaged concentrations by values from the peak-to-mean distribution according to their relative frequency. Figure 8.3-5 and Figure 8.3-6 show the probability of response as a function of the hourly averaged concentration for different assumed values of the Peak-to-Mean Ratio, for outdoor and indoor exposures, respectively. Higher values of the PMR lead to a higher probability of response. The curve marked "Weighted" in each of these figures is the result of using the full distribution of PMRs observed, weighted by their relative frequency as described in more detail below.

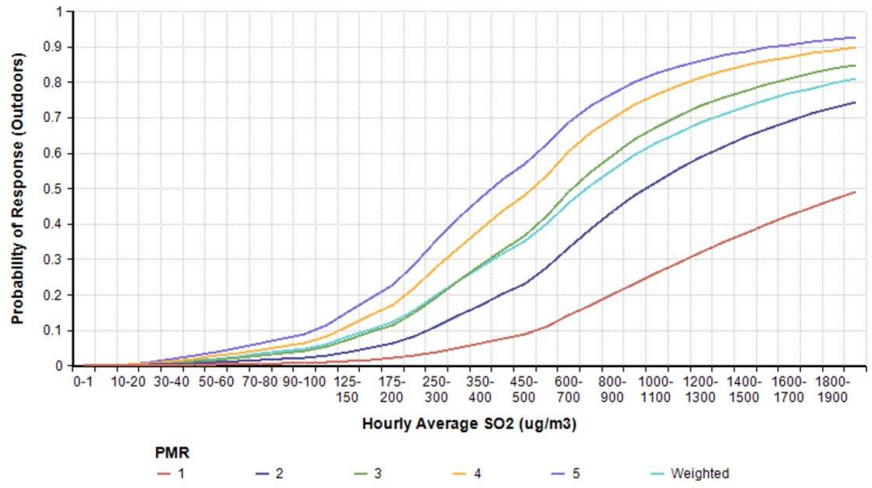


Figure 8.3-5: Concentration-response curves under various peak-to-mean ratios (PMR) for sample outdoor SO_2 concentrations. The curve labeled "Weighted" is employed by the risk assessment model.

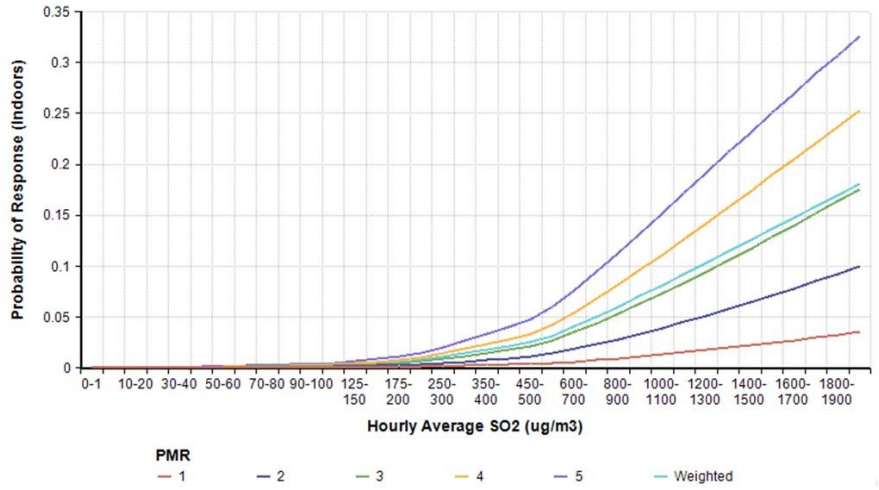
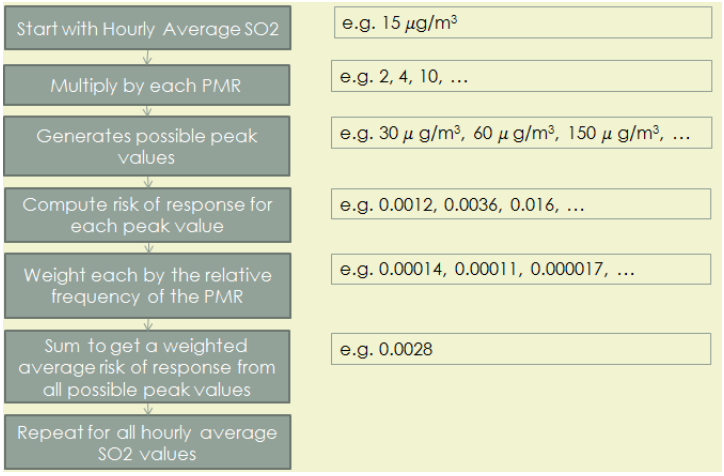


Figure 8.3-6: Concentration-response curves under various peak-to-mean ratios (PMR) for sample indoor SO_2 concentrations.

Sample computation of a weighted probability of response using peak-to-mean ratios to convert 1-hour average concentrations to 5-minute peak concentrations

For the purposes of this example, five peak-mean-ratios will be used: 1.5, 2, 3, 4 and 5. Additionally, only the first 11 concentration bins will be used: 0-1, 1-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, 70-80, 80-90, and 90-100. The overall algorithm is described in Figure 8.3-7 below.

Figure 8.3-7: Illustration of algorithm to calculate probability of response for 5-minute peak concentrations, based on hourly-averaged data.



Step 1: Hourly Average SO_2 Concentration

For this example, the histogram of SO_2 concentration values for Lower Kitimat was selected for noon for any day in August (Table 8.3-4).

Table 8.3-4: Sample data showing hourly average concentration bins and their relative frequency.

Bin	Frequency	Mean 1 Hour Average Concentration (µg/m^3)
0-1	0.716232	0.094975
1-10	0.265724	2.935511
10-20	8.47E-03	14.39198
20-30	4.12E-03	24.24359
30-40	1.80E-03	34.77489
40-50	1.51E-03	45.56325
50-60	1.40E-03	54.53454
60-70	5.52E-04	63.63136
70-80	1.84E-04	71.26967
80-90	0	0
90-100	0	0

In the shown in Table 8.3-4, 71.6% of days in August in Lower Kitimat have a concentration between 0 and 1 µg/m^3 at noon (row 1). The mean value within this range is approximately 0.095 µg/m^3. Note that, for this location and time of year, no concentrations were modelled at levels above 80 µg/m^3 and, therefore, the frequency and mean values for these bins are zero.

Step 2: Peak-to-Mean Ratio Frequency

For illustration purposes, the following frequency of each peak-to-mean ratio is assumed (Table 8.3-5).

Table 8.3-5: Sample data to illustrate relative frequency of different values of the peak-to-mean ratio.

PMR	Frequency
1.5	0.15
2	0.3
3	0.3
4	0.15
5	0.1

Step 3: Computing Peak Concentration Values from Hourly Concentration Values

All possible PMR values are applied to the mean concentration value of each bin. For example, for the bin 1-10, the following peak values would be computed (Table 8.3-6).

Table 8.3-6: Sample calculation of peak concentrations for one bin, with different values of the peak-to-mean ratio.

Bin	Mean Hourly Concentration	PMR	Peak Concentration
1-10	2.936	1.5	4.40
		2	5.87
		3	8.81
		4	11.74
		5	14.68

Step 4: Compute Probability of Response for each Peak Concentration Value

Using the selected EPA dose-response function (described above), the probability of response from each peak value can be computed (Table 8.3-7).

Table 8.3-7: Probability of response for each peak concentration estimated.

PMR	Peak Concentration	Probability of Response
1.5	4.40	5.51E-05
2	5.87	8.75E-05
3	8.81	1.67E-04
4	11.74	2.66E-04
5	14.68	3.80E-04

Step 5: Weight the Probability of Response by the Freqeuency of the PMR

Each peak-to-mean ratio is assigned a likelihood equivalent to its frequency of occurrence. This likelihood is used to compute the weighted probability of response for each PMR. Summing the individual weighted probability of response provides the weighted probability of response for the hourly concentration bin (Table 8.3-8).

Table 8.3-8: Illustration of calculation of the final probability of response for a single hourly averaged concentration bin. The final value is calculated as the sum of probabilities of response from each potential peak-to-mean ratio, weighted by their relative likelihood.

PMR	Peak Concentration	Probability of Response	Frequency	Weighted Probability of Response
1.5	4.40	5.51E-05	0.15	8.27E-06
2	5.87	8.75E-05	0.3	2.62E-05
3	8.81	1.67E-04	0.3	5.02E-05
4	11.74	2.66E-04	0.15	3.98E-05
5	14.68	3.80E-04	0.1	3.80E-05

Step 6: Compute the Weighted Probability of Response for all Concentration Bins for the Current 1-hour Average Concentration Histogram

The process is repeated to compute the weighted probability of response for each bin (Table 8.3-9).

Table 8.3-9: Weighted probability of response calculated for all hourly averaged concentration bins.

Bin	Frequency	Mean 1 Hour Average Concentration ($\mu g/m^3$)	Weighted Risk of Response
0-1	0.716232	0.094975	6.65E-07
1-10	0.265724	2.935511	1.63E-04
10-20	8.47E-03	14.39198	2.07E-03
20-30	4.12E-03	24.24359	4.77E-03
30-40	1.80E-03	34.77489	8.45E-03
40-50	1.51E-03	45.56325	0.012956
50-60	1.40E-03	54.53454	0.017182
60-70	5.52E-04	63.63136	0.02186
70-80	1.84E-04	71.26967	0.026063
80-90	0	0	0
90-100	0	0	0

Step 7: Compute the weighted probability of response for any activity occurring at the location and time of the histogram

Summing the risk of response weighted by bin frequency provides the final weighted risk of response in August for Lower Kitimat. This value is multiplied by the number of exposures in that region to determine the number of respiratory responses. Summing the probability of response weighted by the relative frequency of the hourly averaged concentration bins (last column in Table 8.3-10) provides the final weighted probability of response in August for Lower Kitimat. This value is later multiplied by the number of exercise events in that region to determine the predicted number of respiratory responses.

Table 8.3-10: Final calculation of probability of response as the sum of the probability of response at each concentration bin, weighted by the relative frequency of each concentration bin.

Bin	Frequency	Mean 1 Hour Average Concentration ($\mu g/m^3$)	Weighted Probability of Response	Weighted by Bin Frequency
0-1	0.716232	0.094975	6.65E-07	4.76E-07
1-10	0.265724	2.935511	1.63E-04	4.32E-05
10-20	8.47E-03	14.39198	2.07E-03	1.76E-05
20-30	4.12E-03	24.24359	4.77E-03	1.97E-05
30-40	1.80E-03	34.77489	8.45E-03	1.53E-05
40-50	1.51E-03	45.56325	0.012956	1.96E-05
50-60	1.40E-03	54.53454	0.017182	2.40E-05
60-70	5.52E-04	63.63136	0.02186	1.21E-05
70-80	1.84E-04	71.26967	0.026063	4.80E-06
80-90	0	0	0	0
90-100	0	0	0	0
		Weighted Probability of Response		1.57E-04

Indoor SO_2 concentrations

SO_2 levels are generally lower indoors than outdoors partly due to SO_2 reactions with indoor surfaces. The indoor-outdoor SO_2 concentration ratios depend on how air-tight the home is, which varies with season and the use of air conditioning.

We identified six original studies and two reviews providing information on ratios of indoor to outdoor SO_2 concentrations. We selected data on indoor/outdoor SO_2 concentration ratios

from two relatively recent studies conducted in North America (Leaderer et al. 1999; Kindzierski and Sembaluk 2001).

Kindzierski and Sembaluk 2001 reported similar indoor/outdoor SO_2 concentration ratios of 0.13 for two communities (urban and rural) in Alberta. Measurements were performed in late fall. Leaderer et al. (1999) measured outdoor and indoor SO_2 concentrations in homes of southwest Virginia; the indoor/outdoor SO_2 concentration ratios for non-air-conditioned non-kerosene-heated homes were 0.69 in summer and 0.21 in winter. To predict health effects from exposures to SO_2 indoors, we applied the indoor/outdoor SO_2 concentration ratio of 0.13 from (Kindzierski and Sembaluk 2001) to cool-cold seasons (October to April). Assuming that most homes and offices in Kitimat are not air-conditioned, we applied the ratio of 0.69 from (Leaderer et al. 1999) to warm seasons (May to September).

Though this is not reflected in the model, outdoor concentration peaks are not likely to be reflected indoors, in the same way that other meteorological events (wind gusts) may not be as extreme indoors. As a result, indoor estimates of peak exposures are likely to be overestimated due to using the same peak-to-mean distribution as for outdoor exposures.

Note that when computing the probability of response for indoor activity, the mean concentration for each bin is modified by the indoor-outdoor ratio described in the next section before applying the peak-to-mean conversions.

8.3.3 Number of susceptible individuals

According to Statistics Canada, the population of Kitimat (District municipality) was 8,335 in 2011 (Statistics Canada 2012, internet site). B.C. Stats (2012) provides a population estimate of 10,189 for Kitimat (Local Health Area) in 2012, and projects a slight growth to 10,261 in 2020 (B.C. Stats 2012, internet site). In our modelling, we used 10,000 as the total population of the Kitimat area.

Symptoms of asthma are similar to those of chronic obstructive pulmonary disease, the differential diagnosis is sometimes difficult, and there is a significant overlap between the two conditions in individuals 55 years of age and older (British Columbia Ministry of Health 2004a,b, internet site; Ariano and Panzani 2012). For modelling the risk of respiratory responses, individuals with asthma and individuals with chronic obstructive pulmonary disease were grouped.

We used prevalence estimates of asthma and chronic obstructive pulmonary disease by the Public Health Agency of Canada (Public Health Agency of Canada 2010) on the basis of the self-reported Canadian Community Health Survey. As shown in Figure 8.3-8 and Figure 8.3-9, prevalence of asthma and chronic obstructive pulmonary disease in the Northwest Health Service Delivery Area is similar to that in British Columbia, and the combined prevalence of the two conditions is about 12%.

Based on these data, we estimated the number of susceptible individuals in Kitimat at 1,200.

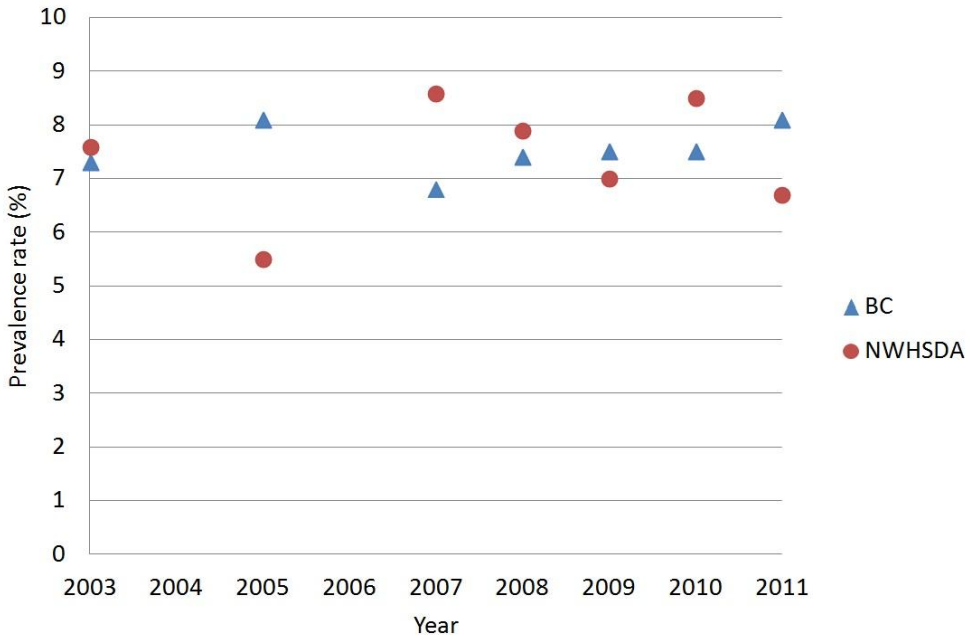


Figure 8.3-8: Prevalence of asthma in British Columbia and in the Northwest Health Service Delivery Area of British Columbia (Public Health Agency of Canada 2010).

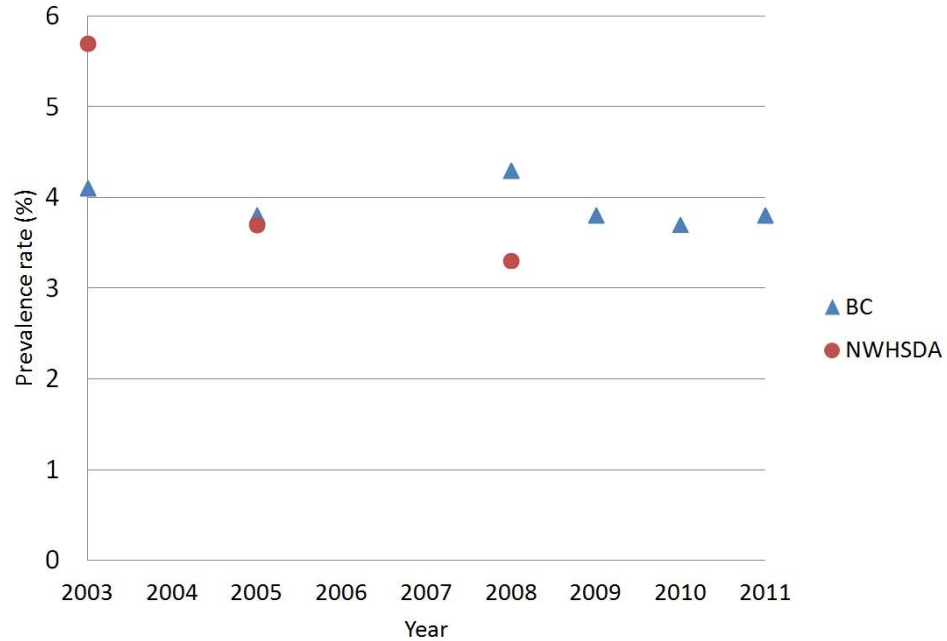


Figure 8.3-9: Prevalence of chronic obstructive pulmonary disease in British Columbia and in the Northwest Health Service Delivery Area of British Columbia (Public Health Agency of Canada 2010).

8.3.4 Assumptions underlying concentration-response modelling

The human health assessment model was developed using the modelling software package Analytica™ (Lumina 2012). The modelled data provided by Trinity Consultants served as an input to this model. The model is structured to estimate the annual number of respiratory responses (bronchoconstriction events). The cause of the respiratory response was assumed to be a result of:

- exposure to a 5-minute peak of SO_2;
- underlying restrictive airway disease in the human receptor; and
- moderate or greater physical activity of the human receptor (corresponding lung ventilation rate ~40 to 48 L/min (U.S. EPA 2008)).

We assumed that only one respiratory response would occur in an individual during a day. Subsequent responses would be prevented by medication and/or restriction of physical activity.

We modelled respiratory responses under various assumptions regarding the proportion of physically active individuals (50%, 75% or 100%), the number of days of physical activity in a year (100, 200, 300 or 365), and the proportion of physical activity events that occur outdoors (25%, 50%, 75%).

For purposes of the health risk assessment, we divided the Kitimat area into four areas: the Service Centre, Lower Kitimat, Upper Kitimat, and Kitamaat Village (see Figure 8.3-2). Kitamaat Village is the area of lowest average exposure to SO_2, and the Service Center is the area of highest average exposure.

8.3.5 Risk assessment framework

As described in Section 8.1, the effects on each receptor are classified according to a framework which outlines both the likelihood of an impact, and its consequences. For health, these likelihood and consequence dimensions of the risk assessment framework are defined in Table 8.3-11 and Table 8.3-12 (respectively). Table 8.3-13 illustrates the resulting impact categories when these two factors are combined.

Table 8.3-11: Likelihood levels used in the risk assessment framework for health.

A – Almost Certain	B – Likely	C – Possible	D – Unlikely	E – Very Unlikely
Whole population, regularly affected	Whole population, infrequently affected	Susceptible sub-population frequently affected	Susceptible sub-population infrequently affected	Very small vulnerable sub-population infrequently affected

Table 8.3-12: Consequence levels used in the risk assessment framework for health.

1 - Minor	2 - Medium	3 - Serious	4 - Major	5 – Catastrophic
Irritation or mild reversible health effect not requiring medication, behaviour modification, or medical attention.	Irritation or mild reversible health effects requiring medication or behavior modification.	Reversible effect requiring medical attention.	Irreversible health effect with ongoing mild or moderate disability.	Fatality or long-term serious disability.

Table 8.3-13: Impact categories from the combined likelihood and consequence dimensions of the risk assessment framework for human health. The low, moderate, high and critical levels of impact are defined in the overall description of the risk assessment framework (Section 8.1).

Likelihood (see definitions in Table 8.3-11)	**Consequence** (see definitions in Table 8.3-12)				
	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**	**Moderate**	**Moderate**	**High**	**Critical**
E – Very Unlikely	**Low**	**Low**	**Moderate**	**Moderate**	**High**

8.4 VEGETATION STUDY

Primary aluminum smelters emit two major pollutants to the atmosphere that are toxic to vegetation: HF and SO_2. A monitoring program to determine the fluoride (F) content of vegetation and to catalog visible effects of HF on trees, shrubs, and understory plants has been in place for over 40 years and was recently reviewed (Laurence 2010) and modified based on an analysis of the historical record. Since 1997, that monitoring program also documented the concentration of sulphur (S) in vegetation using the same plant samples collected for F analysis. Observations of plant health and vigor, including visible effects of SO_2 on many species, are made as part of the program. Lichens have been shown to be sensitive to air pollutants, including SO_2. Little is known about lichens in the Kitimat area. A study was conducted by Reid, Collins and Associates (Bunce 1978; Richards 1986) that reported a decline in the population in the 1970s, however little additional information is available. Two species, *Nephroma occultum* and *Pseudocyphellaria rainierensis,* protected under the Canadian Species at Risk Act have been reported in the area. *P. rainierensis* was collected in 1970 from a location about 7.8 km east of KMP. *N. occultum* was collected in 1991 from a location near Kitamaat Village. Although both lichens were collected long after the smelter and other industries began operation (at least 17 and 37 years), it is not known whether either persists today.

The forest in the vicinity of Kitimat experienced a destructive outbreak of saddleback looper (*Ectopus crepuscularia*) and spruce budworm (*Cristoneura orae*) from 1960 to 1969. Studies by Reid, Collins and Associates (Bunce 1985) calculated the volume loss due to the infestation and

estimated growth reductions that could be ascribed to emissions from the smelter, which were substantially greater then, especially in particulate fluoride, than they are today. The stands at the time were classified as “uneven-aged, overmature, decadent and stable climax forest.” The authors advanced seven hypotheses for the outbreak, ranging from attraction of insects to lights in the valley to emissions from the smelter either weakening the trees or killing parasites of the insects. They state in the end that “there is no direct evidence to relate any of these hypotheses to actual events.” They note that such infestations have not been documented in the vicinity of other smelters. Also, as of this writing, there have been no other noteworthy infestations in the area, more than 50 years later.

SO_2 effects on vegetation have not been of great concern at Kitimat for two reasons. First, S is an essential element for plants, thus the concentrations that cause direct injury to plants are generally in the parts per million (ppm) range. Details of the effects of SO_2 on vegetation may be found in the literature review in Appendix 3.5-1. Second, the emissions from the current smelter are modest. There is little or no evidence of direct injury to vegetation in the past with only occasional suspicious symptoms being observed.

The purpose of this analysis is to document the relationship between S emissions from the current facility and S in vegetation, and to assess the likely effects of future emissions on vegetation in the vicinity of KMP.

8.4.1 Design of field monitoring program

The field monitoring program relies on a set of permanent sampling and observation points. The network has been modified over the years to account for changes in access and to address particular concerns (e.g., the infestation of saddleback looper in the 1960s). In 2010, a retrospective analysis (Laurence 2010) of the monitoring and observation program resulted in the current array of sampling and observation locations (Figure 8.4-1), that constitute transects over distance in north, northeast, and south directions, and an additional north transect on the east side of Minette Bay.

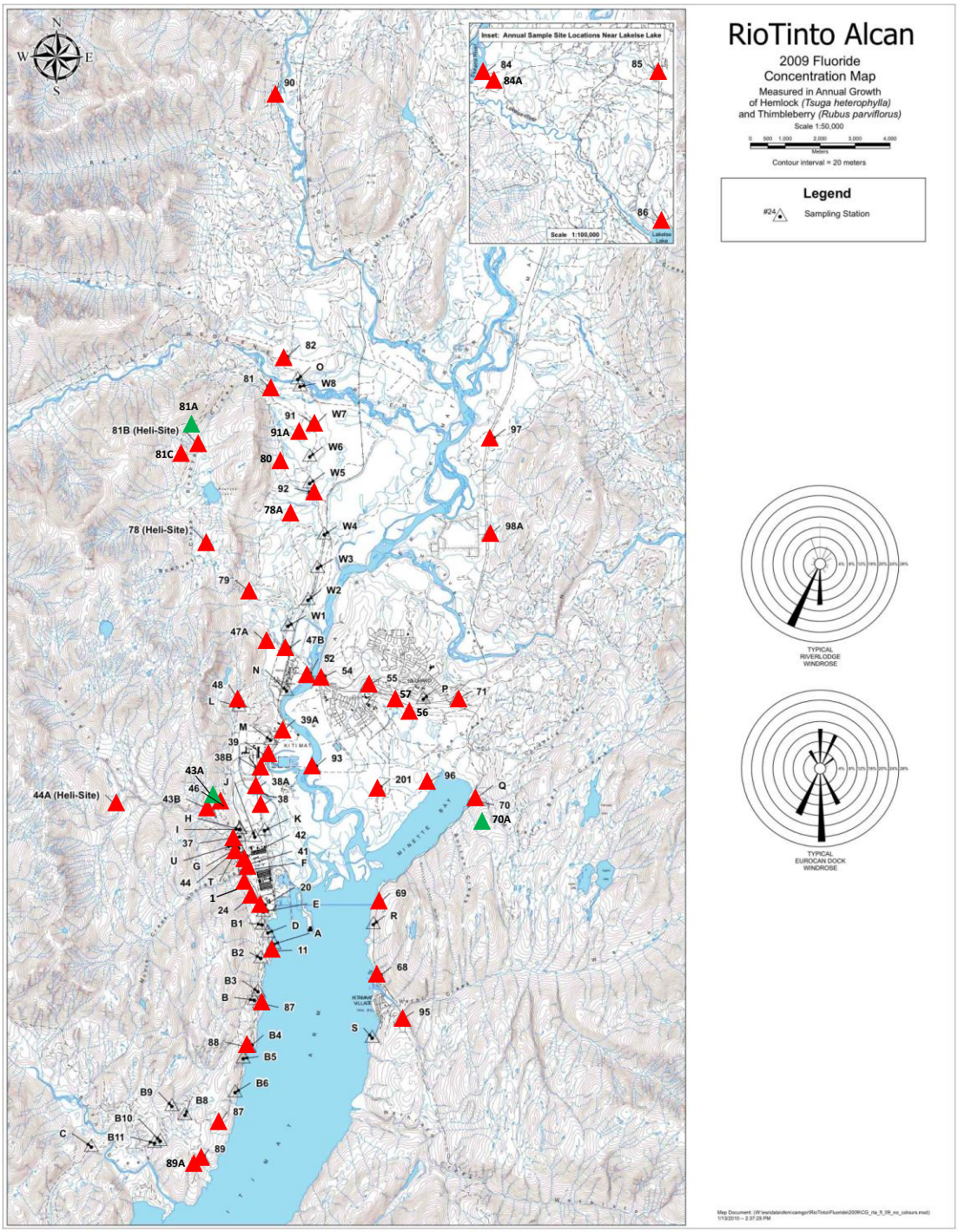


Figure 8.4-1: Vegetation sampling and observation locations. Sites identified with red or green triangles correspond to sampling sites listed in Table 9.2-1. The green triangles denote locations where the designated sampling site could not be accessed, and one nearby was used instead (e.g., site 70A is close to site 70). The sites marked by red triangles are therefore more precisely located on the map than the sites marked by green triangles.

Western hemlock was selected for sampling because it produces a single flush of needles annually, all of the needles are present for most of the growing season and thus receive full exposure to the atmosphere, and it is not so sensitive to any pollutant that needle tissue is killed, and therefore would not absorb pollutants.

In mid-to-late August each year, a sampling crew visits each site and collects needles from tagged trees (so the same trees are sampled each year). The sampled tree and the sample are photographed for archival purposes, and the samples are bagged for transport to the laboratory for processing. Chemical analysis is performed by RTA.

Every other year, a QP accompanies the sampling crew and makes observations on the health and condition of all vegetation at each site. Notes are made concerning any symptoms due to air pollutants, but also due to diseases, insects, nutritional disorders, and environmental stresses, such as drought.

8.4.2 Analysis of field data and modelling

Data for the analysis of the sampling program, including the emissions of S from all processes at the Kitimat smelter and the results of S analysis in vegetation, were provided by RTA. Average annual and growing season (April-September) emissions in tonnes/day were calculated from monthly emissions measurements. Descriptive statistics were calculated to characterize the S in hemlock foliage measurements at each of 67 sampling sites (displayed in Figure 8.4-1). Due to accessibility and adaptation of the monitoring program, not all sites have been sampled each year, so the number of observations varies from year to year and site to site.

We calculated coefficients of correlation to determine the relationship between emissions of S and S concentration in vegetation. Additionally, we constructed scatter plots to explore the relationship between S concentration in foliage and distance from the RTA Kitimat smelter along transects that were established in 2010 using, for the most part, existing sampling sites. A reasonable hypothesis might be that S in foliage would decrease with distance from the RTA Kitimat smelter, assuming that soil conditions and S availability remain constant.

In addition to the analysis of historical data, we analysed output from CALPUFF dispersion modelling, using model results from the 2006, 2008, and 2009 meteorological years. We calculated the frequency of exposures and the number of receptors where concentrations exceeded thresholds of concern (see Section 8.4.3). Similar calculations were made for the same years, but with the current facility in operation (i.e., pre-KMP conditions). All output and summaries were supplied by Trinity Consultants. Since plants are dormant during the winter, the analysis separated exposures occurring during the growing season from those during the course of the entire year. The growing season is defined as the period from April 15 to September 15.

8.4.3 Thresholds of concern

To relate the results of dispersion modelling to potential effects on vegetation, we established thresholds of concern based on the Canadian Objective and Guideline (NAAQ O&G) (Source: http://www.hc-sc.gc.ca/ewh-semt/air/out-ext/reg-eng.php) and the U.S. EPA Secondary National Ambient Air Quality Standard (SNAAQS) (Source: http://www.epa.gov/air/criteria.html). To provide a conservative estimate, an additional threshold of one-half the U.S. standard was also included to provide an intermediate exposure level that falls in line with the Canadian Objectives and Guidelines. Based on the available literature and the review of the SNAAQS in 2008, that threshold is quite conservative with respect to direct effects of SO_2 on vegetation. The resulting thresholds are presented in Table 8.4-1. The International Cooperative Programme on Modelling and Mapping of Critial Loads (WHO Standard) lists Critical Levels (annual averages) of SO_2 for cyanobacterial lichens of 10 µg/m^3 and for forested ecosystems of 20 µg/m^3 (Source: http://www.unece.org/env/lrtap/workinggroups/wge/mapping.html). We chose to conduct our analysis based on the North American governmental standards, objectives, and guidelines since they take into account the climate of appropriate ecosystems. For instance, northern North America has a well-defined dormant period for vegetation whereas many European countries experience climates that favor active metabolism of plants in the winter.

Table 8.4-1: SO_2 thresholds of concern based on the Canadian Objective and Guideline and the U.S. EPA Secondary National Ambient Air Quality Standard. The 1-hour NAAQ maximum desirable and maximum acceptable levels (491 and 873 µg/m^3, respectively) are very similar to the 1-hour B.C. Ministry of Environment minimum and maximum Pollution Control Objectives in Table 7.6-10 (450 and 900 µg/m^3).

Concentration	Averaging Period
163 µg/m^3	24 hr NAAQ O&G maximum desirable level
329 µg/m^3	24 hr NAAQ O&G maximum acceptable level
491 µg/m^3	1 hr NAAQ O&G maximum desirable level
873 µg/m^3	1 hr NAAQ O&G maximum acceptable level
1307 µg/m^3	3 hr SNAAQS
653 µg/m^3	½ of the 3 hr SNAAQS

We calculated the numbers of times that exposures exceeded the thresholds, and the maximum concentrations projected by the CALPUFF model.

8.4.4 Risk assessment framework

As described in Section 8.1, the effects on each receptor are classified according to a framework which outlines both the likelihood of an impact, and its consequences. For vegetation, these likelihood and consequence dimensions of the risk assessment framework are defined in Table 8.4-2 and Table 8.4-3 (respectively). Lichens are not included in this framework since the sensitivity of lichens species in the area to SO_2 is unknown. Table 8.4-4 illustrates the resulting impact categories when these two factors are combined.

Table 8.4-2: Likelihood levels used in the risk assessment framework for vegetation.

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 or more 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 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

Table 8.4-3: Consequence levels used in the risk assessment framework for vegetation.

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 KMP	Symptoms of SO_2 injury extending beyond immediate vicinity of KMP Chronic symptoms (chlorosis/necrosis) indicating potential growth effects	Severe & repeated symptoms of SO_2 injury on more than the most sensitive species, including species of economic or social importance Symptoms of 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 8.4-4: Impact categories from the combined likelihood and consequence dimensions of the risk assessment framework for vegetation. The low, moderate, high and critical levels of impact are defined in the overall description of the risk assessment framework (Section 8.1).

Likelihood (see definitions in Table 8.4-2)	**Consequence** (see definitions in Table 8.4-3)				
	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**

8.5 SOILS STUDY

8.5.1 Terrestrial critical loads

The critical load (CL) of acidity (sulphur (S) + nitrogen (N)) is the maximum load of acidic deposition that an ecosystem can receive during the long-term without damage to specified sensitive biological components (Nilsson and Grennfelt 1988). For terrestrial ecosystems, critical loads are usually estimated using the Simple Mass Balance (SMB) model (Sverdrup and De Vries 1994). This is a steady state model and as such does not provide an estimate of when adverse biological effects may occur or whether impacts (i.e., soil acidification) have already occurred. The critical load for acidity is dependent upon a number of factors, but base cation weathering rate is considered to be the single most important factor for critical load estimates (Skeffington 2006; Li and McNulty 2007; Klaminder et al. 2011). Therefore, estimating base cation weathering rates using representative mineral soil samples collected for forested regions distributed within the entire study region (area of Kitimat Valley with modelled S deposition) was a key component of this work.

Critical loads also depend upon the ecological receptor; trees are the common receptor for terrestrial ecosystems and the critical limit is usually based on a base cation:aluminum (Al) ratio in soil solution that will not adversely impact tree health (damage roots; *see* Sverdrup and Warfvinge 1993; Cronan and Grigal 1995). The SMB has been widely applied in Europe (e.g., De Vries and Reinds 1994; Hettelingh et al. 2007; Lorenz et al. 2008), the United States (U.S.; e.g., McNulty et al. 2007; McDonnel et al. 2010) and in Canada (e.g., Arp et al. 1996; Foster et al. 2001; Ouimet et al. 2001; Whitfield et al. 2010, 2011) to assess the regional impact of acidic deposition, and serve as a valuable tool in the development of emissions management policies (Environment Canada 1998).

Depending on the study objective, critical loads may be calculated for specific sites or large regions (provinces, countries). In the case of regional applications, critical load estimates based on soil plot measurements are generally related to broader landscape features such as soil parent material (as indicated by bedrock or surficial geology), which then allow regional maps to be generated. When acidic deposition is greater than the critical load, the site or region is considered to be *exceeded*, i.e., the level of acidic deposition has the potential to cause adverse biological effects. For example, in eastern Canada, the SMB was applied to the eastern Provinces (Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland) and approximately half the forest area was estimated to receive acidic deposition in excess of the critical load (Ouimet et al. 2006).

In the Georgia Basin, British Columbia, Mongeon et al. (2010) calculated the critical load for 19 sites and estimated that up to nine sites received acidic deposition in excess of their critical load. Estimates of critical load and exceedance are therefore influenced by the sensitivity of the receptor and the magnitude of acidic deposition. The objective of this study was to

determine the maximum level of S deposition that would not lead to unacceptable acidification in forest ecosystems on mineral soil in the Kitimat Valley. The associated field and laboratory analysis focused on providing data to estimate base cation weathering; and the field survey design focused on sampling soils representative of the region.

The Simple Mass Balance Model. The SMB model represents sources and sinks of acidity for forest soils (Sverdrup and De Vries 1994):

$$CL\ (S + N) = BC_{dep} - Cl_{dep} + BC_w - Bc_u + N_i + N_u + N_{de} - ANC_{le(crit)} \qquad \{8.5\text{-}1\}$$

where:

- BC refers to base cations (BC = Bc + Na^+ (sodium), Bc = Ca^{2+} (calcium) + Mg^{2+} (magnesium) + K^+ (potassium));
- the subscripts dep, w, u, i, de and le refer to deposition, weathering, uptake, immobilisation, denitrification and leaching, respectively;
- Cl = chloride;
- N = Nitrogen; and
- $ANC_{le(crit)}$ is the critical (or acceptable) leaching of ANC (Acid Neutralizing Capacity), defined as:

$$ANC_{le(crit)} = -Q^{\frac{2}{3}} \cdot \left(1.5 \cdot \left(\frac{Bc_w + Bc_{dep} - Bc_u}{(Bc:Al)_{crit} \cdot K_{gibb}} \right) \right)^{\frac{1}{3}} - 1.5 \cdot \left(\frac{Bc_w + Bc_{dep} - Bc_u}{(Bc:Al)_{crit}} \right) \qquad \{8.5\text{-}2\}$$

where Q is the annual water flux through the soil at the bottom of the rooting zone (soil percolation), and $(Bc:Al)_{crit}$ is the chemical criterion associated with ecosystem damage. The gibbsite equilibrium constant (K_{gibb}) is used to describe the relationship between Al^{3+} and H^+ ions in soil solution; in the current study a regional default value of log K_{gibb} = 8.5 was used.

Removal of base cations by forest harvesting. Forest harvesting results in a net removal of base cations (e.g., K^+, Ca^{2+}, Mg^{2+}) from the soil (Bc_u in equation {8.5-1}). As trees grow, they take up base cations, incorporating them into their biomass. When the trees are harvested, a portion of that biomass is removed from the landscape, resulting in a net export of base cations. In order to estimate the long-term, average, annual flux of base cations per hectare out of the study landscape, we estimated: (1) the amount of biomass that would be harvested; and (2) the concentration of cations within that biomass. As stated previously, because a steady state mass balance model was applied, the impacts of past harvesting activities were not taken into account. However past harvesting activities will have no impact on the steady state critical load; only potential future harvesting activities need to be considered in the calculations.

Our first step in this process was to estimate the long-term, average, annual removal of biomass through harvest from forested mineral soils. The study area represents a complex region because it intersects many different forest tenures (with different management practices and data availability), including two tree farms licenses (TFL 1 and TFL 41), three timber supply areas (TSAs) (Kalum, Pacific and Cascadia), and one community forest (Terrace). Many of these tenures exist in multiple, discrete polygons. Our general approach was to estimate the long-term harvest (biomass removal) within the full extent of each of these areas, then allocate a portion of that harvest to the study area, proportional to the area intersecting the study area. We developed these rough estimates based on the publicly available data and in consultation with a timber supply forester familiar with recent timber evaluations in the Kalum TSA and TFL 41 (representing the majority of the study area) (D. Hubert Burger, B.C. Ministry of Forests, Lands and Natural Resource Operations, pers. comm.). The estimates of the long-term, average, annual harvest levels could not be specified by species or in a spatially explicit manner. We approximated the spatial distribution of harvesting within each polygon by removing areas in which forestry operations would not occur (alpine and other non-forested regions, parks, reserves, agricultural and developed areas). We based our estimates of long-term harvest levels on the long-term estimates of the allowable annual cut (AAC). Over the past decade, actual harvest levels in this region have been approximately 1/3 of AAC, but to be conservative, we have assumed that timber markets will recover such that the long-term harvest levels will once again reflect AAC.

Our second step was to convert our estimates of average, long-term biomass removal into estimates of base cation export based on the nutrient concentrations in the harvested biomass. Nutrient concentrations vary by species (especially between conifer and deciduous trees) and by tree component (i.e., wood, bark, roots, foliage, etc.). It was not possible to generate species-specific estimates of long-term harvesting. However, the Kalum TSA and TFL 41 are approximately 68% and 75-80% western hemlock, respectively, and both consist of only 2% deciduous trees; therefore, we focused our estimates on western hemlock. We assumed that 90% of the harvested biomass is wood, 10% is bark; the rest of the biomass (twigs, branches) is left onsite. Given the general paucity of nutrient concentration data for western hemlock and the variability within the data for other species, we developed a range of estimates (a “best” value for base analyses, and high and low values for sensitivity analyses) for the K^+, Ca^{2+}, and Mg^{2+} concentrations in both wood and bark for western hemlock to apply in our overall estimates of base cation flux. Wherever known, we used actual data for western hemlock for the “best” estimate and data on other B.C. coastal conifers to inform the potential range of values (Moore et al. 2005; CFS 2011).

Estimates of critical loads and exceedance. Post-KMP modelled N deposition is estimated to be very low (average <0.1 kg N /ha/a), significantly less than N sinks (e.g., average removal in forest biomass under allowable annual cut is 0.19 kg N /ha/a); as such, we focused solely on the maximum critical load for S which excludes the acidifying potential of N:

$$CL(S) = BC_{dep} - Cl_{dep} + BC_w - Bc_u - ANC_{le(crit)} \quad \{8.5\text{-}3\}$$

Exceedance was calculated simply as total S deposition minus CL(S).

8.5.2 Design of field monitoring program

There were no soil data suitable to estimate CL(S) for the study area, hence this study involved a comprehensive field soil sampling campaign. In order to produce a regional critical load map, we used the bedrock geology map (scale 1:250 000; Massey et al. 2005) for the Kitimat Valley to stratify the soil sampling design (Figure 8.5-1).

It is important to note that all critical load estimates were based on actual soil observations including measured mineralogy for each bedrock class. The bedrock geology map was used solely to guide the soil sampling campaign because it was the best resolution database available in digital format. While bedrock geology is representative of soil parent material in alpine and till soils (63% of the study domain; Fulton 1996, scale 1:5000 000), it is recognised that in some regions (particularly at the bottom of the Kitimat Valley) surficial geology is disconnected from the underlying bedrock (and hence contains different minerals; Figure 8.5-2). However, regions dominated by alluvial or galciofluvial surficial deposits (26% of the study domain) generally contain a greater proportion of base-rich minerals and have greater base cation weathering rates. Higher resolution surficial geology was mapped by Clague (1983) but the underlying data were not available in georeferenced digital format; nonetheless, all surficial classes were capture by Fulton (1996). Furthermore, even though the soil sampling was stratified by bedrock geology, all surficial geology types (alluvial, glaciomarine and glaciofluvial materials as mapped by Fulton (1996) and Clague (1983)) were captured in the sampling campaign (Figure 8.5-2). Finally, the soil sampling design was based on the inital study domain consistent with the modelled S deposition field generated by CALPUFF. Subsequent to the field campaign, the modelling domain was expanded to the south (i.e., S deposition was estimated for this area) and hence no sampling was conducted in this area (Table 8.5-1). However, this area does not contain any distinct bedrock categories that were not captured in the sampling design.

We only considered undisturbed forest sites on mineral soils (covering ~69% of the study area). In the study domain, 13 bedrock types or categories were identified (Table 8.5-1).

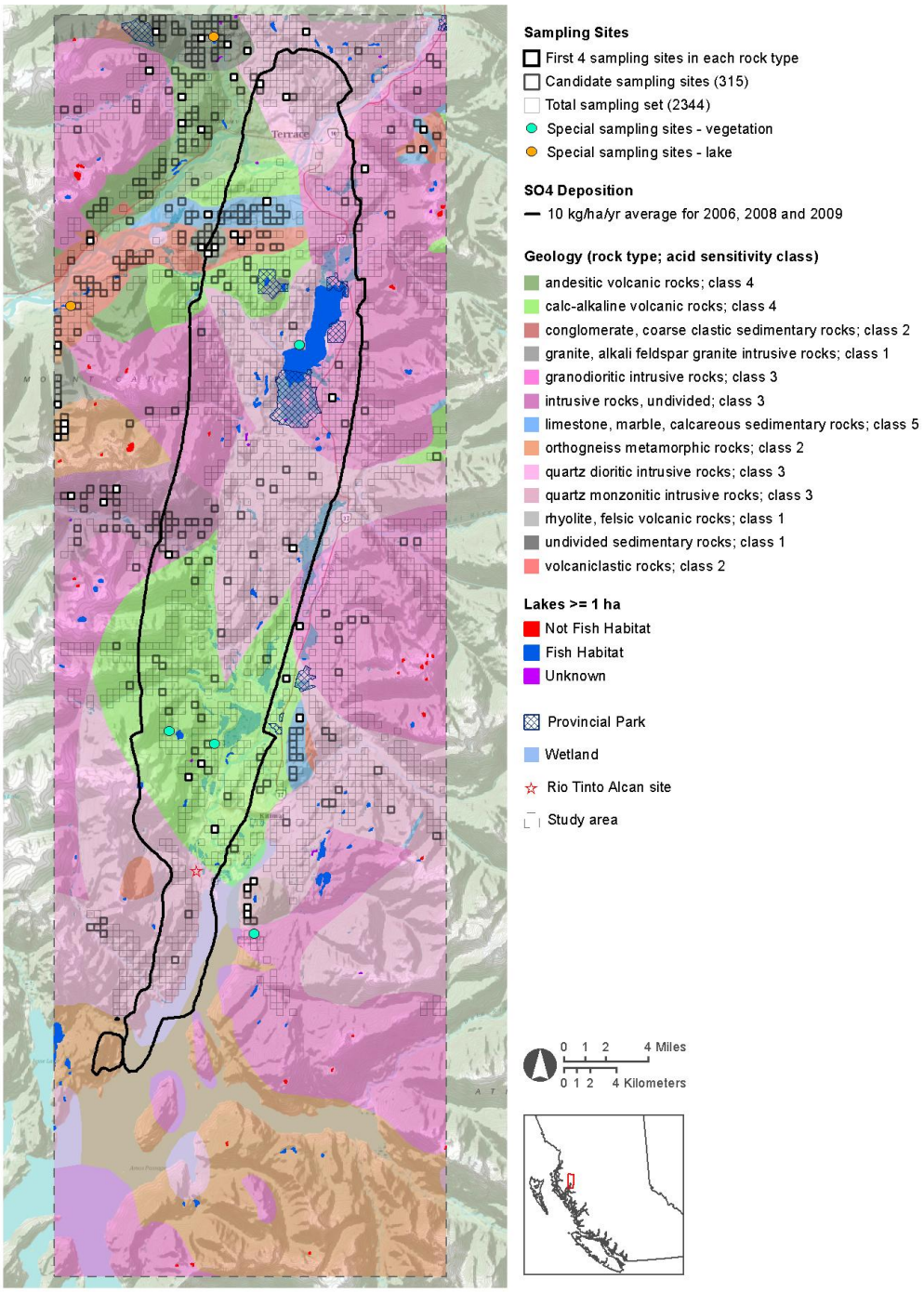


Figure 8.5-1: Location of the candidate (open squares) and sampled (bolded squares) soil sites in the Kitimat Valley (study domain is indicated by dashed line). Bedrock geology (scale 1:250,000; Massey et al. 2005) rock type, and acid sensitivity class (see Section 4.3) are also shown.

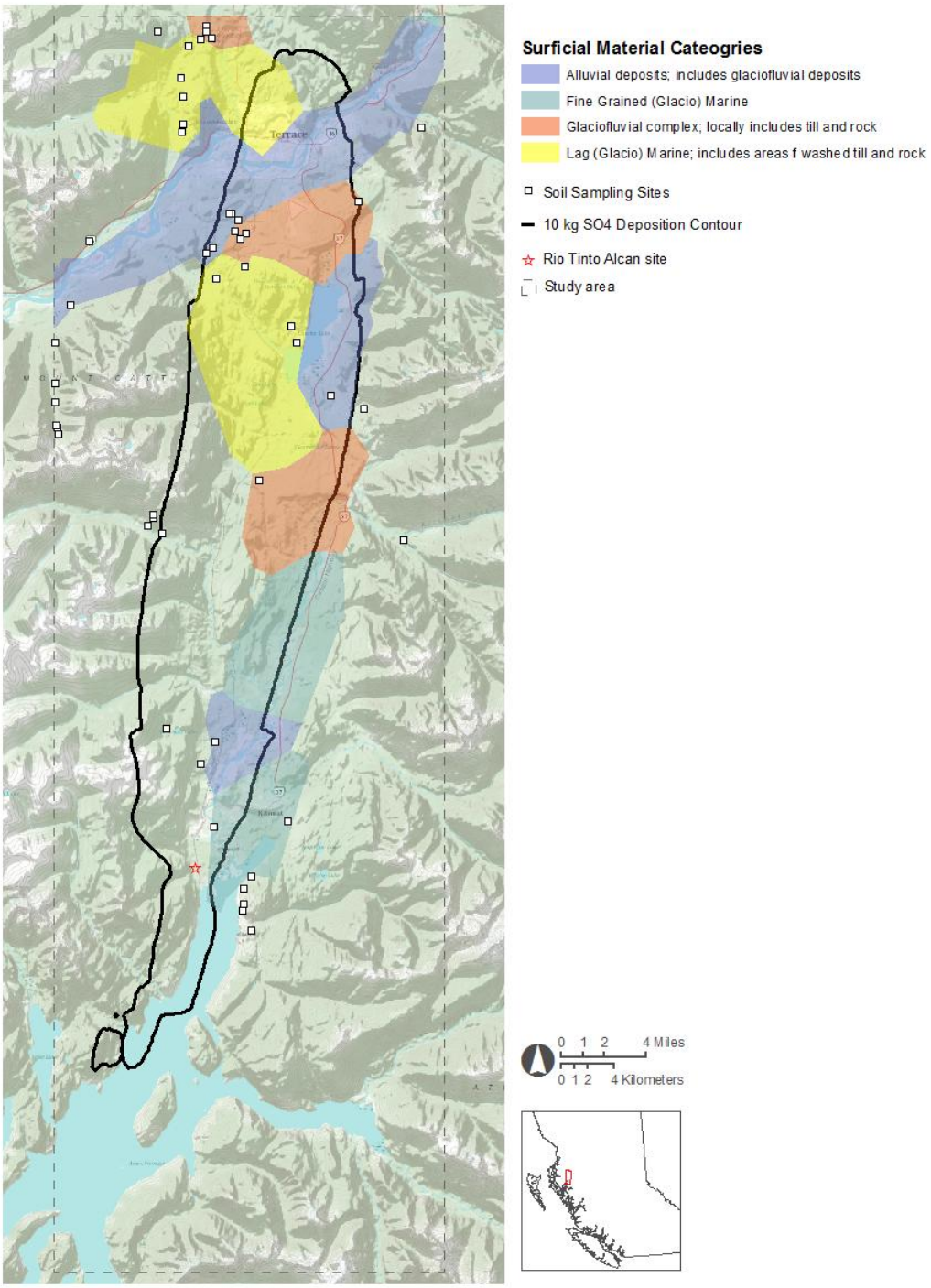


Figure 8.5-2: Location of the sampled soil sites (bold squares) in the Kitimat Valley. Surficial geology (scale 1:5 000 000; Fulton 1996) is also shown. Note: alpine complexes and till surficial materials cover remaining study area.

Sampling design

We delineated the study region into 500 m x 500 m grids consistent with the modelled deposition field generated by CALPUFF. Our objective was to sample soils at ~50 sites (minimum of four per geological bedrock type) representative of the range of soil characteristics in the study area (Figure 8.5-1). Three bedrock types (calc-alkaline volcanic rocks, granodioritic intrusive rocks and quartz dioritic intrusive rocks) accounted for 72% of the study area (in contrast, two surficial materials, alpine complexes and till veneer, accounted for ~63% of the study area). We identified candidate sampling cells (500 m x 500 m) within each bedrock type. Potential sampling cells were excluded if they:

1. were along the boundary of two rock types (to ensure sampling the correct rock type);
2. were further than 250 m from a road;
3. contained more than 50% coverage of areas that could not be sampled, defined as:
    a. within 50 m of a road;
    b. on urban land cover type or within 50 m of urban areas;
    c. on lakes, or within 50 m of a lake;
    d. on rivers, or within 50 m of a major river;
    e. within a provincial park;
    f. with a slope >45 degrees (for safety reasons);
    g. within a wetland.
4. the centre of the cell had a site coordinate that could not be sampled based on #3.

As two of the bedrock types (conglomerate, coarse clastic sedimentary rocks; and rhyolite, felsicvolcanic rocks) accounted for less than 1% of the study area (Table 8.5-1), were generally inaccessible and within areas with low modelled S deposition, we excluded these bedrock types from the field sampling.

For the remaining 11 bedrock types, a maximum of 30 potential candidate sampling cells per bedrock type were randomly selected. Sampling sites within each bedrock type were chosen sequentially from this list. If a site was not accessible (based on local knowledge or site visit) the sampling team moved on to the next site until four sites per bedrock type were sampled (44 sites in total). An additional two sites were selected to be co-located with lakes and four sites were selected to be co-located with vegetation monitoring sites (early warning sites) such that 50 sites were selected to be sampled (one additional site was sampled, n = 51; Figure 8.5-1).

Table 8.5-1: Aerial coverage of the 13 distinct bedrock geologies in the initial study area, Kitimat Valley, used for site selection.

	Rock Type/Category	Bedrock category		Road accessible	Inaccessible
		area (ha)	% total area	area (ha)	area (ha)
VA	andesitic volcanic rocks	9,917	4	7,102	2,815
CA	calc-alkaline volcanic rocks	32,113	14	22,967	9,147
N/A	conglomerate, coarse clastic sedimentary rocks	335	0	0	335
GR	granite, alkali feldspar granite intrusive rocks	1,830	1	956	874
GD	granodioritic intrusive rocks	81,680	36	35,325	46,356
GO	intrusive rocks, undivided	7,325	3	4,048	3,277
LM	limestone, marble, calcareous sedimentary rocks	3,939	2	3,373	565
OG	orthogneiss metamorphic rocks	5,819	3	490	5,330
QD	quartz dioritic intrusive rocks	72,385	32	40,650	31,734
QM	quartz monzonitic intrusive rocks	1,542	1	584	958
N/A	rhyolite, felsicvolcanic rocks	476	0	57	420
S0	undivided sedimentary rocks	3,960	2	2,933	1,027
VC	volcaniclastic rocks	8,174	4	6,562	1,612

Field Sampling

Field sampling was conducted during June to July 2012 by Cambria Gordon Consultants following training by Dr. Shaun Watmough (Trent University); the field sampling protocol is given in Appendix 8.5-1. At each sampling location, a representative area was located within and close to the centre of the sampling grid (500 m x 500 m). At each location, we recorded the site number, co-ordinates, elevation, aspect, slope, as well as a general description of the site (e.g., forest type, rooting depth, etc; Appendix 8.5-2), and took photographs documenting the appearances of the site. Field sheets, photographs and soil samples were sent to Trent University for further analysis.

We established a 10 m by 10 m quadrate at each sampling site, took soil samples from the four corners and centre point using a soil auger, and composited the samples to obtain a representative sample. At each sampling location, we collected soil samples (approximately 150 g per depth) from three fixed depths (0 to 10 cm, 15 to 25 cm, and 40 to 50 cm) representing A, upper and lower B horizons, and placed the samples into a labelled plastic bag. At one location (the centre pit), a small quadrate (400 cm^2) was used to collect the LFH (litter-fibric-humic) layer; additionally, the average depth of the LFH layer was recorded at all five sampling points per site. In addition to the composite samples, we collected a single fixed-volume bulk density core sample for each soil depth from the centre point. All soil samples (composite (n = 153), LFH (n = 51) and bulk density cores (n = 153)) were received at Trent University by the end of July 2012.

8.5.3 Laboratory analysis of soil samples and critical load modelling

We analysed all composite soils (3 depths per site) for pH, loss-on-ignition (LOI) and particle size (sand, silt and clay). Field soil moisture content (during sampling) and bulk density were determined on the fixed-volume core samples from the centre pit for each site. We also tested a weighted-average sample for each site (composite of all depths) for total oxide content, and a weighted-average composite sample of the 4 to 6 sites per bedrock type for qualitative mineralogy and surface area. Prior to analysis, all samples were air dried and sieved to 2 mm, the weight and volume of the >2 mm coarse fraction were recorded for the fixed-volume core samples, and samples for oxide and qualitative mineralogy were further pulverized to ~ 100 µm.

Soil pH: Five grams of oven-dried (105^{o}C) soil were mixed with 20 mL Milli-Q water and stirred every two minutes for 20 minutes. Each sample was left to stand for a further 40 minutes before pH was recorded using a glass-probe pH electrode. This procedure was repeated with 0.01 M calcium chloride ($CaCl_2$).

Loss-on-ignition (LOI): Approximately 1 g of oven-dried soil was weighed into a crucible and placed in a muffle furnace at 400^{o}C for 12 hours. Repeat (duplicate samples) were run every 10 samples. Loss-on-ignition (measure of organic matter content) was calculated as:

$$LOI = \left(\frac{initial\ \ weight - final\ \ weight}{initial\ \ weight} \right).100 \qquad \{8.5\text{-}4\}$$

Soil moisture content: Each fixed-volume bulk density core sample was weighed, oven-dried at 105°C for 24 hours and then reweighed. Moisture content was based on the difference in sample weight.

Bulk density: Bulk density (mass per unit volume) was estimated after adjusting for coarse content. Mineral sample bulk density was calculated by adjusting for organic matter content.

Particle size analysis: The distribution of particles in sand, silt and clay size classes (<2 µm, 2 to 60 µm, and 0.06 to 2 mm) was measured in triplicate by laser ablation (Horbia Partica LA-950) and averaged for each soil depth sample.

Surface area: Specific surface area of mineral soil was estimated using BET analysis which is based on the physical adsorption of gas molecules on a solid surface. Surface area was estimated on composite samples from each bedrock category. Two grams of sample were weighed into a glass vial, degassed for 24 hrs, and analysed using a Gemini VII surface area analyser.

Oxide content: A mass-weighted composite soil sample (3 g) for each site was pulverized and sent to Analytical Sciences Laboratory, Western University, Ontario for total oxide analysis (on a PANalytical PW-2400 X-ray Flourescence Spectrometer).

Mineralogy: A mass-weighted composite soil sample (3 g) representing each bedrock geology type was pulverized and sent to Earth and Ocean Sciences, University of British Columbia for Mineralogy analysis (X-ray Diffraction: Siemens (Bruker) D5000 Bragg-Brentano diffractometer).

Weathering Rate Estimation

Mineral weathering rates were estimated for each soil sampling site and bedrock type in the study area using the PROFILE model (Sverdrup and Warfvinge 1988; Warfvinge and Sverdrup 1992) and Analysis to Mineralogy (A2M) solver (Posch and Kurz 2007) as outlined in Figure 8.5-3.

PROFILE: PROFILE (Version 5.1*)* is a steady-state soil chemistry model that includes a weathering sub-model describing the release of alkalinity and base cations via mineral breakdown (Sverdrup and Warfvinge 1988; Warfvinge and Sverdrup 1992). The combination of minerals of different weathering classes and reactive surface area are considered the primary determinants of soil weathering (Brahy et al. 2000; Malmström et al. 2000) and shown to be the most important inputs in determining weathering rate in PROFILE (Jönsson et al. 1995).

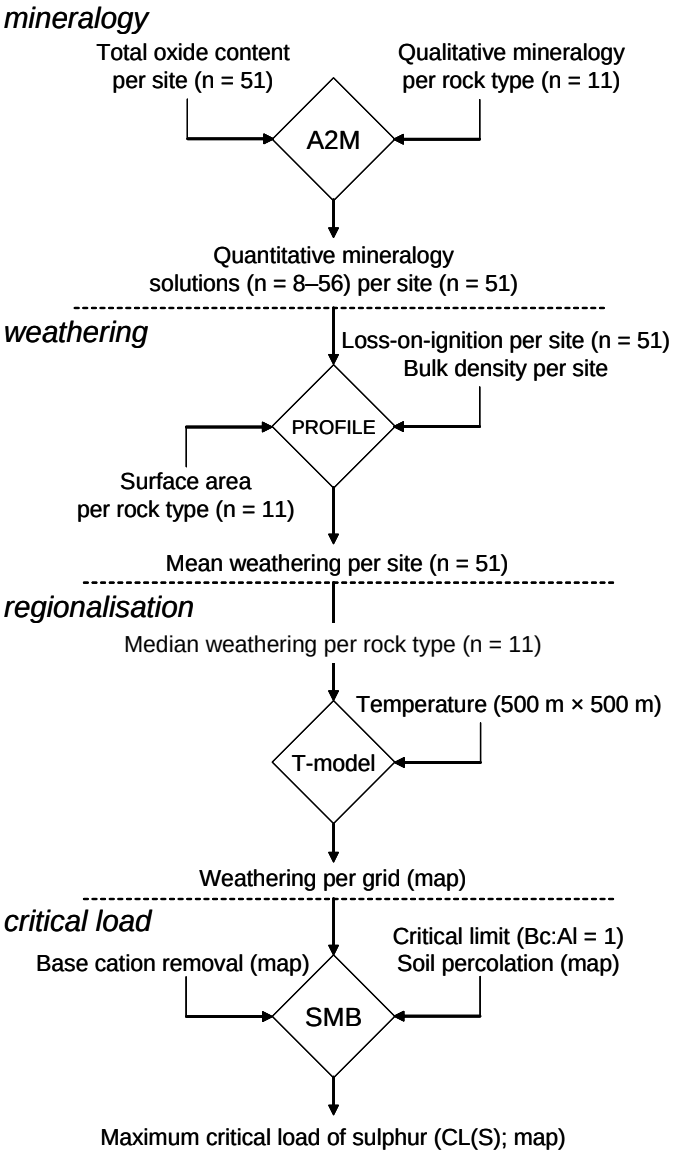


Figure 8.5-3: Schematic representation of the model chain used to estimate base cation weathering rates and critical loads for forested mineral soils in the study area. The four steps were: estimating quantitative mineralogy using A2M; combining these data with site specific observations to estimate weathering rates using PROFILE; estimating the median weathering per rock type using downscaled temperatures for each 500 m × 500 m grid across the region (T-model); and estimating critical loads using the SMB model for each receptor grid cell (n = 10,545) in the study area.

Analysis to Mineralogy is a matrix-based model that estimates relative mineral content of soils based on total chemical analysis (total oxide content) and all molecular formulations for a defined set of minerals. The model is best suited for soils where the number of minerals is greater than the number of element oxides associated with these minerals (Posch and Kurz

2007). In this study, the measured qualitative mineralogy for each bedrock category (based on soil measurements) and the oxide content of each site within a bedrock category were used in A2M to calculate the possible quantitative mineral combinations for each site. This was repeated for all 51 sites.

We estimated base cation weathering rates (eq/m^3/a) for each soil pit (n = 51) located within the 11 bedrock categories using the range of possible quantitative mineralogy values obtained from A2M (see Appendix 9.3-1). A soil depth of 0.5 m was chosen as roots were generally not observed below this depth. Default values for soil carbon dioxide partial pressure (15 × atm, Bouten et al. 1984), dissolved organic carbon (7 mg/L, Findeis et al. 1993), log gibbsite dissolution constant (8.5, Umwelt Bundes Amt 2004) and order of the gibbsite dissolution reaction (3, Umwelt Bundes Amt 2004) were set based on literature values and previous model applications in North America. The influence of different log gibbsite dissolution constants on critical load exceedance was also evaluated, and did not affect exceedance area. The average base cation weathering rate for each bedrock category (based on 4 to 6 sites) was modified for each 500 m x 500 m grid cell using the long-term average temperature (Spittlehouse 2006) to estimate weathering rates for the entire study region.

8.5.4 Thresholds of concern

The most widely used threshold to connect soil chemical status and plant response is via a critical molar base cation to aluminum ratio (Bc:Al). Here, Na^+ is excluded, since it provides no protection against Al^{3+} for plants. We chose a soil solution critical Bc:Al value of 1.0 within the top 50 cm (the principal rooting zone) to be conservatively protective of the dominant tree species (Western Hemlock) in the region (Sverdrup and Warfinge 1993).

Critical Load Calculations and Input Data

In addition to BC_w (base cation weathering) several other input parameters are required to estimate CL (S) using the simple mass balance model (SMB; equation {8.5-3}).

Base cation and chloride deposition (BC_{dep}, Cl_{dep}) were not regionally available for the study area. Consequently we took a conservative approach and assumed that both non-marine BC_{dep} and Cl_{dep} were zero.

Base cation uptake (Bc_u) values were obtained for each forested grid cell using a combination of estimated timber removals (AAC) and literature values for wood (Western hemlock) base cation (Ca^{2+}, Mg^{2+} and K^+) concentrations.

Long-term runoff (Q; based on 1960 to 1990 climate normals) for each grid cell in the region was obtained following a special application of the model published by Moore et al. (2012), as described in Section 8.6.3.4.

8.5.5 Risk assessment framework

As described in Section 8.1, the effects on each receptor are classified according to a framework which outlines both the likelihood of an impact, and its consequences. For soils, these likelihood and consequence dimensions of the risk assessment framework are defined in Table 8.5-2 and Table 8.5-3 (respectively). Table 8.5-4 illustrates the resulting impact categories when these two factors are combined.

Table 8.5-2: Likelihood levels used in the risk assessment framework for soils. Each category indicates the likelihood of exceeding a critical load (CL).

A – Almost Certain	B – Likely	C – Possible	D – Unlikely	E – Very Unlikely
Predicted deposition ≥10 meq/m^2/yr **above CL**	Predicted deposition 0 to 10 meq/m^2/yr **above CL**	Predicted deposition 0 to 10 meq/m^2/yr **below CL**	Predicted deposition 10 to 20 meq/m^2/yr **below CL**	Predicted deposition more than 20 meq/m2/yr **below CL**

Table 8.5-3: Consequence levels used in the risk assessment framework for soils.

1 - Minor	2 - Medium	3 - Serious	4 - Major	5 - Catastrophic
<5% of mapped area	**5-10%** of mapped area	**>10-15%** of mapped area	**>15-25%** of mapped area	**>25%** of mapped area

Table 8.5-4: Impact categories from the combined likelihood and consequence dimensions of the soils risk assessment framework. The low, moderate, high and critical levels of impact are defined in the overall description of the risk assessment framework (Section 8.1).

Likelihood (see definitions in Table 8.5-2)	**Consequence** (see definitions in Table 8.5-3)				
	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**	**Moderate**	**High**	**Critical**
D – Unlikely	**Low**	**Low**	**Moderate**	**Moderate**	**Moderate**
E – Very Unlikely	**Low**	**Low**	**Moderate**	**Moderate**	**Moderate**

8.6 SURFACE WATER STUDY (LAKES AND STREAMS)

8.6.1 Design of field sampling and measurements

Under KMP, an area of 710 km^2 north and south of the Kitimat smelter would potentially receive total deposition of sulphur (i.e., dry plus wet deposition) at rates ≥10 kg/ha/yr as SO_4 (Figure 8.6-1). The 710 km^2 area within the 10 kg/ha/yr isopleth of total deposition shown in Figure 8.6-1 is an average value from modelling plume distribution using KMP modelled emissions, as described in Sections 7.5 and 7.6. Modelled distribution of sulphur deposition was broadest for 2008 meteorological conditions (i.e., greater dispersion of the plume, and lower peak concentrations).

Most of the water sampling was focused within the area of 10 kg/ha/yr or more of total sulphate deposition. The specific criteria used to include or exclude lakes in the sampling are outlined below. The 10 kg/ha/yr isopleth of total S deposition as SO_4 is a useful threshold for focused sampling because analyses that we completed of U.S. data in Baker et al. (1991a) show that virtually no acidic lakes and streams (ANC <0) are found where wet SO_4 deposition is less than 10 kg/ha/yr (Figure 8.6-2), and the bedrock geology of the Kitimat Valley is generally less acid-sensitive than many of the areas studied by Baker et al. (see Section 4.3).

Using 10 kg/ha/yr of *total* sulphate deposition as a criterion in the Kitimat valley offers an additional safety margin over 10 kg/ha/yr of *wet* deposition, because wet deposition is always less than total deposition. For example, Trinity Consultants has estimated that wet deposition averaged about 44 % of total deposition across all modelled sites in the study area over the 3 years of 2006, 2008 and 2009.[20] Using the average of 44 %, 10 kg/ha/yr of *total* sulphate deposition would correspond to 4.4 kg/ha/yr of wet deposition, which is the level of deposition observed in western regions of the United States, an area with virtually no acidic lakes (see green oval at bottom left of Figure 8.6-2). Areas with less than 10 kg/ha/yr of *wet* sulphate deposition generally have fewer than 5 % of their lakes with pH <6 (lower left of Figure 8.6-3). The percentages are higher in Figure 8.6-3 (pH <6) than in Figure 8.6-2 (ANC <0), because a pH of 6.0 corresponds to an ANC of about 25 to 40 µeq/L, and therefore encompasses a larger proportion of a region's lakes (i.e., occupies more of the regional frequency distribution of lake ANC).

[20] Anna Henolson, unpublished data, Nov. 2012; wet deposition as a percentage of total deposition ranges from 11 % to 78 % depending on the location.

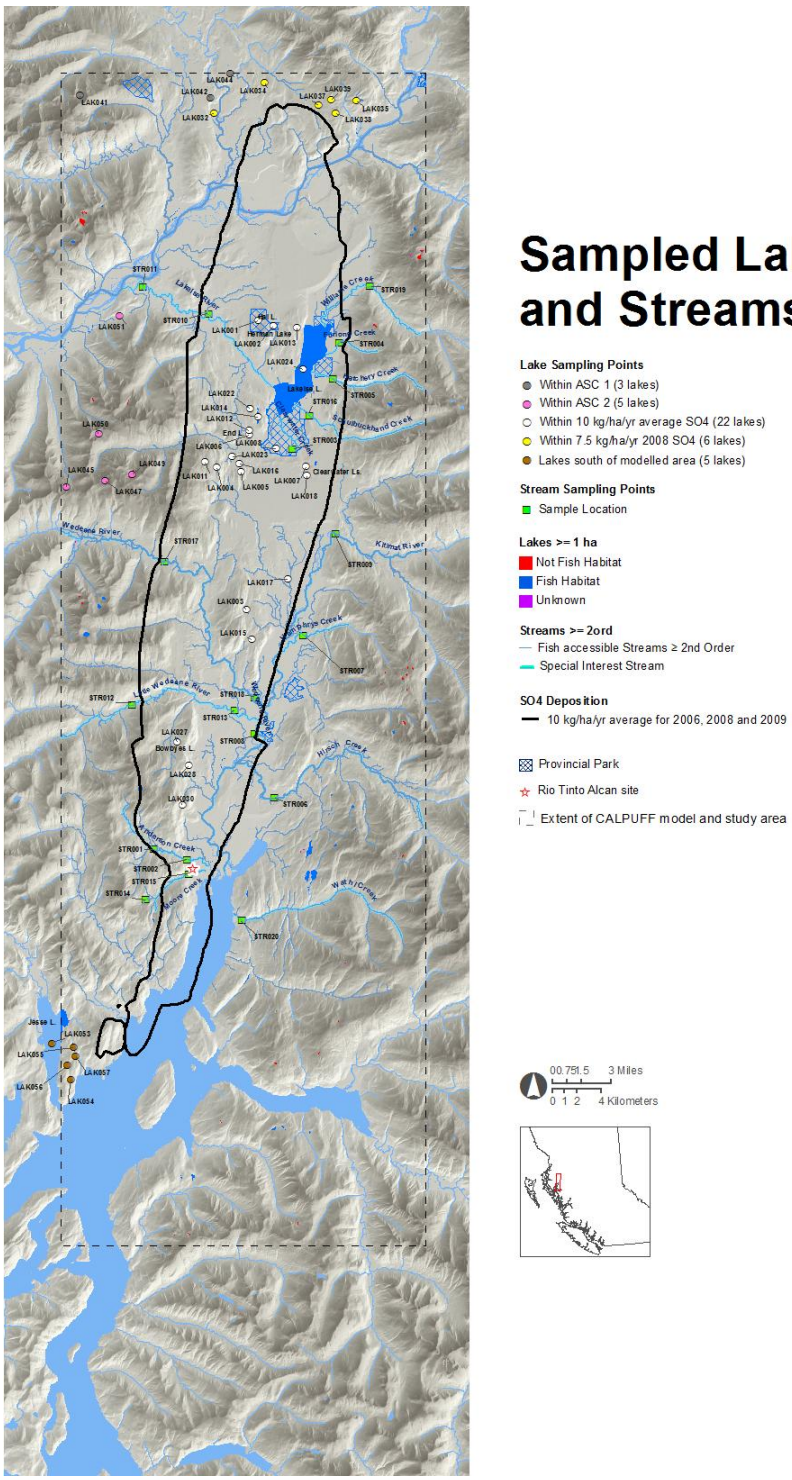


Figure 8.6-1: Study area showing the 10 kg SO_4 /ha/yr isopleth (black line) of total sulphur deposition (wet plus dry) and location of lake and stream sampling sites, with site labels.

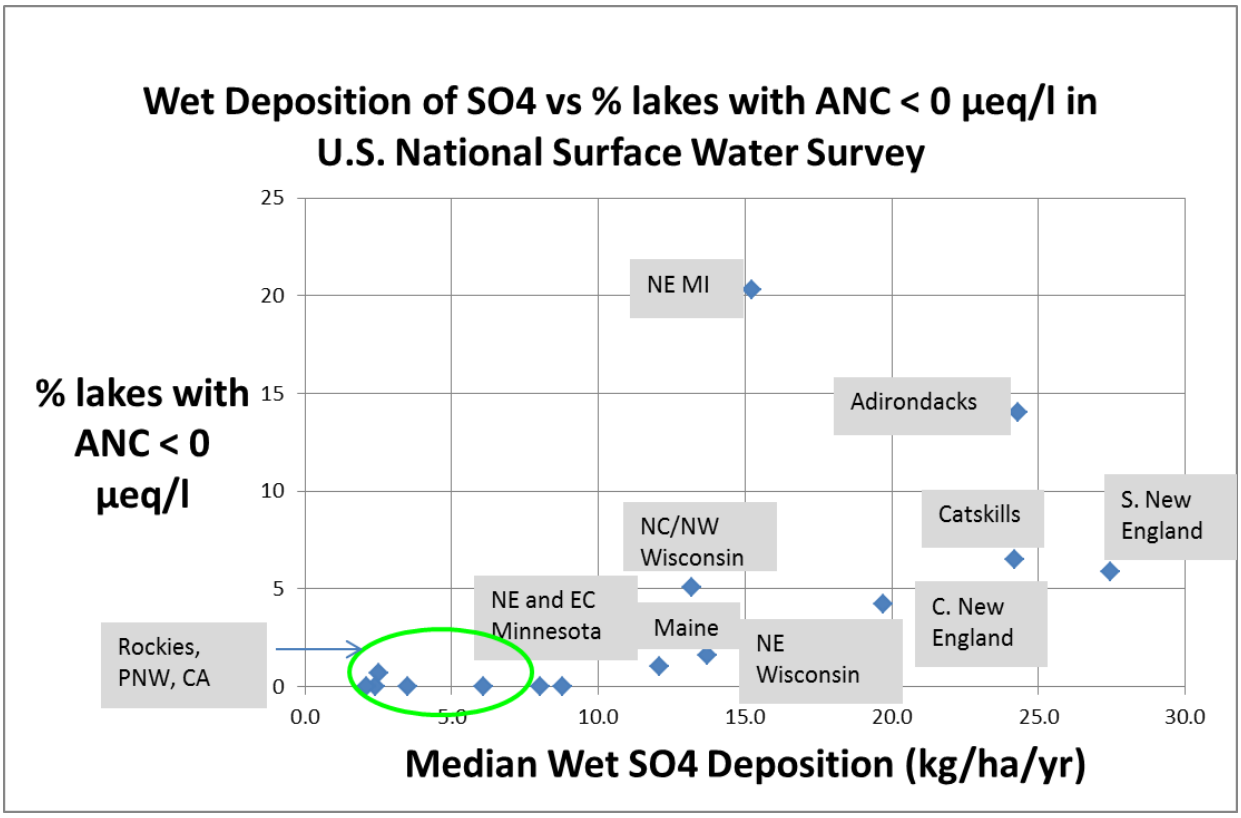


Figure 8.6-2: Percent of acidic lakes (ANC <0 µeq/L) vs. median level of wet deposition of sulphate, for 15 regions of the United States.

Each data point represents the best estimate of the percentage of acidic lakes out of a statistical sample of lakes for each region; most regions had 120-160 sampled lakes (total of 2,058 lakes across all regions). In these representative samples of lakes taken in various regions of the U.S., there are virtually no acidic lakes (ANC <0 µeq/L) in areas with **wet** deposition of SO_4 <10 kg/ha/yr (e.g., green oval showing lakes in the western U.S.). At wet deposition levels >10 kg/ha/yr, the percentage of acidic lakes begins to increase, though varying with the ability of each region's watersheds and lakes to neutralize acidic deposition. Lakes do not only become acidic due to sulphate deposition. Some acidic lakes are dominated by organic acids (e.g., 23.6 % of the acidic lakes in the Upper Midwest region, 8 % of the lakes in the NE region). Source of data: Baker et al. 1991a.

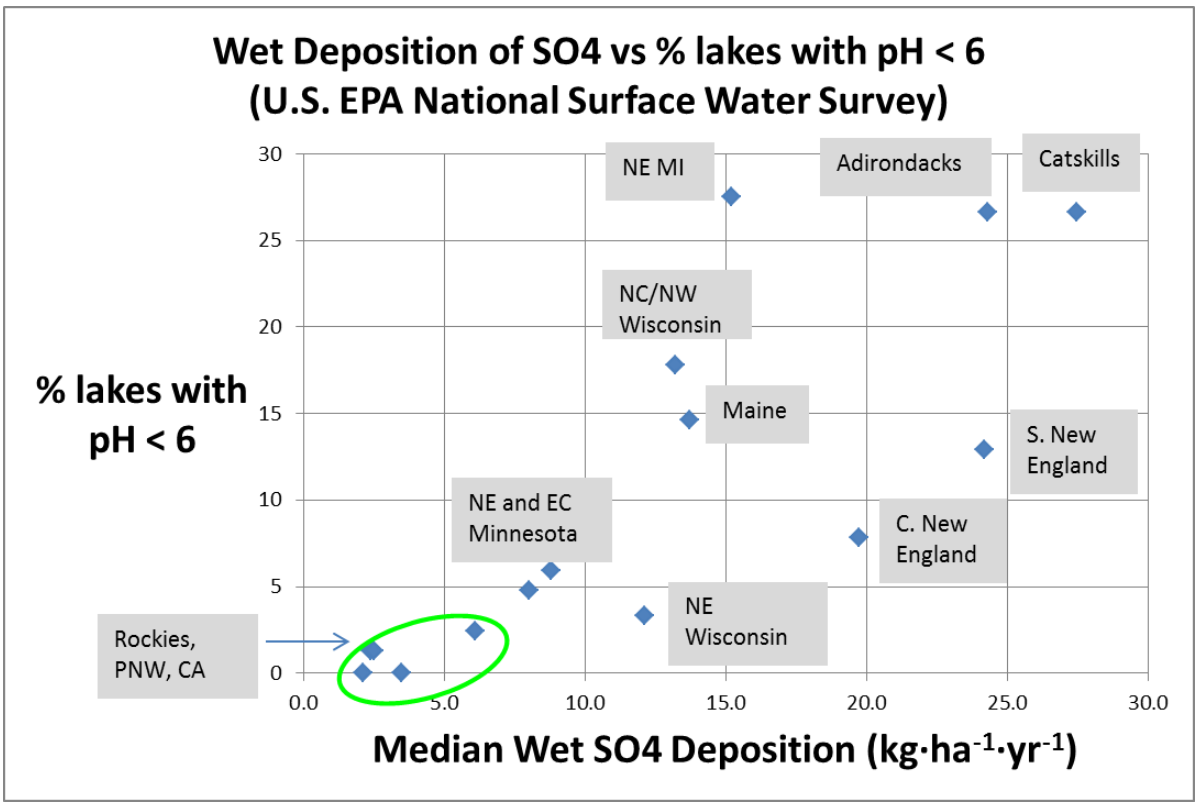


Figure 8.6-3: Percent of lakes with fall pH <6 vs. median level of wet deposition of sulphate, for 15 regions of the United States.

Regions with a median *wet* deposition less than about 8 kg/ha/yr had a fall pH <6 in fewer than 5 % of their lakes (e.g., green oval showing lakes in the western U.S.). Source of data: Baker et al. 1991a (see caption to Figure 8.6-2 for more information on data set).

As discussed in Section 4.3.2, bedrock geology types can be grouped into five acid sensitivity classes (ASC), where ASC 1 is the most sensitive to acidic deposition and ASC 5 the least sensitive (Hornung et al. 1995; J. Aherne, Trent University, July 2012, pers. comm.). As shown on Figure 8.6-4, the sampling design included lakes in the study region within ASC 1 and 2 to the west and north of the isopleth of 10 kg/ha/yr of total sulphate deposition, as these bedrock types potentially contained lakes highly sensitive to acidic deposition. Lakes within the area of ASC 2 in the extreme southeast of the study region were not sampled as total sulphate deposition in this region under KMP is projected to be very low, less than 2 kg/ha/yr. We further discuss this unsampled region after presentation of the results for the sampled region.

The sampling design began with a set of 57 candidate lakes, made up of all 57 lakes greater than 1 ha in area in the study area, distributed across the following four *sampling regions of interest*:

- 31 lakes entirely within the three year average 10 kg SO_4·/ha/yr isopleth of total sulphate deposition;
- nine lakes north of the isopleth that would be potentially exposed to total sulphate deposition of more than 7.5 kg SO_4·/ha/yr based on meteorological conditions in 2008;
- five lakes south of the smelter that potentially receive SO_4 deposition during wind outflows; and
- 12 lakes within ASC class 1 and 2 water bodies that could potentially receive acid deposition from the smelter.

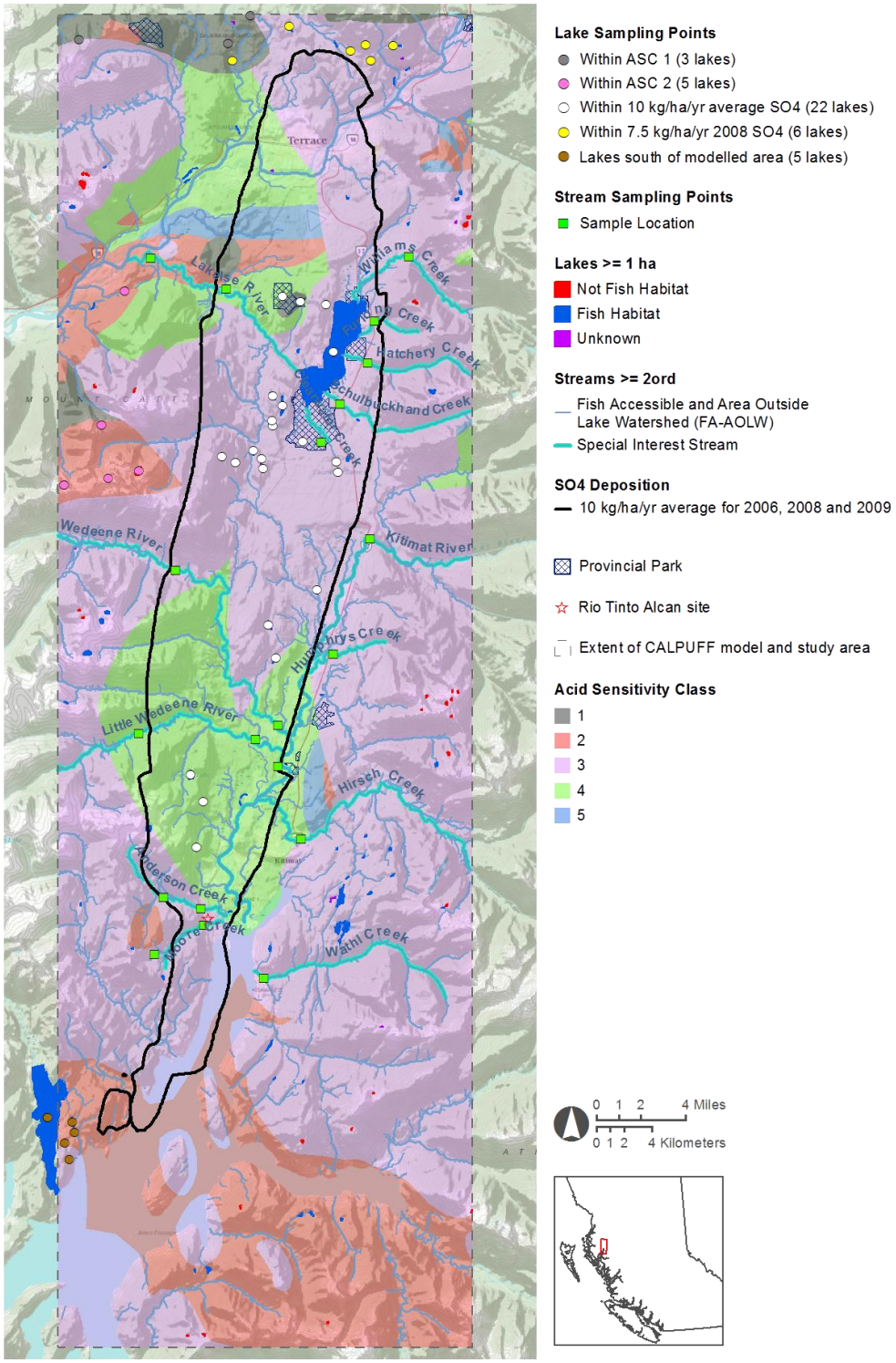


Figure 8.6-4: Overlay of sampling sites and acid sensitivity classes (ASC). Grey and pink points show sampled lakes within ASC 1 and ASC 2, the two most sensitive classes.

Lakes were chosen for this study in preference to streams as has been done in past studies involving calculation of critical load (e.g., Henriksen et al. 2002; Dupont et al. 2005; Strang et al. 2010). Water is retained in lakes for various periods of time, which results in temporally integrated chemistry that is less influenced by episodic storm and snowmelt events than are streams. These attributes make lakes better choices for estimating critical loads for surface waters. A lake was defined as any freshwater having an open pelagic zone and a wetted surface area >1 ha in size, following the United States Environmental Protection Agency (U.S. EPA) protocols for selection of lakes for acidification studies (Eilers et al. 1987; Landers et al. 1987). Candidate lakes (any water body greater than 1 ha in area) were identified from the British Columbia Freshwater Atlas (GeoB.C. 2012).

To reduce uncertainty about the suitability of lakes for sampling, access, and safety, a field reconnaissance was completed by helicopter on July 11, 2012, as described in Limnotek (2012b) (Appendix 8.6-1). Following criteria applied in the U.S. EPA National Surface Water Survey (Eilers et al. 1987; Landers et al. 1987), a candidate lake (any water body >1 ha in size) was omitted from sampling if any one of the following conditions was found during the reconnaissance:

1. the lake could not be safely accessed;
2. the lake was disturbed by human activity such as runoff from industrial works and roads (the presence of small septic fields was considered acceptable because critical load models have previously been applied to regions where septic fields are present, such as in the studies of Henriksen et al. 2002 and Dupont et al. 2005);
3. the maximum depth of a lake was <0.75 m (water depths were not measured during the reconnaissance but if extensive littoral development and emergent vegetation was present throughout the wetted areas, water depths were considered to be <0.75 m);
4. a lake found in the watershed atlas was not present;
5. a lake found in the watershed atlas was a wetland or stream, meaning that it did not have an open water pelagic zone;
6. a lake found in the watershed atlas was a side channel of a large river; or
7. a lake found in the watershed atlas had open water but was not a natural lake (e.g., town of Kitimat sewage treatment ponds).

Overall, 16 lakes were excluded from the sample set, many of them for multiple reasons. Of the 16 lakes which were excluded: 14 were too shallow; 11 appeared to be primarily wetlands; 6 showed road influence; 1 was very close to an industrial development, and 1 “lake” was actually a sewage treatment pond. After the 16 lakes were excluded, this left 41 lakes to be sampled (i.e., 71.9 % of the original set of 57 candidate lakes fulfilled all sampling criteria). The 41 lakes shown on Figure 8.6-1 are therefore a census of all lakes greater than 1 ha in area that were both within the 4 sampling regions of interest and fulfilled the sampling criteria (i.e., were

not excluded for the reasons identified above). Since the sample of 41 lakes is a census of all lakes within a target population meeting defined criteria, population statistics such as the percent of lakes with pH <6 are precise estimates for this set of 41 lakes. This study focused on the regions with the highest level of sulphate deposition and most acid-sensitive bedrock types. Therefore**, statistics estimated from the sampled sites alone overestimate the sensitivity to acidification of the overall study area.** The extension of findings from the sampled area to unsampled parts of the study area is discussed in the results (Section 9.4).

The sampling design included 20 stream sites on 14 streams (Figure 8.6-1, Table 8.6-1). These streams were selected both due to high public interest, and to fill in parts of the study area where there were few lakes. Many streams have particular value to people in the Kitimat-Terrace area because they support various life stages of Pacific salmon, making them important for commercial, sport, and First Nations fisheries. Stream sampling sites were placed within or a short distance outside of the 10 kg SO_4·/ha/yr isopleth shown in Figure 8.6-1. The stream orders of all these streams were greater than or equal to 2 (i.e., no headwater streams). They were accessible either by helicopter or by hiking a short distance from a road and they were placed upstream of any known disturbance such as highway crossings or solid waste landfill. Two sites were sampled on the Lakelse River to capture a possible range of chemical conditions in passage of water from Lakelse Lake to the Skeena River. Similarly, two sites were placed on each of the Wedeene River and Little Wedeene River to capture a range of conditions as water flows from west to east across a gradient of SO_4 deposition levels. Sampling sites were located both upstream and downstream on Anderson Creek and Moore Creek to capture a range of conditions from the subalpine to near sea level in close proximity to the smelter. The downstream site on Anderson Creek was located where water quality has been sampled over the long term by RTA. Wathl Creek was sampled upstream of a pumphouse compound in Kitamaat Village. That pumphouse supplies water to the village from an underground aquifer via two 20 m deep wells that are adjacent to Wathl Creek.

The sampling design for streams captures the chemistry of the selected sites during the sampling period. We did not implement a statistically representative sample of all streams within the study area, as critical load studies are better focused on lakes, for reasons described above. We did however supplement the sample with pH data from other streams in the region sampled by geologists and included in the B.C. government's geochemistry database; these data were extracted for the Kitimat region (GBCR2008-11) and summarized by Dr. Julian Aherne of Trent University.

In summary, the study surveyed 30.6 % of the lakes greater than 1 ha in size in the study area, 88.4 % of the area of lakes in the study area, and 11.5 % of the length of non-headwater streams in the study area (Table 8.6-2). The two largest lakes sampled were Lakelse (1,374 ha) and Jesse (1,167 ha). The average lake area excluding Lakelse and Jesse lakes was 4.15 ha.

Table 8.6-1: Characteristics of the 14 sampled streams. There were 20 sample sites as six streams had both an upstream and downstream site. *Italicized* total watershed areas are greater than watershed area in study area.

Stream or River (# sites sampled)	Total Watershed Area (km^2) (of downstream site if 2 sampled)	Watershed Area in Study Area (km^2)	Stream Length in Study Area (km)	Stream Order
Kitimat River (2)	*1571.4*	107.1	47	6,7
Williams Ck (1)	*169.8*	28.4	13.6	5
Lakelse River (2)	*573.5*	422.3	21.2	5
Scully (Schulbuckhand) Ck (1)	*33.0*	27.4	13.4	3
Furlong Ck (1)	11.0	11.0	5.5	3
Anderson Ck (2)	37.4	37.4	11.4	3,4,5
Humphreys Ck (1)	30.7	30.7	5.7	3
Hirsch Ck (1)	*352.9*	103.9	25.6	5,6
Moore Ck (2)	13.5	13.5	6.6	2,3,4
Clearwater Ck (1)	4.5	4.5	4.3	2,3
Hatchery Ck (1)	*30.5*	26.2	10.7	3,4
Wedeene River (2)	*315.7*	192.1	32.3	5,6
Little Wedeene River (2)	*182.8*	116.0	21.6	4,5
Wathl Creek (1)	*121.5*	120.3	17.8	3,4,5
Total (20 sites)	**3448.4**	**1240.9**	**236.7**	

Table 8.6-2: Lakes and streams within the total study area compared to the sampled population.

	Accessible to fish	Inaccessible or unknown	Total in study area	Sampled in 2012 { % of total}
LAKES >1 ha				
# lakes	87	47	**134**	41 {30.6 %}
(area)	(2963 ha)	(126 ha)	**(3089 ha)**	(2732 ha) {88.4 %}
% of total	65 %	35 %	100 %	
	(96 %)	(4 %)	(100 %)	
STREAMS ≥ order 2				
km streams	1505	548	**2053**	236.7 {11.5 %}
% of total	73 %	27 %	100 %	

8.6.2 Field and laboratory methods

8.6.2.1 Water quality attributes of interest

The water quality and other variables measured at these sites or analysed in the lab are those commonly used in other acidification studies (Eilers et al. 1987; Landers et al. 1987; Baker et al. 1991a), those required to determine charge balance in the solution (an important quality control test) and those required to run the Steady State Water Chemistry Model (SSWC) (Henriksen et al. 2002). These measurements included:

- **Standard water quality parameters providing contextual information on the site:** dissolved oxygen, conductivity, total dissolved solids, temperature, turbidity, total phosphorus;
- **Major anions**: chloride, fluoride, nitrate, bicarbonate, carbonate, sulphate;
- **Major cations:** calcium, magnesium, sodium, potassium, ammonium, hydrogen (pH);
- **Metals:** strontium, aluminum, manganese, iron (potentially contributing to charge balance);
- **Gran Acid Neutralizing Capacity (Gran ANC):** the capacity of a solution to neutralize strong acids, used to determine the sensitivity of lakes to acidification, and determined by titration to the inflection point of the pH-alkalinity titration curve;
- **Fixed end point alkalinity:** similar to Gran ANC, but more commonly applied in historical studies (thereby allowing comparisons to historical data), and determined by titration to a fixed end point of pH 4.5;
- **Dissolve organic carbon:** used to estimate the concentration of organic anions, and indicator of influence from wetlands and vegetation on water quality;
- **General composition of riparian vegetation:** used to evaluate likely sources of dissolved organic carbon and nutrients; and

- **Stream characteristics:** used to interpret water quality data (clarity, bankful width, substrate, stream disturbance indicators, land use, erosion, indications of non-point source pollution).

8.6.2.2 Selection of analytical laboratory

Limnotek distributed a survey requesting method detection limits (MDL) to four candidate labs: ALS Environmental (ALS), the Pacific Environmental Science Centre (PESC), the Cultus Lake Salmon Research Laboratory (Cultus), and the Trent University lab run by Drs. Aherne, Watmough and Dillon. The MDL is the concentration above which there is a high probability that a substance can be detected (Ministry of Environment Lands and Parks 1988).

Without preliminary data from the Kitimat area to guide the selection of detection limits, the observed minimum concentrations found in the Western Lake Survey (conducted by the U.S. Environmental Protection Agency; Eilers et al. 1987; Landers et al. 1987) were set as targets (provided in Limnotek 2012b; Appendix 8.6-1). Chemical parameters included Gran ANC, calcium, chloride, dissolved organic carbon, manganese, potassium, sodium, sulphate, nitrate, ammonium, aluminum, magnesium, and iron.

Responses were received by Limnotek from three labs. PESC declined to respond. Only one lab, the Trent University lab, was capable of running Gran ANC. ALS was not able to meet the MDL for potassium, sodium, sulphate, nitrate, ammonium and fluoride. Only the Cultus Lake Salmon lab was able to meet detection limits for ammonium and nitrate. Based on these survey results, the Trent University lab was selected to run all analyses except ammonium and nitrate, which were run at the Cultus lab.

8.6.2.3 Field methods

This section summarizes Limnotek's field methods, described in more detail in Limnotek (2012b, see Appendix 8.6-1). Prior to the start of field activities, a health and safety plan was submitted and approved by LaPointe Engineering on behalf of Rio Tinto Alcan (Limnotek 2012a). The safety plan was based on WorkSafe B.C. standards, and included protocols developed by Limnotek as general practice with modifications from RTA, LaPointe Engineering Ltd., and Canadian Helicopters to ensure the safety of the crew while working on lakes and rivers using helicopter and boat support.

Sampling of lakes for acidification studies is usually done in the fall when the water column of each lake is fully mixed and a surface water sample is representative of the whole water column (Landers et al. 1987; Strang et al 2010). The project schedule, however, required sampling in August 2012, when some of the lakes could be density stratified. Chemical attributes may vary over water depth at that time (Wetzel 2001). To determine if chemical variation with water depth was present, Limnotek collected a water sample at a depth of 2 m off bottom and from

the surface at five of the lakes (Lakelse, Bowbyes and Jesse lakes, and Lakes 034 and 044). Only a surface sample was collected from all of the other lakes.

Using data from the Ontario Ministry of Environment, we found that while both pH and ANC can vary in a given lake between times of lake stratification in summer and times of full mixing in the fall, there is no difference in the overall relationship between pH and ANC across multiple lakes (Figure 8.6-5). This relationship is used to determine the critical ANC associated with pH 6, an important parameter in the SSWC model (Henriksen et al. 2002), as described below in Section 8.6.3. This finding supported the use of data collected in August for calculation of critical loads without correction for time of year.

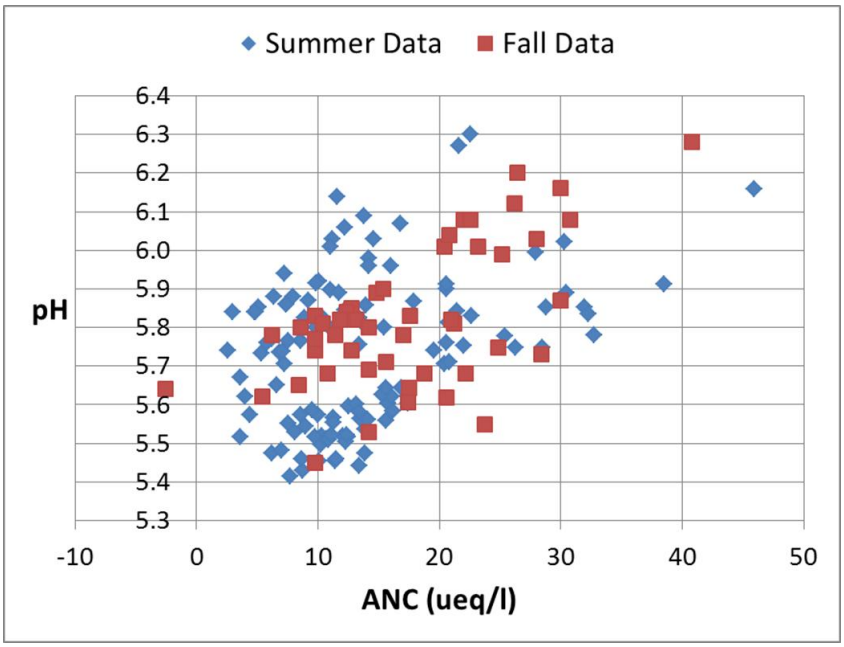


Figure 8.6-5: Combined ANC and pH data from 163 samples across five low pH lakes in the Muskoka-Haliburton region of Ontario.

These lakes (Plastic, Crosson, Chub, Heney, Dickie) were sampled in both August during a period of lake stratification (blue diamonds) and in late October/November after fall overturn (red squares). Though ANC and pH values are generally both higher in fall than summer, the critical ANC associated with a pH of 6 is around 25 µeq/L using either summer or fall data, and is therefore not affected by the time of sampling. Source of data: Dr. Norman Yan (York University) and Andrew Paterson (Ontario Ministry of Environment).

Water sampling and measurements were completed during August 14-20, 2012 (details on sampling methods in Limnotek 2012b; Appendix 8.6-1). Only Lakelse Lake was accessed by truck

and boat; the remaining 40 lakes were accessed by helicopter, and in the case of Jesse Lake, by helicopter and an inflatable boat. Six of the stream sites were accessed by helicopter and the remaining 14 were accessed by truck and on foot. Five high elevation lakes had ice cover on the day of sampling and the lack of open water confined sampling to the lake outlets or pockets of open water along shorelines.

Sampling of all lake sites that were accessed by helicopter was completed from the helicopter in a hover position, approximately 4 m above the water surface. The activities were completed by a three person crew plus pilot. Limnotek used three devices to complete measurements and water collections from the helicopter. They measured water depths by a Lowrance Mark-5X portable depth sounder equipped with custom-weighted transponder designed for deployment from a helicopter. Limnotek used a Yellow Springs Instrument (YSI) multiparameter Sonde (model 6920), calibrated the evening before sampling, to measure depth of sampling, water temperature, pH, specific conductivity, total dissolved solids concentration, turbidity, and dissolved oxygen concentration. The dissolved oxygen and depth sensors were calibrated at each site to correct for elevation and barometric pressure. They collected water samples using a VanDorn water bottle (Wildlife Supply Co. Yulee, FL) that was lowered on a calibrated line from the helicopter and closed with a mechanism that was activated by a messenger.

The field crew used the following procedure at each lake. Crew members and the pilot were in constant communication via headsets at all times. As the helicopter approached the lake, the crew leader (front seat) provided the pilot with general guidelines about where the sampling station should be located, which was usually at an expected deep point, based on lake morphometry. The pilot decided on the actual location, approximately 50 m from shore as required in safety protocols. Station location coordinates from the helicopter GPS were logged on the field form. Once on station in stable hover, the sliding back door of the helicopter was opened, a weighted transducer was lowered to an elevation just under the water surface and the water depth was recorded. Next, the YSI was lowered to the water surface and the pressure transducer was calibrated to zero to accommodate the changing barometric pressure at each lake. The probe was then lowered to 1 m below the surface, held in place for approximately one minute while the sensors reached equilibrium, and all sensor measurements were recorded into Sonde memory. The data were recorded on the field sheet as backup. At seven lakes, a vertical profile of measurements was saved to the YSI data logger (at 1 m intervals for the first 10 m, 2 m intervals between 10 m and 20 m and every 5 m at depths greater than 20 m). The VanDorn water bottle was lowered to a depth of 1 m, triggered to collect a water sample and retrieved. Sample water was dispensed from the VanDorn into 1 L and 500 mL pre-labeled polyethylene bottles. Each bottle was rinsed twice with the sample water and then filled, capped, and placed in a cooler on ice. At the lakes where a vertical profile was recorded, a second set of water samples was collected from 2 m off the lake bottom. Total time on station to complete these measurements and collections was 8 to 12 minutes at lakes where only surface data and samples were collected, and up to 20 minutes at

the seven lakes where profiling and surface and bottom water samples were collected. Measurements of descriptive habitat variables were compiled on the field data form at each site.

At Jesse Lake and Lakelse Lake that were sampled by boat, the procedures were the same as those used on the helicopter but the boat was anchored and the sampling instruments were operated from the side of the boat. Station coordinates at these sites were recorded on a handheld Garmin GPSMap 76CSx receiver. At streams and lake outlets, sampling and measurements were conducted in active flowing water near the centre of the channel. Water samples were collected by submerging each bottle by hand. Again, each bottle was rinsed twice with the sample water and then filled, capped and placed in a cooler on ice.

At the end of each field day, the 500 mL sample bottles were placed directly in a refrigerator for storage at 4°C until shipment to Trent University laboratory for analysis of total cations, anions, and Gran ANC. Water from the 1L bottles was filtered through pre-combusted 0.45 µm glass fibre filters in a Swinnex syringe filter apparatus and used to rinse and fill two 125 mL polyethylene bottles and one 250 mL polyethylene bottle. The 125 mL bottles were placed in the freezer at -15°C for later shipment to the Cultus Lake Salmon Research Laboratory for analysis of NO_3-N and NH_4-N. The 250 mL bottle was placed in the refrigerator for later analysis of dissolved organic carbon and dissolved cations at the Trent University laboratory. All water samples were packed on cube ice (all samples for Trent University) or dry ice (the ammonium and nitrate samples for Cultus) and shipped on August 21st, which was seven days after the sampling started.

8.6.2.4 Laboratory analytical methods

ANC was measured with Gran titration on a PC-titration Plus system. Sulphate, fluoride and chloride were measured by ion chromatography on a Dionex IC. Total and dissolved base cations (calcium, potassium, magnesium, sodium, strontium, aluminum, manganese, and iron) were measured using PerkinElmer inductively coupled plasma – optical emission spectroscopy. Dissolved organic carbon was measured by combustion with a Shimadzu TOC-V CPH carbon analyser using standard methods reported in APHA (2010). At the Cultus lab, ammonium (NH_4-N) and nitrate (NO_3-N) were analysed by colourimetry using a Technicon autoanalyser equipped with a long flow cell (Stainton et al. 1977).

8.6.3 Analysis and modelling

We performed the analysis and modelling described within this section. We have separated the analysis and modelling approaches into “Level 0” and “Level 1” approaches, consistent with UNECE (2004). Level 0 approaches focus on risk assessments based on current water quality and Level 1 approaches include the application of steady state models to predict critical loads, potential exceedances of those critical loads, and predictions of steady state ANC pH levels. Level 2 approaches use dynamic models involving intensive data collection to estimate how long it would take for a lake or stream to exceed its critical load. We did not apply Level 2 approaches in this study because they are most appropriate for examining a few lakes or streams very intensively, and require mulitiple years of data for model calibration. Our focus was different - estimating the extent and magnitude of critical load exceedance over many lakes and streams in a large region, objectives best served by Level 0 and Level 1 approaches.

8.6.3.1 Data preparation

The subset of the field data utilized in the analysis and modelling of surface waters described in the remainder of this section is as follows:

- Only the surface measures were used; deeper samples, where taken, were not used.
- Lakes and streams were distinguished but combined for some analyses as appropriate.
- 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 fluctuation throughout each day (based on variation in dissolved CO_2), whereas field pH captures a particular moment within that fluctuation. This procedure is consistent with the practices of the Ontario Ministry of Environment (N. Yan, York University, July 2012, pers. comm.).
- 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 their analytical detection limits (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. This approach is commonly applied in other limnology projects (C. Perrin, Limnotek, October 2012, pers. comm.).

Field 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 $[SO_4^{-2}]$ 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 per mg of dissolved organic carbon (DOC), based on previous work (J. Aherne, Trent University, October 2012, pers. comm.). The method of Oliver et al. (1983) also uses empirical estimates of an average dissociation constant for organic anions (pK), and the pH of the sample to determine the concentration of organic anions in µeq/L.

8.6.3.2 Data quality assurance

We applied three methods to confirm quality of the data inputs prior to their use for the analysis and modelling.

First, our colleagues at Limnotek and Trent University evaluated the accuracy and precision of field and laboratory methods, described in more detail in Limnotek (2012b) (see Appendix 8.6-1). One blank sample was processed on each day of field sampling to provide information on contamination from handling and one blind duplicate sample (no site label) was collected each day from a stream or lake site to estimate field sampling precision. All seven blanks and seven duplicates, corresponding to the seven days of sampling, were analysed for each chemical parameter. Blanks were double de-ionized water samples provided by the Cultus Lake lab and handled the same way as all test samples including filtration, water transfers to sample bottles, storage in the fridge or freezer, and shipping. The presence of cations and anions in the blank samples indicated contamination during sample processing and the chemical concentration showed the amount of contamination. Lab precision was tested from results of repeat analyses that were run on every 10^{th} sample, and lab accuracy was tested by calculating percent recovery on solutions of known concentrations. A solution containing known analyte concentration was prepared in each lab using inorganic standards. The average value from up to nine separate spiked samples was used to show average percent recovery from known standards of each cation and anion. The accuracy of lab pH measurements has been determined to be ± 0.1 pH units (J. Aherne, Trent University, November 2012, pers. comm.).

Second, we assessed the charge balance for all of the sampled lakes and streams. The charge balance is the difference between the sum of all of the cations (positively charged ions) and the sum of all of the anions (negatively charged ions). The true charge balance for natural waters is neutral (i.e., total anions and total cations balance). The calculated charge balance should be reasonably close to neutrality, 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 will have high confidence that the data accurately reflect the true ion composition of the water samples. The U.S. EPA (Baker et al. 1991a) uses only the concentrations of major ions to assess the charge balance:

$$\text{Anion Sum } (\mu eq/L) = [Cl^-] + [F^-] + [NO_3^-] + [HCO_3^-] + [CO_3^{2-}] + [SO_4^{2-}] + [OH^-] \quad \{8.6\text{-}1\}$$

$$\text{Cation Sum } (\mu eq/L) = [Ca^{2+}] + [Mg^{2+}] + [Na^+] + [K^+] + [NH_4^+] + [H^+] \quad \{8.6\text{-}2\}$$

We increased the accuracy of our charge balance calculations by including organic anions as well.

Third, we compared the measured conductivity for each sample to a calculated estimate of conductivity based on the ion concentrations. If the difference between the measured and

estimated conductivity were relatively small, our confidence that the data accurately reflect the true ion composition of the water samples would be further increased. We used the U.S. EPA's CONCAL method for calculated conductance (Baker et al. 1991a; original method from Kerfoot and Faber 1986) to estimate conductivity:

$$\text{CONCAL } (\mu S/cm) = (([Ca^{2+}]*9.47) + ([Mg^{2+}]*53.0) + ([K^{+}]*73.48) + ([Na^{2+}]*50.08) + ([NH_4^{+}]*73.5) + ([H^{+}]*349.65) + ([SO_4^{2-}]*80.0) + ([HCO_3^{-}]*44.5) + ([Cl^{-}]*16.31) + ([NO_3^{-}]*71.42) + ([F^{-}]*5.4) + ([CO_3^{2-}]*69.3) + ([OH^{-}]*198))/1000 \quad \{8.6\text{-}3\}$$

8.6.3.3 Level 0 methods to assess sensitivity to acidification[21]

Level 0 methods of critical load assessment involve examining water quality data to determine general sensitivity to acidification, and to assess potential sources of current acidity, but do not integrate surface water chemistry with deposition, and are therefore less sophisticated than Level 1 approaches, which combine water body sensitivity (assessed through sampling of lake chemistry) with estimates of deposition. For Level 0 methods, we looked at three indicators: ANC, pH and anion composition.

ANC is a useful indicator of the sensitivity of surface waters to acidification. We examined the frequency distribution of ANC values across the sampled lakes and streams, since the shape of the frequency distribution indicates the proportion of lakes which might acidify under different acid loadings (Jones et al. 1991). Three important ANC thresholds are:

- **0 µeq/L**, since lakes with ANC <0 are considered acidic (Baker et al. 1991a).
- **26 µeq/L**, the critical ANC associated with a pH value of 6.0 for this study area, derived using methods described below. Henriksen et al. (2002) note that the critical ANC is typically in the range of 20 to 40 µeq/L. We derive a critical ANC value for the Kitimat study region.
- **50 µeq/L**, since lakes with ANC <50 µeq/L are vulnerable to acidic episodes during storm or snowmelt events, and lakes with ANC >50 µeq/L are relatively insensitive to acidification (Driscoll et al. 2001).

As discussed in the literature review in Section 3.5.5, the structure and function of lake and stream biota changes below a pH of 6.0. We therefore use a pH of 6 as the critical pH for lakes and streams in the study area. We also examined the frequency distribution of pH values, and the spatial distribution of waters with a pH below 6.0. We used lab rather than field pH values for reasons explained above in Section 8.6.3.1.

[21] *Acidification* is defined as a decrease of ANC in water, as caused by either natural or anthropogenic processes. An *acidic* lake or stream is defined by ANC <0. Therefore, it is possible for a lake or stream to *acidify* or undergo *acidification* without becoming *acidic*.

The relative contribution of different types of anions is helpful for evaluating which sources of acidity are either dominant or influential, and how these sources combine to determine the current acidity of a lake or stream. We focused on waters with pH <6, using methods described in Marmorek et al. (1989), which were similar to those applied by Baker et al. (1991a). We calculated the percentage of total anions contributed by bicarbonate, sulphate, organic anions, fluoride, chloride and nitrate. Anions contributing more than 50 % of total anions were classified as *dominant*, and those contributing more than 25 % were classified as *influential*. For lakes or streams with pH <6, this approach helps to distinguish lakes and streams which have a pH <6 due to the influence of organic acids from wetlands and forest vegetation, versus those which may be acidic due to other causes (i.e., sulphur deposition, watershed sources of sulphur, chloride, or fluoride). We present these anion analyses in tables, pie charts and ternary plots. Ternary plots illustrate the percent ionic composition of different samples within a triangle, as in Baca and Threlkeld (2000). We used an Excel spreadsheet provided by W. Vaughn (http://wvaughan.org/ternaryplots.html) to plot lake and stream data on the following 3 axes: (1) bicarbonate; (2) organic anions; and (3) the sum of sulphate, fluoride, nitrate, and chloride.

8.6.3.4 Level 1 methods to estimate critical loads, exceedance, future pH and original pH

As noted above, Level 1 approaches combine water body sensitivity (assessed through sampling of lake chemistry to determine lake and stream-specific critical loads) with estimates of deposition. The Level 1 methods that we have used are described in UNECE (2004) and Marmorek et al. (1990). Concentration thresholds for SO_2 developed by the Ministry of Environment, the World Health Organization and the U.S. EPA are useful for examining direct impacts of SO_2 on people and vegetation, but do not have relevance to evaluating impacts on surface waters.

Determining critical ANC

For a particular set of lakes and streams, the critical ANC is the level corresponding to a critical pH threshold, which we assumed to be 6.0 (as discussed in Section 3.5). If ANC decreases below this threshold, it is expected that the pH will decrease below 6.0. ANC and pH have a non-linear relationship that varies somewhat among regions based on regional water chemistry properties. We evaluated the relationship between pH and ANC using the methodology of Small and Sutton (1986), who derived the relationship (the "titration curve") as an inverse hyperbolic sine function:

$$pH = a + \frac{1}{\ln 10}\operatorname{arcsinh}\left[\frac{(Gran\ ANC) - d}{c}\right] \quad \{8.6\text{-}4\}$$

The *d* parameter in the above equation is related to the data set's average effective organic anion concentration in µeq/L. A water sample with organic anions will have a lower pH than

another sample with identical Gran ANC, but no organic anions (Hemond 1990), though the magnitude of pH reduction per unit of DOC (dissolved organic anions) will depend on the types of organic anions present (Marmorek et al. 1996). Sites with higher than average DOC values in a data set would be expected to fall below the fitted curve.

Marmorek et al. (1996) developed a modified version of the Small and Sutton (1986) titration curve to account for the influence of dissolved organic carbon on pH. We tested both the unmodified and modified Small and Sutton titration curves using the lab pH data and the Gran ANC as the measure of alkalinity. We analysed the lakes and streams separately but there were too few data for streams to properly fit either model, so we only fit the models to the lake data. We then compared the fit of the best-fit model using each approach. We fit the titration curves to the data according to Marmorek et al. (1996), using a non-linear least squares parameter fitting procedure. We then assessed the relative fit of the two models by comparing their respective R^2 and RMSE (root mean square error) values. We determined the critical ANC by solving equation {8.6-4} analytically for Gran ANC and then calculating the value of Gran ANC for a pH of 6.0.

The Steady-State Water Chemistry model

We used the Steady-State Water Chemistry (SSWC) model to estimate both the critical loads of acidity for each of the lakes and streams in the study area and the amount (if any) by which these critical loads might be exceeded under scenarios of increased deposition from emissions. 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, cited in Henriksen et al. 2002). The SSWC is an empirical model for calculating critical loads and exceedances that has been applied across Europe as well as in southern Ontario and southwestern British Columbia (Sverdrup et al. 1990; Posch et al. 1995, 2001; Werner and Spranger 1996; Henriksen and Posch 2001; Henriksen et al. 2002; Strang et al. 2010). The SSWC is described in detail by Henriksen and Posch (2001), Henriksen et al. (2002) and UNECE (2004).

We have closely followed the implementation of the SSWC as described by Henriksen et al. (2002). Figure 8.6-6 describes the general approach, while Table 8.6-3 and Table 8.6-4 describe the core structure of the model, including key equations and variables. Further details on each of these components, including their foundation in the literature or intermediate steps in their derivation are described in both Henriksen et al. (2002) and UNECE (2004). 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.

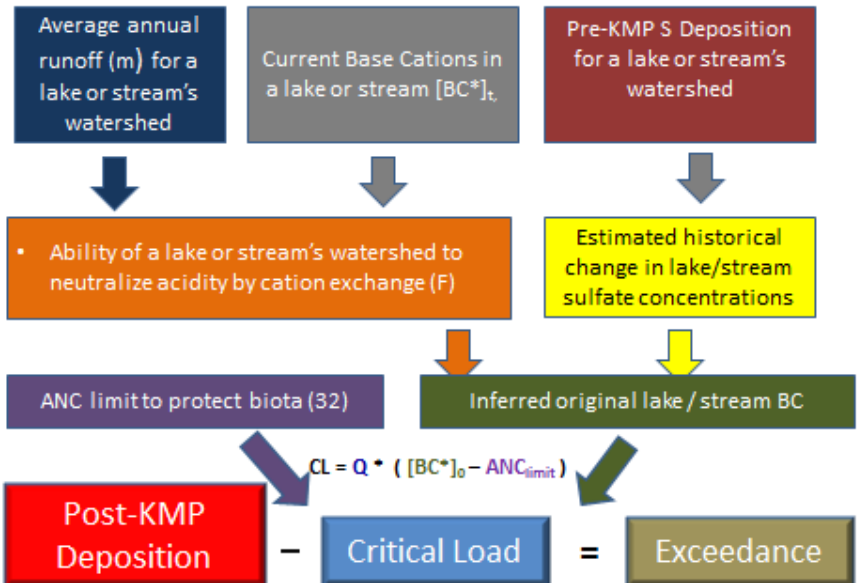


Figure 8.6-6: Illustration of how the SSWC model (Henriksen et al. 2002) was applied to estimate critical loads for sampled lakes and streams and exceedances under KMP.

Table 8.6-3: Core components of the SSWC model.

Component	**Equation applied**	**Modification relative to Henriksen et al. (2002)**
Critical load of acidity	$CL(A) = BC^*_0 - ANC_{limit}$	
Original non-marine base cations	$BC^*_0 = BC^*_t - F \times (SO_4{}^*_t - SO_4{}^*_0)$	Does not include ΔNO_3
F-factor	$F = (BC^*_t - BC^*_0)/(SO_4{}^*_t - SO_4{}^*_0)$	Does not include ΔNO_3
F-factor (empirical estimate)	$F = \sin\left(\frac{\pi}{2} \times Q \times [BC^*]_t}{S}\right)$	
Original non-marine sulphate	$[SO_4{}^*]_0 = [SO_4{}^*]_t - [SO_4{}^*]_{exp}$	Alternate calculation (see text)
Exceedance of acidity	$Ex(A) = S^*_{dep} + N_{leach} - CL(A)$	

Table 8.6-4: 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	
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 and are sulphate and base cation fluxes per unit area within the watershed (meq/m^2/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/m^3.

Negative critical loads (CL <0)

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 non-marine contribution of base cations from weathering (i.e., $ANC_{limit} = BC^*_0$). The rationale for this constraint is that our assessment focuses on estimating exceedances due to KMP. 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 KMP, and is also consistent with methods applied in Europe (J. Aherne, Trent University, October 2012, pers. comm.).

The effects of nitrogen (N) on calculated critical loads and exceedances

The acidifying potential of N is much lower than S in the study area because N deposition in the region is low, nitrogen concentrations in surface waters are low and N is taken up by plants, immobilized in soils and lost to the atmosphere via denitrification and fire. We did, however, consider *current* deposition of N in determining the exceedance of critical loads for surface waters in the lakes and streams that we sampled. As shown in the equation for exceedance in Table 8.6-3, the steady state water chemistry model assumes that any nitrate and ammonium found in runoff represents current leaching of N from watersheds with a potential acidifying effect, and incorporates that into the calculation of exceedance. However, since nitrate and ammonium concentrations were very low in the 61 sampled lake and stream sites, this had only a minor effect on our estimates of exceedance. With the exception of four lakes that are naturally acidified due to organic acids (lakes 044, 047, 054, 056) and have a critical load equal or close to zero, the N leaching factor averaged only 0.7% of each site's estimated critical loads (range from 0.0 to 3.9%). Pre-KMP emissions of N are low (0.7 to 0.8 t/d) relative to S emissions (up to 27 t/d), and as stated above, most N is taken up by vegetation. Projected post-KMP increases in emissions of nitrogen oxides are also low (about 0.1 t/d; A. Henolsen, Trinity Consultants, April 2013, pers. comm.). In summary, our estimates of exceedance consider acidification due to current levels of N deposition, and N deposition is not expected to change significantly post-KMP.

F-factor

The F-factor is a simple way to represent cation exchange processes, specifically the proportion of incoming acidity accompanying sulphate that is exchanged in the soil for base cations. By considering cation exchange processes, the F-factor complements the estimate of original, non-marine base cations (BC^*_0), which describes the background weathering rates. If *F*=1.0, then a 10 µeq/L increase in lake [SO_4] results in a 10 µeq/L increase in lake [BC]. If *F*=0.0, then lake

[BC] would not increase regardless of how much of an increase there is in lake [SO_4]. In a watershed with *F*=0.5, lake [BC] would increase 5 µeq/L as lake [SO_4] increased by 10 µeq/L. The F-factor we applied only accounts for changes in sulphate but not nitrates, differing from Henriksen et al. (2002) but consistent with other applications of the SSWC and reasonable given that emissions of nitrogen oxides are not expected to increase under KMP.

In the SSWC model, the F-factor is derived from a sine function driven primarily by current base cation concentrations and runoff (third row of Table 8.6-3). This function was developed by examining empirical estimates of F-factors from lakes which have been exposed to changes in levels of sulphate deposition, as summarized in Henriksen et al. (2002). Future monitoring of a small set of acid sensitive lakes in the Kitimat Valley (see Section 10) could provide estimates of Δ [BC] and Δ [SO_4], from which we could empirically estimate lake-specific F-factors. Such empirical estimates could be used to provide updated estimates of critical loads and exceedances in the SSWC model. However, it should also be recognized that the F-factor can change over time in response to changes in watershed geochemical processes (Watmough et al. 2005).

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 ($[BC^*]_t$). We also fit a similar regression to the lakes in our study area outside of the 10 kg/ha/yr zone, under the assumption that they are relatively pristine lakes with sulphate and base cation levels that are representative of historic, pre-deposition conditions. 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. In those cases this leads to an estimated change in sulphate of zero and therefore no effect of the F-factor. If we were to assume no change in sulphate concentration since pre-industrial conditions, we might overestimate watershed weathering rate (BC_o) and critical load, and therefore underestimate exceedance.

Instead, we used a new approach to estimate original sulphate. 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 pre-KMP deposition (estimated as the average for 2006, 2008 and 2009). We therefore estimated original sulphate by subtracting the change in sulphate from the current observed sulphate:

$$[SO_4^*]_0 = [SO_4^*]_t - \Delta SO_4^*_{(pre\text{-}KMP)} \quad \{8.6\text{-}5\}$$

We calculated the sulphate attributable to pre-KMP deposition as the expected steady-state sulphate under the pre-KMP deposition scenario (i.e., $\Delta SO_{4*(pre\text{-}KMP)} = SO_4*_{exp\ (pre\text{-}KMP)}$). Expected sulphate is calculated based on total sulphate deposition and runoff (Marmorek et al. 1989):

$$[SO_4*]_{exp} = S*_{dep} / Q \quad \{8.6\text{-}6\}$$

Using this approach, original sulphate was consistently estimated to be less than current sulphate, resulting in larger estimated changes in sulphate. This approach is therefore both more realistic and much more conservative than the previously described methods because it yields the lowest estimates of original sulphate. In very few cases, this approach generated estimates of original sulphate that were less than zero (potentially due to overestimation of pre-KMP sulphate deposition), and these were reset to zero.

In the above equations for estimating $[SO_4*]_0$, we combine 2012 estimates of $[SO_4*]_t$ with deposition estimates from 2006, 2008 and 2009. A legitimate concern with this approach is that emissions of sulphur dioxide from the Kitimat smelter declined over the period from 2006 to 2011, as discussed in Sections 7.2 and 7.3. Annual smelter emissions over 2006, 2008 and 2009, the period used for pre-KMP deposition estimates, were 8,127, 7,355 and 6,516 t/yr respectively, for an average of 7,333 t/yr over the 3 simulated years (A. Henolson, Trinity Consultants, pers. comm.). Emissions were lower in 2010 and 2011 (5,514 and 5,158 t/yr respectively; average of 5,336 t/yr. Thus the average annual SO_2 emissions during 2010-2011 (the two years prior to lake sampling in 2012) were 27.2% lower than during the period for which pre-KMP deposition estimates were made (2006, 2008 and 2009). Equations {8.6-5} and {8.6-6} could therefore potentially *overestimate* $[SO_4*]_{exp}$ and $\Delta SO_4*_{(pre\text{-}KMP),}$ This would result in *underestimates* of $[SO_4*]_0$ (equation {8.6-5}), $[BC*]_0$ (second equation in Table 8.6-3), and critical loads (first equation in Table 8.6-3). From the second equation in Table 8.6-3 it can be seen that the degree of underestimation of critical loads would be directly proportional to the F-factor (i.e., a larger effect in less sensitive watersheds). In any case, underestimating critical loads would make our analysis *more precautionary,* i.e., more likely to overestimate exceedance and conclude that a lake was at risk of acidifying, when in fact it was not. This concern can therefore be dismissed with respect to the SSWC model, though it is of importance for the ESSA/DFO model, as discussed below.

We used the ratio of $[SO_4*]_t / [SO_4*]_{exp}$ as an indication of watershed sulphur sources. When this ratio is greater than 2.0, the watershed may contain natural sources of sulphur that contribute to observed lake and stream sulphate concentrations (Marmorek et al. 1989; Baker et al. 1991b). An overestimate of $[SO_4*]_{exp}$ would result in an underestimate of $[SO_4*]_t / [SO_4*]_{exp}$, and the potential to miss watersheds with natural sulphur sources.

Deposition

Total deposition of SO_4 for pre-KMP and post-KMP scenarios was obtained from the emissions and deposition modelling performed by Trinity Consultants (see Section 7.6). Deposition of NO_3

was not included in the SSWC model. Current NO_3 deposition is accounted for through the NO_3 leaching component of the SSWC and the project team assumed that there will be no increase in NO_3 deposition in the future based on no anticipated other sources of N emissions. Modelled N deposition is estimated to be very low (average <0.1 kg N /ha/a). Fluoride deposition is not considered because fluoride emissions are expected to decrease by ~46 % in the future (S. Zettler, Rio Tinto Alcan, March 2012, pers. comm.). The amount of fluoride that is retained in watersheds is unknown but fluoride represents a small percentage of total anions in all of the lakes except one.

Runoff

Joel Trubilowicz (Ph.D. student, Department of Geography, University of British Columbia) performed a special application of Moore et al.'s (2012) province-wide model for calculating runoff to estimate the amount of runoff on a 0.4 km x 0.4 km grid over the study area (Figure 8.6-7). As is evident from the critical load equation in Figure 8.6-6, higher runoff values result in a proportionally higher critical load.

GIS methods to determine watershed areas and average runoff and deposition

We defined upstream watersheds for each sampled lake and for each stream sampling point using flow direction calculated from the Canadian Digital Elevation Data 1:50K digital elevation model (DEM). We used the 1:20K Freshwater Atlas stream network to enforce drainage within the DEM, ensuring that the modelled flow of water followed the same stream network as used for defining the sample points. We applied ESRI's hydrology toolset within ArcMap to define the watershed polygons, and then determined area-weighted averages of the 0.5 km x 0.5 km grid deposition estimates and the 0.4 km x 0.4 km grid runoff estimates, for all of the full or partial grid cells within each upstream watershed.

There were four lake and 13 stream/river watersheds which extended beyond the study area, including the watersheds of Jesse and Lakelse Lake, Lakes 044 and 045, and all stream watersheds except for Anderson, Clearwater, Furlong, Humphreys and Moore creeks (Table 8.6-1). For the 17 sampling sites with watersheds extending beyond the study area, we applied the deposition and runoff values for the grid cells at the boundary of the study area to all of the area outside the boundary. The largest extensions (ratio of true watershed area to watershed area within the study area) were for the watersheds of Jesse Lake, Hirsch Creek, Kitimat River and Williams Creek. This procedure may lead to an overestimate of deposition values for these watersheds, though deposition values are in any case relatively low at the edge of the study area. Since in most cases the watershed areas outside of the study area boundaries were at higher elevations, this procedure may also underestimate runoff (Figure 8.6-7). These potential biases together lead to a potential overestimate of the concentration of sulphate and the risk of exceedance (i.e., overestimated sulphate deposition, divided by underestimated runoff leads to overestimated $[SO_4]$). The procedure is therefore precautionary, and likely to overestimate, rather than underestimate the risk of exceedance for these sites.

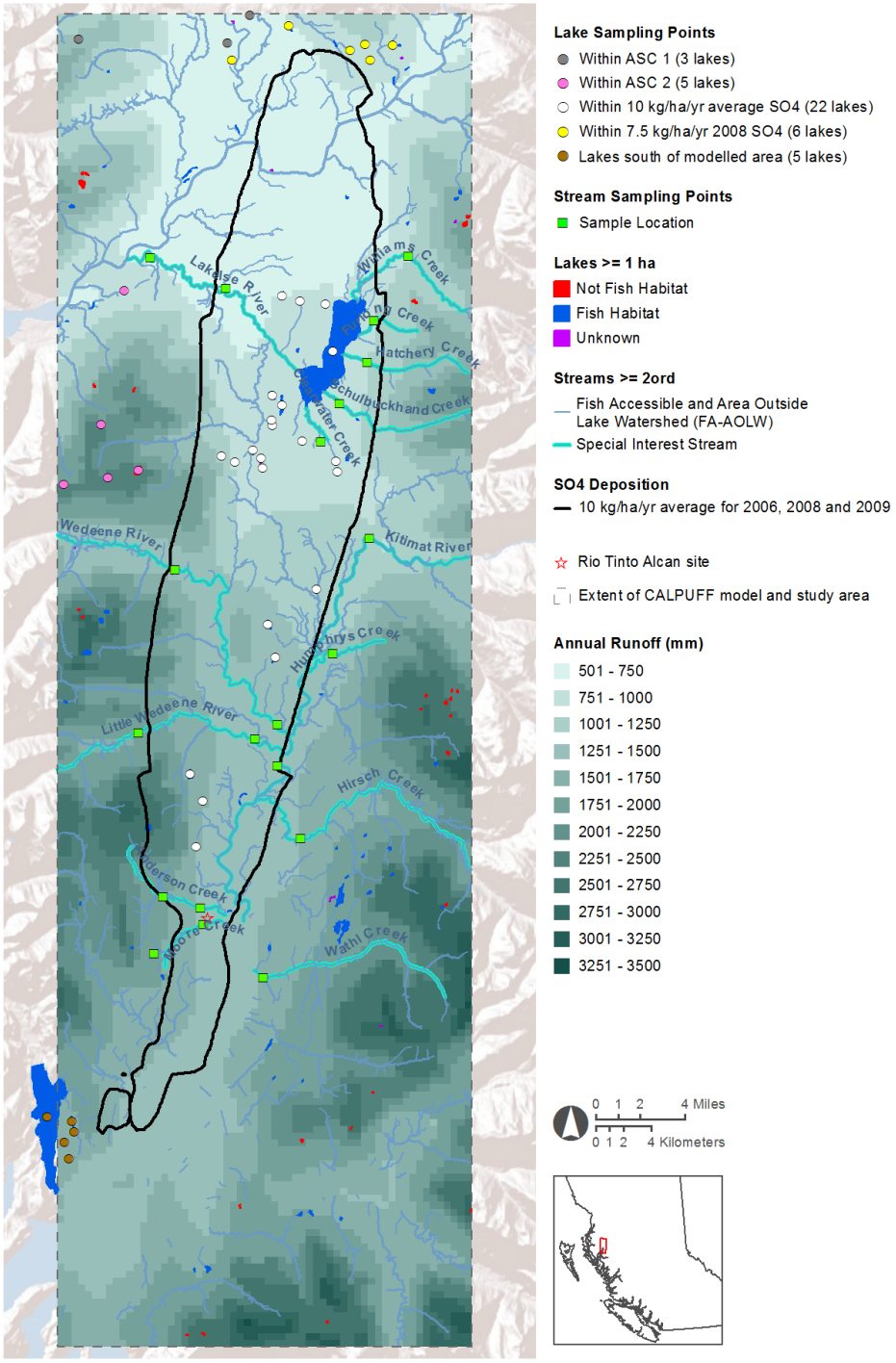


Figure 8.6-7: Runoff estimates for the study area. Source: Application of Moore et al.'s (2012) province-wide model by Joel Trubilowicz (Ph.D. student, Department of Geography, University of British Columbia).

Exceedance

We calculated the level of exceedance (if any) of the critical loads of each lake and stream under the scenarios of zero deposition, pre-KMP modelled levels of deposition, post-KMP 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 sulphate deposition from half to twice the predicted level under KMP.

Predicted steady state ANC and pH using a modified ESSA/DFO model

We developed an approach to predicting the eventual steady state ANC and pH, building on the approach of the ESSA/DFO model described in Marmorek et al. (1990). We predicted the change in Acid Neutralizing Capacity (ΔANC) with KMP, and the steady state ANC (ANC_∞) as follows:

$$\Delta ANC = -1*(1-F)*(DEP_{KMP} - DEP_{pre\text{-}KMP}) / Q \quad \{8.6\text{-}7\}$$

$$ANC_\infty = ANC_t + \Delta ANC \quad \{8.6\text{-}8\}$$

Explanation of terms:

- *F* (F-factor) = proportion of incoming acidity neutralized by cation exchange (proportional to base cations);
- DEP_{KMP} = sulphate deposition (meq/m^2/yr) due to KMP
- $DEP_{pre\text{-}KMP}$ = pre-KMP sulphate deposition due to Kitimat smelter (meq/m^2/yr) (average of 2006, 2008, 2009)
- Q = runoff (m)
- ANC = Acid Neutralizing Capacity (µeq/L, or meq/m^3); ANC_t = current ANC measured in 2012; ANC_∞ = eventual steady state ANC

We then used the titration curve based on Small and Sutton (1986), described in Section 8.6.3.4, to estimate the steady state pH (pH_∞) associated with ANC_∞, correcting for the residual in the fit of the curve to 2012 data (i.e., if a pH value was originally below the pH-ANC titration curve, it stayed below the curve). As discussed above, lakes with higher DOC would be expected to fall below the curve. This is a semi-independent method for estimating potential change in pH, as it is based on the ESSA/DFO model rather than the SSWC model, and relies on current ANC rather than current base cations as a starting point. However, both methods use the same F-factor, which in turn is derived from current base cation concentrations, and is a key uncertainty in both models.

The decline in SO_2 emissions over the 2006-2011 period discussed above could affect predictions from the ESSA/DFO model. If average annual deposition declined on average by the same percentage as emissions between 2006-2009 and 2010-2011 (i.e., by 27.2%), then it is possible that the term (DEP_{KMP} - $DEP_{pre\text{-}KMP}$) will underestimate the future change in deposition (e.g., a lake which is estimated to have a 2-fold increase in sulphate deposition with KMP could

actually experience a 2.27-fold increase in deposition). A higher level of deposition could cause a lower future ANC and pH at a few sensitive lakes. We examine the effect of this issue in our results. We note that the sensitivity analysis described above varied deposition over a much wider range (i.e., from a 50% decrease to a 200% increase), so the uncertainty due to recent declines in emissions is of a much smaller magnitude than that considered within the sensitivity analysis.

We estimated each lake's original, pre-industrial pH (pH_o) in the absence of any deposition by setting DEP_{KMP} to zero in equation {8.6-7}, serving to reflect a *decrease* in current deposition by the amount $DEP_{PRE\text{-}KMP}$. Analyses of deposition scenarios completed by Environment Canada for southeastern Canada (the basis of the Canadian Acid Rain Assessment) have excluded lakes with an original, pre-industrial pH <6 (Jeffries et al. 2000). Jeffries et al. used the Integrating Acid Rain Assessment Model to estimate the original or pre-industrial pH (pH_o). As noted by Jeffries et al. (2000):

> "The pH 6 threshold raises a methodological problem because there is a class of "brown-water" lakes that are naturally acidified by organic acids, and some, probably those with low base cation concentrations, are unlikely to ever have had pH ≥6. To deal with this problem, we have taken the simplest approach possible by identifying the subset of lakes in each cluster that had estimated pH_o ≥6.0 and then using only this subset to assess response to the SO_4^{2-} deposition scenarios. We quantified damage by determining the number of lakes in each cluster that have scenario pH <6 [pH_∞ <6] and then expressing it as a percentage of the overall cluster population, an approach equivalent to assuming that lakes with pH_o <6 (i.e., the excluded lakes) are not damaged by any deposition scenario. This assumption is clearly not true, but using it does establish a lower boundary for the estimated damage levels and is in keeping with the other factors that also lead to conservative damage estimates."

To ensure that there is no bias in our estimates of KMP effects, we estimate the percent of **all** lakes that are predicted to exceed their CL, and then examine how that percent would change if we were to follow the procedures applied by Jeffries et al. (2000) for the Canadian Acid Rain Assessment, and exclude lakes with pH_o <6. The approach by Jeffries et al. (2000) was also used by Dupont et al. (2005) who assessed critical loads and exceedances for 2,053 lakes in Quebec, the Maritimes, and the northeastern United States. Dupont et al. separated out the 59 lakes (2.9% of their data set) which had an original CL <0, and recognized that these lakes would not recover to a pH >6 even if all anthropogenic acidic deposition were eliminated. As noted by Dupont et al. (2005), *emphasis added*:

> "Another factor to take into account is that not all lakes had a pre-acidification pH of 6 or more. For this reason, many authors use a statistical limit to exclude these cases. In Canada, a 5% damage level (or the minimum-affected-area criterion in Holdren et al., 1993b) was set for the pH 6 threshold criterion (Jeffries, 1997). **This damage level excluded highly sensitive lakes that may be**

acidic even without anthropogenic acidic deposition. We did not rely on a preselected damage level. Instead, we considered those lakes showing critical loads lower than zero as surface waters that probably never maintained a pH above 6. Among the 2053 lakes studied, 59 (2.9%) had a negative critical load value."

8.6.4 Risk assessment framework

As described in Section 8.1, the effects on each receptor are classified according to a framework which outlines both the likelihood of an impact, and its consequences. For surface waters, these likelihood and consequence dimensions of the risk assessment framework are defined in Table 8.6-5 and Table 8.6-6 (respectively).

Table 8.6-5: Likelihood levels used in the risk assessment framework for surface waters. Each category indicates the likelihood of exceeding a critical load (CL).

A – Almost Certain	**B – Likely**	**C – Possible**	**D – Unlikely**	**E – Very Unlikely**
Predicted deposition ≥10 meq/m^2/yr **above CL**	Predicted deposition 0 to 10 meq/m^2/yr **above CL**	Predicted deposition 0 to 10 meq/m^2/yr **below CL**	Predicted deposition 10 to20 meq/m^2/yr **below CL**	Predicted deposition more than 20 meq/m^2/yr **below CL**

Table 8.6-6: Consequence levels used in the risk assessment framework for surface waters.

1 - Minor	**2 - Medium**	**3 - Serious**	**4 - Major**	**5 - Catastrophic**
<5 % of study area lakes exceed CL	**5-10 %** of study area lakes exceed CL	**>10-15 %** of study area lakes exceed CL	**>15-25 %** of study area lakes exceed CL	**>25 %** of study area lakes exceed CL
AND	AND	OR	OR	OR
0 sampled streams exceed CL	**0** sampled streams exceed CL	**1-2** sampled streams exceed CL	**3-4** sampled streams exceed CL	**5+** sampled streams exceed CL
AND	AND	AND	AND	OR
Lakelse Lake does not exceed CL	Lakelse Lake does not exceed CL	Lakelse Lake does not exceed CL	Lakelse Lake does not exceed CL	Lakelse Lake exceeds CL

Table 8.6-7 illustrates the resulting impact categories when these two factors are combined. We explain the rationale for the adopted categories in the paragraphs that follow these tables.

Table 8.6-7: Impact categories from the combined likelihood and consequence dimensions of the surface water risk assessment framework. The low, moderate, high and critical levels of impact are defined in the overall description of the risk assessment framework (Section 8.1).

Likelihood (see definitions in Table 8.6-5)	**Consequence** (see definitions in Table 8.6-6)				
	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**	**Moderate**	**High**	**Critical**
D – Unlikely	**Low**	**Low**	**Moderate**	**Moderate**	**Moderate**
E – Very Unlikely	**Low**	**Low**	**Moderate**	**Moderate**	**Moderate**

Likelihood categories

The likelihood levels in Table 8.6-5 are based on the exceedance categories used by Dupont et al. (2005), though Dupont et al. did not explicitly discuss likelihood of exceedance. We were very precautionary in assigning likelihood categories, which affects the assigned colours (impact categories) in Table 8.6-7:

- A lake with predicted deposition ≥10 meq/m^2/yr *above* its critical load is labeled as "almost certain" to have exceedance. However, it would not actually exceed its critical load if total sulphate deposition were overestimated by 11 meq/m^2/yr. This scenario is conceivable, as CALPUFF simulations assumed worst-case emissions from KMP, as discussed in Section 7.6.
- We have assigned a "possible" likelihood of exceedance to a situation where the predicted deposition is 0 to 10 meq/m^2/yr *below* a lake's critical load. This likelihood

level assumes that predicted deposition levels could have been underestimated by up to 10 meq/m^2/yr.

- If deposition is more than 20 meq/m^2/yr below the critical load, exceedance is considered to be very unlikely.

Consequence categories

The first part of the "minor" consequence category ("<5 % study area lakes exceed CL"; first column of Table 8.6-6), was based on standards adopted in both Canada and Europe, and applied to both the number and area of lakes in the study area. Both the Canada-Wide Acid Rain Strategy for post-2000 (CCME 1998:4) and the Canadian Acid Rain Assessment (Jeffries 1997) define critical loads as "the amount of sulphate that can be deposited on the area and still maintain 95 % of the lakes in the region at or above a pH of 6". As discussed above, more recent analyses for the Canadian Acid Rain Assessment (Jeffries et al. 2000) exclude naturally acidified "brown water" lakes with pH_o <6 from the set of "lakes in the region". The Gothenburg Protocol (EMEP 1999), an agreement developed by the Cooperative Programme for Monitoring and Evaluation of Long-range Transmission of Air Pollutants in Europe, utilizes a manual on methodologies and criteria for mapping critical levels/loads (UNECE 2004). This manual uses the 5^{th} percentile of the cumulative distribution function of critical loads in a grid cell as the critical load criterion (i.e., protecting 95 % of the *area* or resources within a grid cell). We examine both the percentage of lakes and the percentage of area affected within each of the grid cells in the risk assessment framework (Table 8.6-7), with and without consideration of lakes with pH_o <6.

The other consequence categories (5-10 %, 10-15 %, 15-25 %, >25 %) were based on an examination of the proportion of lakes with pH <6 in different parts of the U.S. EPA's National Surface Water Survey (NSWS). We assigned colours in Figure 8.6-8 to each of the NSWS regions based on the definitions of impact levels in Section 8.6.4, the generally accepted scientific consensus on the relative level of acidification impact in each of these regions (Baker et al. 1991a,b), and additional information on critical load exceedances for New England and Maine from Dupont et al. (2005). The higher deposition level in central New England and higher risk of exceedances of critical loads resulted in an orange colour (moderate impact) though less than 10 % of the lakes have a pH <6. While scientific information from these U.S. regions is informative, the assignment of specific impact levels and colours (i.e., low, moderate, high, and critical) is ultimately a subjective decision.

In Table 8.6-6, the second part of the "minor" and "medium" consequence categories has the additional phrases: "AND 0 sampled streams exceed CL", as well as "AND Lakelse Lake does not exceed CL". This wording is meant to ensure that for a minor or medium consequence rating to be assigned both the sampled streams (which were chosen due to their high public interest and use) and Lakelse Lake (the most important lake in the region for fisheries and recreation) need to have deposition levels below their CL (i.e., fall into likelihood categories C, D or E). We maintained the same phrase "AND Lakelse Lake does not exceed CL" for the "serious" and

"major" categories of consequences. If the CL for Lakelse Lake were to be exceeded (i.e., fall into likelihood categories A or B), the consequence is deemed to be "catastrophic", through the use of the phrase "**OR** Lakelse Lake exceeds CL" in column 5 of Table 8.6-6 (i.e., even if <5% of lakes exceeded their CL, the consequence would be considered catastrophic if one of those lakes were Lakelse Lake). For the "serious", "major" and "catastrophic" categories we consider an escalating level of impacts on the 14 sampled streams (1-2 streams with CL exceeded for "serious", 3-4 for "major" and 5 or more for "catastrophic"). These categories of impacts on sampled streams are connected to lake effects by "OR", so that these effects would be sufficient to trigger the consequence category regardless of how many lakes had CL exceedances. We apply such a high weight to these streams not only because of their public importance, but also because they are mostly higher order streams (Table 4.2-2) and would be expected to have higher critical loads than the most sensitive headwater streams.

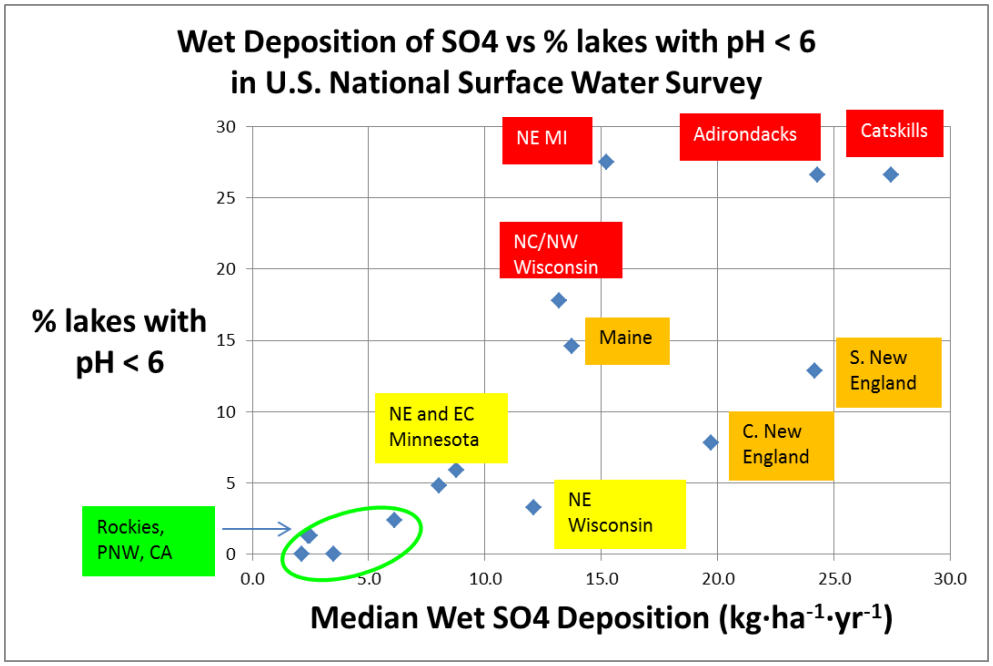
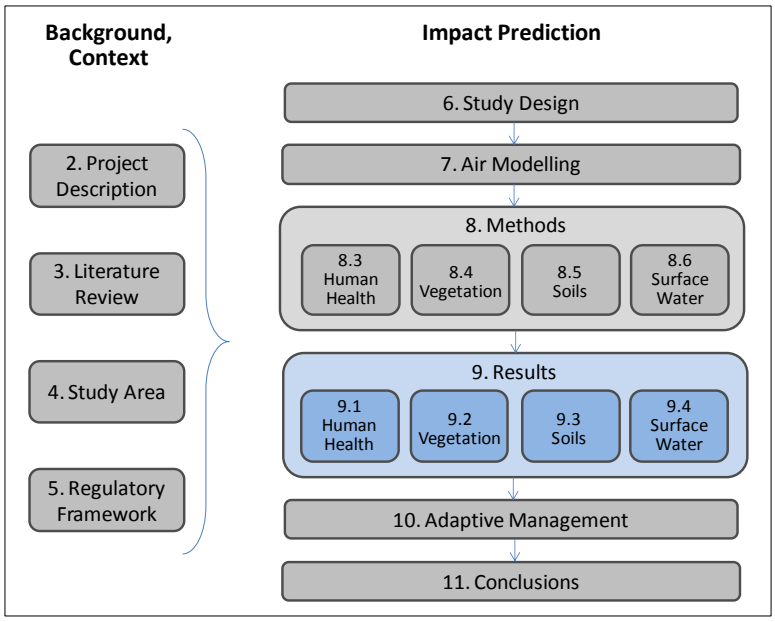


Figure 8.6-8: Risk assessment categories applied to 15 regions of the United States which were part of the National Surface Water Survey.

Regions are colour-coded based on the general risk assessment framework presented in Section 8.1, the water-specific assessment framework in Figure 8.6-8, the generally accepted scientific consensus on the relative level of acidification impact in each of these regions (Baker et al. 1991a,b) and additional information on critical load exceedances for New England and Maine from Dupont et al. (2005). The low, moderate, high and critical levels of impact are defined in the overall description of the risk assessment framework (Section 8.1). Source of data: Baker et al. 1991a (see caption to Figure 8.6-1 for more information on the data set).

9.0 Assessment Results and Discussion



9.1 HUMAN HEALTH STUDY

9.1.1 Results

9.1.1.1 SO_2 concentrations used in exposure-response analysis

Hourly average concentrations

Modelled exposures are well below the British Columbia Ministry of the Environment PCOs (450 µg/m^3 and 900 µg/m^3) for a great majority of the time, with less than 100 hours per year above 450 µg/m^3 (i.e., less than 1% of the time) and less than 10 hours per year above 900 µg/m^3 (i.e., less than 0.1% of the time). As demonstrated in Figure 9.1-1, ≥90% of the 1-hour average SO_2 concentrations in all residential areas are <10 µg/m^3. In the Service Centre, over 80% of the 1-hour average SO_2 concentrations are <10 µg/m^3. In all areas, ≥99% of the 1-hour average SO_2 concentrations are <100 µg/m^3. Note that these ranges (<10 µg/m^3 and <100 µg/m^3) are provided for illustration of the typical range of exposures, and do not have any particular meaning as thresholds for health effects.

It is important to note that the B.C. PCOs (as well as those of other organizations such as WHO and U.S. EPA) should not be interpreted as thresholds for health effects. For susceptible individuals (people with pre-existing respiratory diseases), a respiratory response is possible at

any level of SO_2 concentration, though the probability of an SO_2 induced respiratory response decreases toward zero as the SO_2 level decreases toward zero. To predict health outcomes, the entire distribution of SO_2 levels must be considered, rather than focusing on the number of exceedances of any given level.

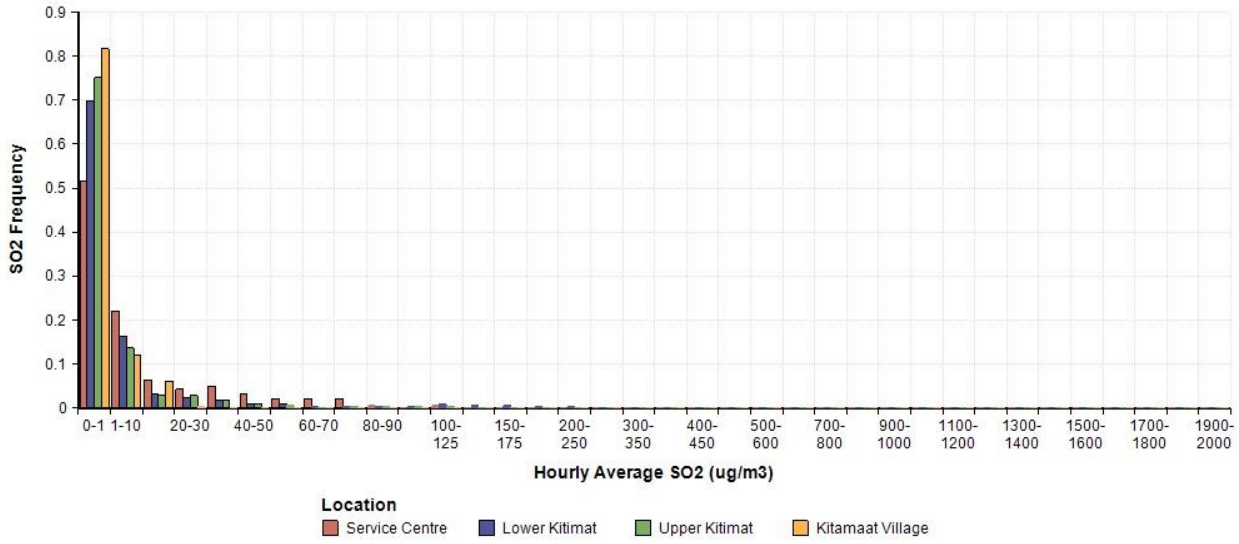


Figure 9.1-1: Modelled 1-hour average SO_2 concentrations by location.

As illustrated in Figure 9.1-2, the frequency distribution of 1-hour averaged SO_2 concentrations is highly skewed, and a significant majority of concentrations are <10 µg/m^3.

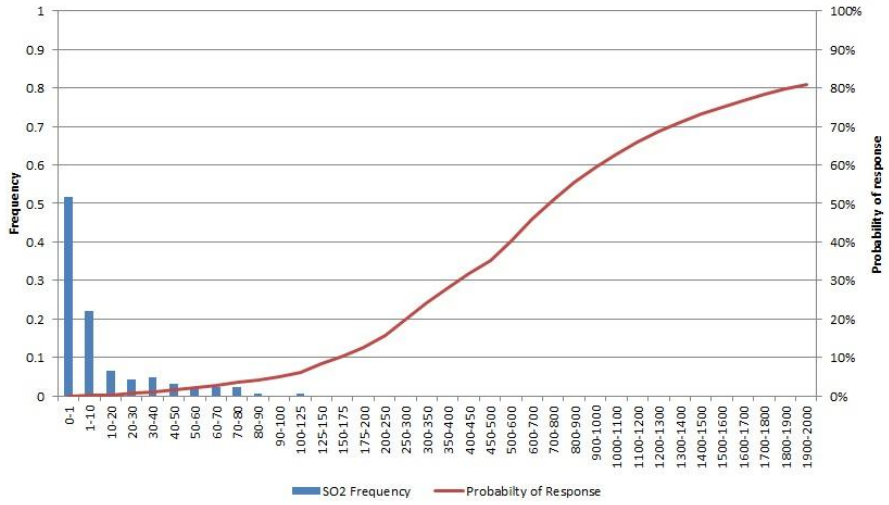


Figure 9.1-2: Frequency distribution of hourly average SO_2 concentrations and probability of respiratory response due to SO_2. The y-axis provides the relative frequency (for the bars) and the probability of response (the line).

Table 9.1-1 illustrates the percentage of respiratory responses corresponding to each hourly average concentration bin. The number of responses per bin is determined by both the exposure level and the fraction of exposures that occur at that level. The following results are for Lower Kitimat, though other regions would have similar relationships with respect to the contribution of each concentration bin to the overall number of responses.

Note that for this location, there were no incidents of concentrations above 800 µg/m^3 and, therefore, the risk contribution of these bins is zero.

Table 9.1-1: Percentage of predicted respiratory responses corresponding to hourly average SO_2 concentrations.

Concentration (µg/m^3)	Percentage of Respiratory Responses	Cumulative Percentage of Responses
0-50	19.2	19.2
50-100	20.4	39.6
100-150	17.8	57.4
150-200	14.5	71.9
200-250	11.6	83.4
250-300	7.4	90.8
300-350	4.1	95.0
350-400	2.0	97.0
400-450	1.2	98.2
450-500	0.7	98.9
500-600	0.7	99.6
600-700	0.3	99.9
700-800	0.1	100.0

From the above table, it can be seen that hourly-averaged exposures below 450 µg/m^3 would contribute approximately 98% of the responses due to their much higher likelihood as compared to higher exposures. This is the basis for considering the entire distribution and not just the exposures above a given threshold when considering the sources of health risk.

9.1.1.2 Baseline health risk estimates

Our "baseline" scenario is characterized by the following assumptions.

1. Seventy five percent of the 1,200 susceptible individuals (900) are physically active during 200 days per year, yielding 180,000 exercise events per year.

2. Half of physical exercise events (90,000) occur outdoors.
3. Exercise events in susceptible individuals are distributed among the four areas in Kitimat according to the baseline allocation scenario as illustrated in Figure 9.1-6 (below).

Under these assumptions, we estimated that between 150 and 200 respiratory responses per year would occur. Numbers of responses vary by area (Figure 9.1-3) as a result of two factors: estimated SO_2 levels and annual numbers of exercise events in each area.

People with pre-existing respiratory disease such as asthma are considered, from the clinical perspective, to be "well controlled" when they experience less than one restricted airway event per week (National Heart Lung and Blood Institute 2007, internet site). If we assume that the population of asthmatics in Kitimat experiences asthma symptoms at a rate of approximately once per week (or approximately 50 events per year), then the assumed susceptible population of 1,200 people would experience approximately 60,000 restricted airway responses per year. The actual number of responses may be much higher given that not all asthmatics' symptoms would be considered to be "well controlled." As such, the predicted exposure to SO_2 causing, for example, an additional 150 respiratory responses would constitute an increase in the overall number of approximately 0.25%.

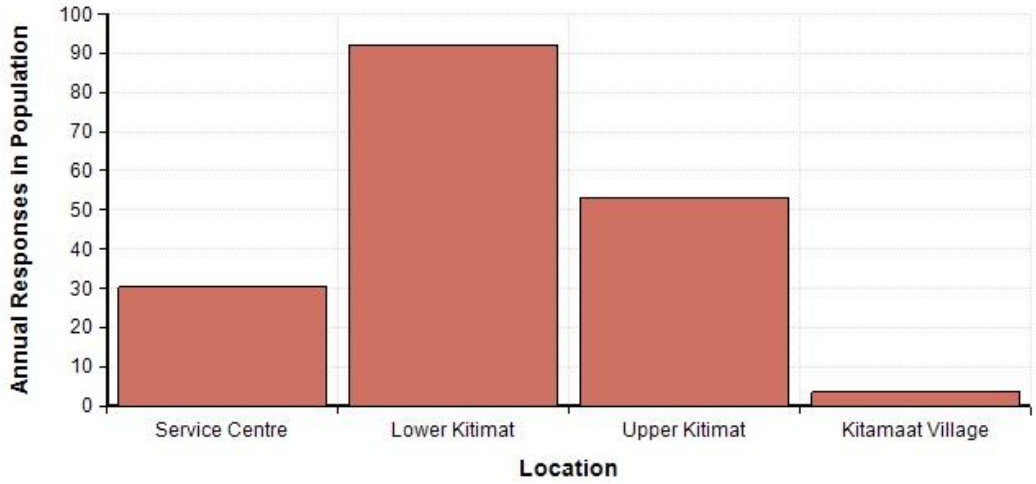


Figure 9.1-3: Estimated annual respiratory responses by area (baseline scenario).

9.1.1.3 Sensitivity analyses

Sensitivity analyses were performed to evaluate how the estimated number of respiratory responses is affected by changes in the following parameters:

- indoor-outdoor fraction of exercise events;
- exercise frequency (proportion of physically active individuals and number of days of physical activity per year); and
- allocation of exercise events to the four areas of interest in Kitimat.

Indoor-outdoor fractions of exercise events

As illustrated in Figure 9.1-4, shifting the proportion of outdoor events from 50% to 75% would increase the estimated number of respiratory responses by approximately 30%. Shifting this proportion of outdoor events to 25% would decrease the estimate by approximately 30%.

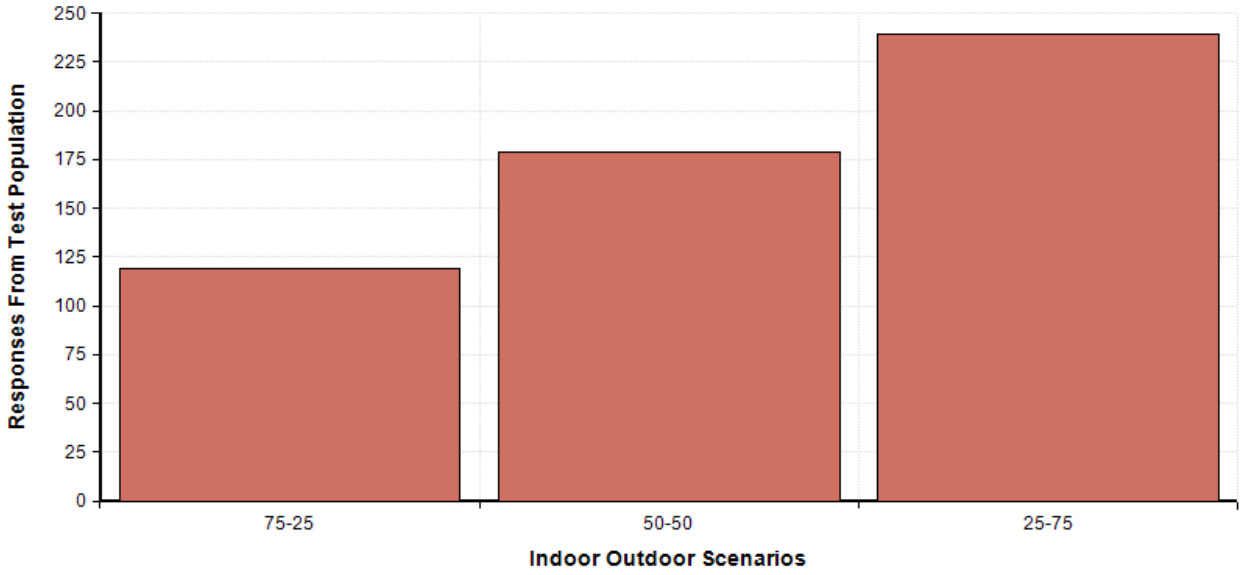


Figure 9.1-4: Estimated number of respiratory responses depending on indoor-outdoor fraction of exercise events.

Exercise frequency

As expected, the annual number of respiratory responses is directly proportional to both variables related to exercise frequency: the proportion of physically active individuals and the annual number of "physically active" days (Figure 9.1-5). For example, a 50% reduction in the number of days of physical activity per year would reduce the risk of respiratory responses by 50%.

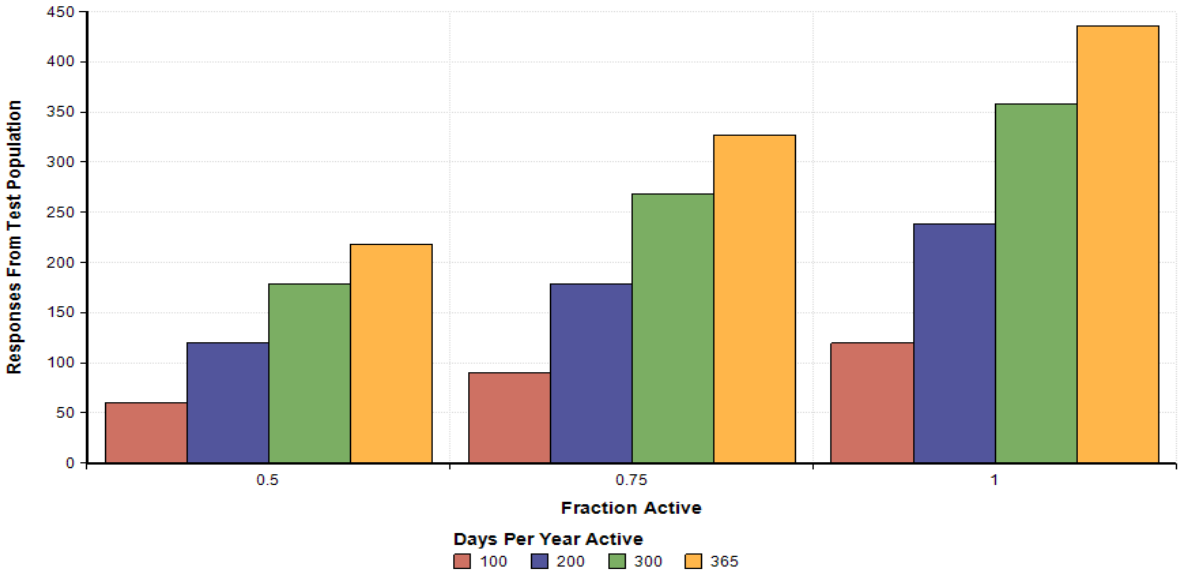


Figure 9.1-5: Estimated number of respiratory responses depending on exercise frequency.

Location of exercise events

The predicted numbers of respiratory responses in susceptible individuals were calculated under two allocation scenarios for exercise events. In the baseline scenario, the Lower and Upper Kitimat areas each account for 40% of the exercise events, with the Service Center and the Kitamaat Village accounting for 10% each. To explore the sensitivity of this result to this exercise location assumption, we used a "Higher Exposure" scenario in which a proportion of exercise events were reallocated from areas of lower exposure (Upper Kitimat and Kitamaat Village) to the area of highest exposure (Service Center). In this scenario, 40% of exercise events occur in the Service Center area. The reallocation of exercise events is shown in Figure 9.1-6.

The assumed shift in the location of some exercise events from the areas of lower exposure to the area of highest exposure increases the predicted number of respiratory responses by approximately 25% (Figure 9.1-7).

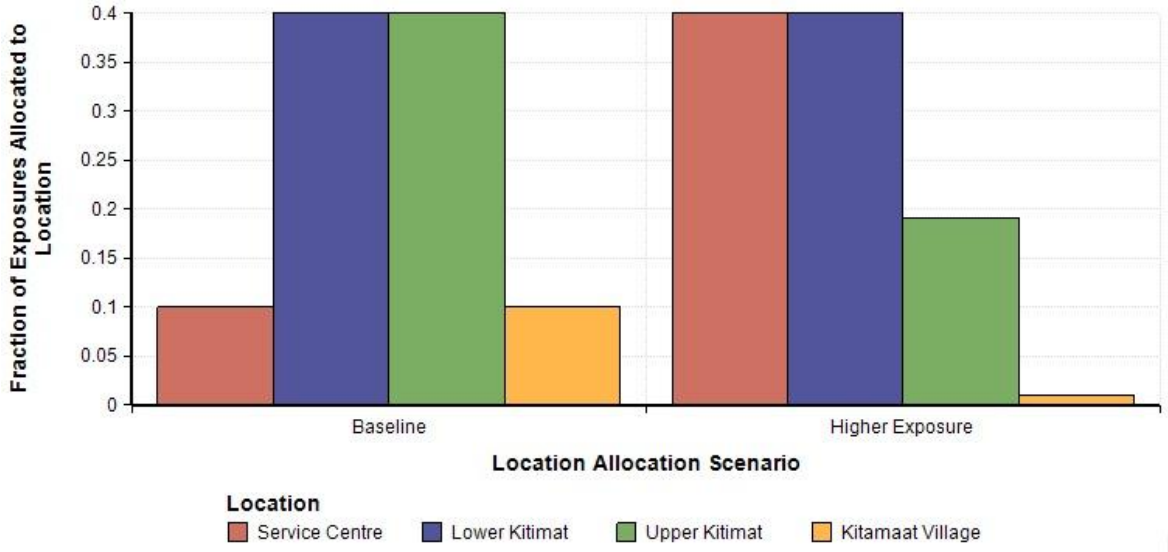


Figure 9.1-6: Allocation scenarios for exercise events in susceptible individuals.

Figure 9.1-7: Estimated number of respiratory responses depending on location of exercise events.

9.1.1.4 Summary

The predicted levels of SO_2 in the Kitimat business and residential areas are well below the British Columbia Ministry of the Environment PCOs, with the exception of less than 100 hours per year (less than 1% of the time). It is important to note that these PCOs do not correspond to thresholds for health effects. The predicted numbers of exceedances of PCOs are not predictive of the number of predicted respiratory responses. The full distribution of SO_2 exposures must be taken into account to predict health risk.

Under a conservative baseline scenario, SO_2 exposures post-KMP could cause between 150 and 200 restricted airway responses per year among physically active susceptible individuals with asthma and/or chronic obstructive pulmonary disease.

When exploring various alternate assumptions associated with patterns of exercise frequency and location, the number of predicted airway responses falls within a range from 50 to 500.

Restricted airway responses are reversible, common among the susceptible individuals and can be caused by exposures other than SO_2 (allergens, cold temperatures, physical exercise). They would generally be treated by reducing the level of physical activity, relocating indoors (where SO_2 levels should be lower) and through use of medication either before exercise or after symptoms are detected.

9.1.2 Discussion and risk assessment

The overall level of health risk associated with exposure to SO_2 in the post-KMP scenario is classified as 2-D, with the **Consequence** categorized as medium and **Likelihood** categorized as Susceptible Population, Infrequently Affected (Table 9.1-2).

Table 9.1-2: Risk assessment results for health according to the combined likelihood and consequence dimensions of the risk assessment framework.

	Consequence				
Likelihood	1 - Minor Irritation or mild reversible health effect not requiring medication, behaviour modification, or medical attention	2 - Medium Irritation or mild reversible health effects requiring medication or behavior modification	3 - Serious Reversible effect requiring medical attention	4 - Major Irreversible health effect with ongoing mild or moderate disability	5 - Catastrophic Fatality or long-term serious disability
A – Almost certain Whole population, frequently affected					
B – Likely Whole population, infrequently affected					
C – Possible Susceptible sub-population, frequently affected					
D – Unlikely Susceptible subpopulation, infrequently affected		X			
E – Very Unlikely Small susceptible population, infrequently affected					

We based the **Consequence** score on the reversibility of the health outcome of restricted airway responses. The health outcome predicted in the risk assessment model is a sensitive endpoint (increase in specific airway resistance) that may or may not be detectable by the susceptible individual. Given the mildness of the predicted health outcomes, the characterization of the **Consequence** as **Medium** could be considered somewhat conservative.

We based the **Likelihood** score on the health evidence that the susceptible population is limited to people with existing restricted airway diseases, which includes approximately 12% of the population. Among this population, less than one restricted airway response per person per year is expected. The increase in the number of restricted airway events due to SO_2 among this

population is expected to be less than 1%. On this basis, we selected the **Likelihood** score of **D - Susceptible Subpopulation, Infrequently Affected**.

Exposure to SO_2 causing restricted airway responses will result in a continuum of potential health consequences ranging from very mild to serious (e.g., emergency room visits); however, increasingly severe health outcomes are also increasingly infrequent. Therefore, when considering the range of health outcome consequences that may result from SO_2 exposure, the alternative categories of **1-D** (**Consequence** is **Minor**; **Likelihood** is **Susceptible Sub-Population, Infrequently Affected**) and **3-E** (**Consequence** is **Serious; Likelihood** is **Small Susceptible Population, Infrequently Affected**) could also be considered to be appropriate.

The overall health impact is characterized as **moderate** (yellow) – acceptable but in need of closer scrutiny with moderate monitoring.

This characterization of **moderate** impact is influenced by the conservative nature of the risk estimation process employed. One method of estimation in the presence of uncertainty is to adopt "conservative" assumptions. By "conservative" assumptions, we mean choosing, from within a range of possibilities, an assumption or number that would lead to an overestimate rather than an underestimate of risk. The following list describes assumptions that we used which are conservative in nature.

1. Given two choices of dose-response relationships available in the U.S. EPA report, we have chosen the relationship leading to higher estimates of the number of respiratory responses.
2. The frequency of exercise of people with asthma and chronic obstructive pulmonary disease has been assumed to be similar to the general population.
3. The overall frequency of exercise in the modelled population (the number of people who exercise and the frequency with which they exercise) has been assumed to be relatively high as compared to the North American population.
4. The health endpoint whose frequency is estimated is a mild outcome that constitutes a sensitive indicator of health risk. The corresponding frequency of more severe symptoms (an asthma "attack" or symptoms requiring medical attention) would be lower than we have predicted for the sensitive indicator.

The net effect of the various conservative assumptions is to generate an estimate of risk that is likely to be somewhat higher than the actual risk.

Critical uncertainties

There are numerous sources of uncertainty in any health risk estimation process. Overall, the sources of uncertainty that are most influential in the risk estimation process are expected to be:

1. uncertainty with respect to the predicted levels and spatial and temporal patterns of SO_2 concentrations that will occur post-KMP;
2. uncertainty in the relationship between the peak exposures and the hourly average exposures;
3. uncertainty in the level of health risk at low SO_2 levels. Because the SO_2 levels are usually relatively low (<10 µg/m^3), most of the exercise events modelled will occur during periods of low SO_2; and
4. uncertainty in the frequency (number of participants, frequency of exercise) and location (region, indoor-outdoor, etc.) of exercise among the susceptible population.

We consider uncertainties #1 and #2 to be *critical* uncertainties worth further investigation in the adaptive management phase. Uncertainty #3 (health risk at low SO_2 levels) is a matter of general public health research, and the uncertainty in this area is not limited to the Kitimat context, nor can it be resolved in the adaptive management plan. Uncertainty #4 is unlikely to change either the assessed level of risk or the most appropriate mitigative actions.

9.2 VEGETATION STUDY

9.2.1 Results

9.2.1.1 Field data – S in vegetation

Descriptive statistics of S in vegetation are shown in Table 9.2-1. Mean concentrations ranged from 0.07% to 0.18%. Typical background concentrations reported in the literature are 0.10 to 0.12%, although they vary with species and location. Concentrations of 0.2% or greater have been reported as background in some species (see the literature review in Appendix 3.5-1). Standard deviations were about 10% to 20% of the mean concentration.

There was a strong correlation between annual and growing season SO_2 emissions (r=0.986), indicating that either measure will serve for the analysis. Coefficients of correlation between S emissions and S in vegetation are provided in Table 9.2-2. The correlation coefficients (annual emissions) range from -0.538 (indicating an inverse relationship between emissions and S in foliage, observed at 4 sites) to 0.808. For growing season emissions, the range was similar, as would be expected given the high correlation between annual and seasonal emissions. In general, the correlation between S in foliage and S emissions, or distance from the Kitimat smelter, was low. Only 16 of 67 sites had correlations greater than 0.6, the minimum correlation considered biologically significant in the analysis of the F sampling program. While correlations less than 0.6 may be statistically significant, the magnitude of the correlation indicates the strength of the relationship. Thus correlations of 0.1 to 0.5 may be statistically significant, but the significance is interpreted as strong evidence of a weak relationship.

Table 9.2-1: Descriptive statistics for the concentration of S in hemlock foliage in the vicinity of RTA, 1998-2011.

Site	Distance from RTA (km)	Mean (%)	Standard Deviation (%)	Maximum (%)	Minimum (%)	Range (%)	Number of Observations
1	1.91	0.11	0.00	0.11	0.11	0.00	15
11	1.99	0.12	0.01	0.14	0.10	0.04	12
20	1.08	0.12	0.02	0.15	0.07	0.08	14
24	0.82	0.15	0.02	0.19	0.12	0.07	10
37	1.11	0.16	0.03	0.19	0.09	0.10	12
38	1.82	0.17	0.03	0.23	0.14	0.09	12
38A	2.54	0.17	0.03	0.22	0.13	0.09	12
38B	2.92	0.14	0.03	0.18	0.10	0.08	12
39	3.25	0.13	0.02	0.16	0.09	0.07	14
39A	4.02	0.12	0.02	0.16	0.10	0.06	11
40	0.41	0.12	0.01	0.13	0.10	0.03	12
41	0.51	0.14	0.01	0.17	0.12	0.05	12
42	0.58	0.16	0.03	0.20	0.09	0.11	14
43A	2.35	0.15	0.02	0.21	0.12	0.09	9
43B	2.52	0.15	0.04	0.20	0.07	0.13	12
44	0.85	0.15	0.04	0.21	0.08	0.13	14
44A	6.59	0.17	0.04	0.23	0.09	0.14	11
46	2.85	0.16	0.03	0.22	0.10	0.12	12
47A	6.45	0.12	0.02	0.16	0.09	0.07	12
47B	6.28	0.12	0.02	0.16	0.08	0.08	14
48	5.05	0.18	0.03	0.24	0.13	0.11	12
51		0.15	0.01	0.16	0.14	0.02	2
52	5.65	0.10	0.02	0.14	0.06	0.08	14
54	5.79	0.10	0.02	0.16	0.08	0.08	14
55	6.15	0.10	0.02	0.13	0.07	0.06	14
56	6.55	0.09	0.02	0.11	0.06	0.05	8
57	6.79	0.08	0.02	0.11	0.05	0.06	8
68	4.43	0.09	0.01	0.11	0.06	0.05	14
69	3.41	0.09	0.01	0.11	0.06	0.05	14
70	6.42	0.09	0.01	0.14	0.08	0.06	12
71	7.42	0.09	0.01	0.10	0.08	0.02	12
78	9.45	0.15	0.02	0.17	0.13	0.04	9
79	7.58	0.12	0.03	0.16	0.07	0.09	12
80	11.15	0.11	0.01	0.14	0.09	0.05	8
81	13.54	0.14	0.02	0.16	0.11	0.05	12
81A	14.04	0.14	0.03	0.18	0.10	0.08	11
81B	12.29	0.14	0.04	0.19	0.06	0.13	13
81C	11.11	0.11	0.03	0.15	0.07	0.08	8
82	14.67	0.11	0.02	0.14	0.06	0.08	14
84	49.08	0.09	0.01	0.10	0.07	0.03	12
85	51.32	0.08	0.02	0.10	0.03	0.07	14
86	41.05	0.08	0.02	0.11	0.05	0.06	14
87	3.99	0.14	0.04	0.21	0.07	0.14	14

Site	Distance from RTA (km)	Mean (%)	Standard Deviation (%)	Maximum (%)	Minimum (%)	Range (%)	Number of Observations
88	5.21	0.13	0.02	0.19	0.10	0.09	14
89	8.96	0.14	0.04	0.21	0.08	0.13	12
90	22.03	0.10	0.02	0.15	0.06	0.09	12
91	12.93	0.10	0.02	0.12	0.06	0.06	10
92	10.87	0.10	0.02	0.13	0.06	0.07	11
93	3.14	0.10	0.02	0.11	0.06	0.05	10
94	11.66	0.08	0.02	0.10	0.03	0.07	9
95	5.91	0.08	0.02	0.12	0.04	0.08	12
96	5.47	0.09	0.01	0.10	0.05	0.05	10
97	14.35	0.09	0.02	0.11	0.05	0.06	12
98							1
99							1
100							1
98A	11.63	0.08	0.02	0.10	0.05	0.05	8
99A							1
100A							1
101A							1
200							1
201	4.53	0.09	0.01	0.10	0.08	0.02	6
70A		0.08	0.01	0.09	0.07	0.02	2
78A		0.08	0.01	0.09	0.07	0.02	2
84A		0.07	0.01	0.07	0.06	0.01	2
89A		0.11	0.02	0.12	0.09	0.03	2
91A		0.10	0.01	0.11	0.09	0.02	2

Table 9.2-2: Correlation (r) between S emissions and S concentration in hemlock foliage, 1998-2011.

Site	Distance from RTA (km)	Annual Emissions r	Growing Season Emissions [a] r	Number of Observations [b]
1	1.91	0.000	0.000	15
11	1.99	0.500	0.516	12
20	1.08	0.667	0.634	14
24	0.82	0.268	0.258	10
37	1.11	0.697	0.684	12
38	1.82	-0.528	-0.445	12
38A	2.54	0.646	0.650	12
38B	2.92	0.210	0.131	12
39	3.25	0.614	0.581	14
39A	4.02	0.048	0.135	11
40	0.41	0.381	0.369	12
41	0.51	0.049	0.005	12
42	0.58	0.646	0.640	14
43A	2.35	0.398	0.404	9
43B	2.52	0.688	0.644	12
44	0.85	0.639	0.600	14
44A	6.59	0.409	0.384	11
46	2.85	0.323	0.305	12
47	6.45	-0.105	-0.118	12
47B	6.28	0.577	0.548	14
48	5.05	0.435	0.528	12
51				2
52	5.65	0.407	0.372	14
54	5.79	0.219	0.206	14
55	6.15	0.114	0.092	14
56	6.55	0.662	0.624	8
57	6.79	0.799	0.808	8
68	4.43	0.783	0.775	14
69	3.41	0.369	0.367	14
70	6.42	0.192	0.180	12
71	7.42	0.194	0.163	12
78	9.45	0.705	0.688	9
79	7.58	0.598	0.600	12
80	11.15	0.807	0.803	8
81	13.54	0.606	0.562	12
81A	14.04	0.419	0.559	11
81B	12.29	0.694	0.750	13
81C	11.11	0.376	0.374	8
82	14.67	0.635	0.628	14
84	49.08	-0.016	-0.048	12
85	51.32	0.397	0.461	14
86	41.05	0.558	0.588	14
87	3.99	0.639	0.594	14

Site	Distance from RTA (km)	Annual Emissions r	Growing Season Emissions [a] r	Number of Observations [b]
88	5.21	0.057	0.087	14
89	8.96	0.748	0.741	12
90	22.03	0.425	0.437	12
91	12.93	0.376	0.348	10
92	10.87	0.414	0.397	11
93	3.14	0.211	0.242	10
94	11.66	0.496	0.559	9
95	5.91	0.692	0.708	12
96	5.47	0.435	0.413	10
97	14.35	0.638	0.650	12
98				1
99				1
100				1
98A	11.63	0.332	0.309	8
99A				1
100A				1
101A				1
200				1
201	4.53	-0.271	-0.237	6
70A				2
78A				2
84A				2
89A				2
91A				2

[a] Growing season emissions are those that occur from April through September.
[b] Sites with fewer than three observations do not have correlations.

Data were grouped by location to create 4 transects that are in use in the vegetation monitoring and assessment program. The Eastside Transect (Figure 9.2-1, Figure 9.2-2, Figure 9.2-3 and Figure 9.2-4) has low concentrations of S in foliage, at or below those reported as background in the literature. Early in the sampling period (Figure 9.2-2), it appears that there were higher concentrations of S in foliage, but not above reported background levels.

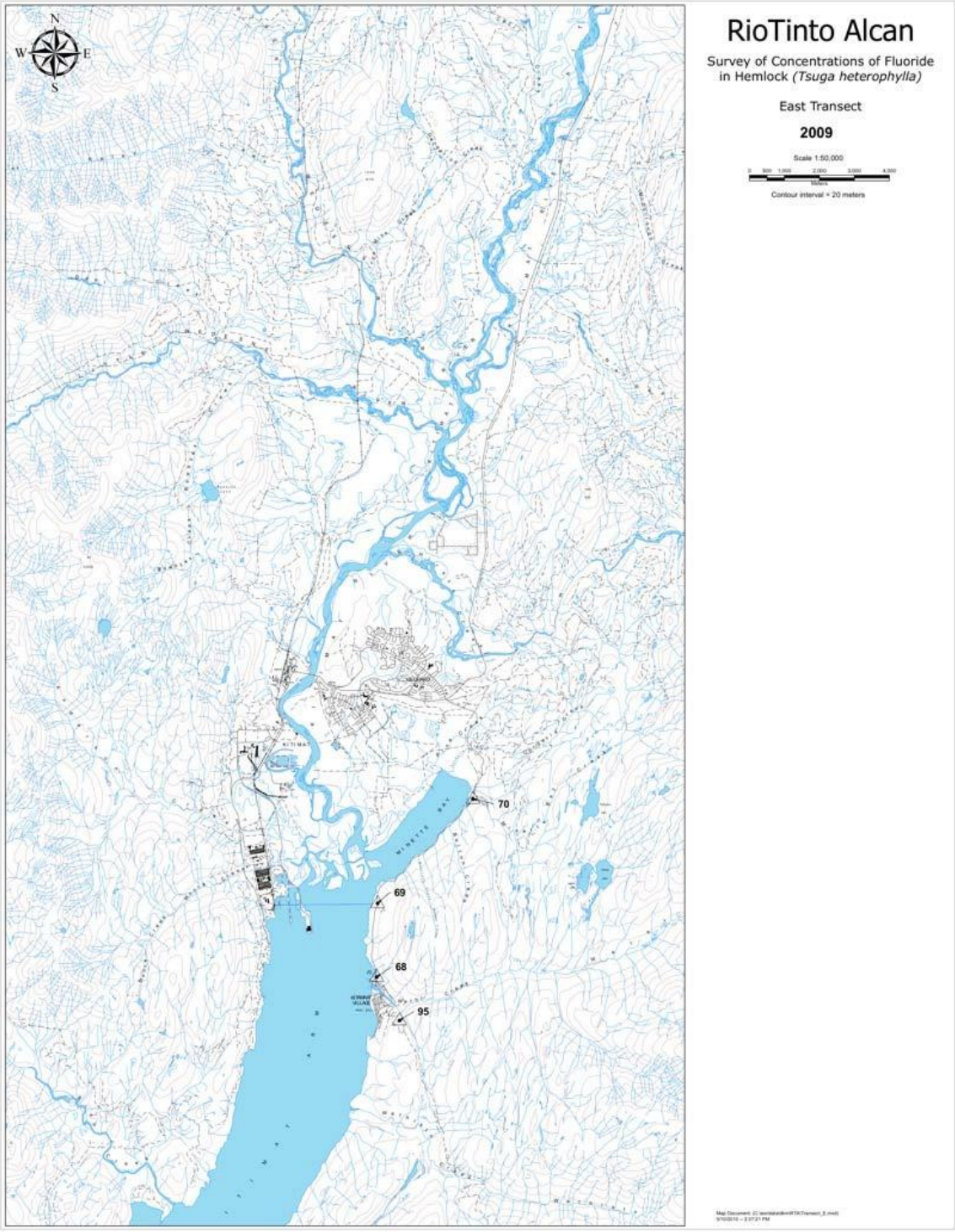


Figure 9.2-1: Location of vegetation monitoring stations on the Eastside Transect.

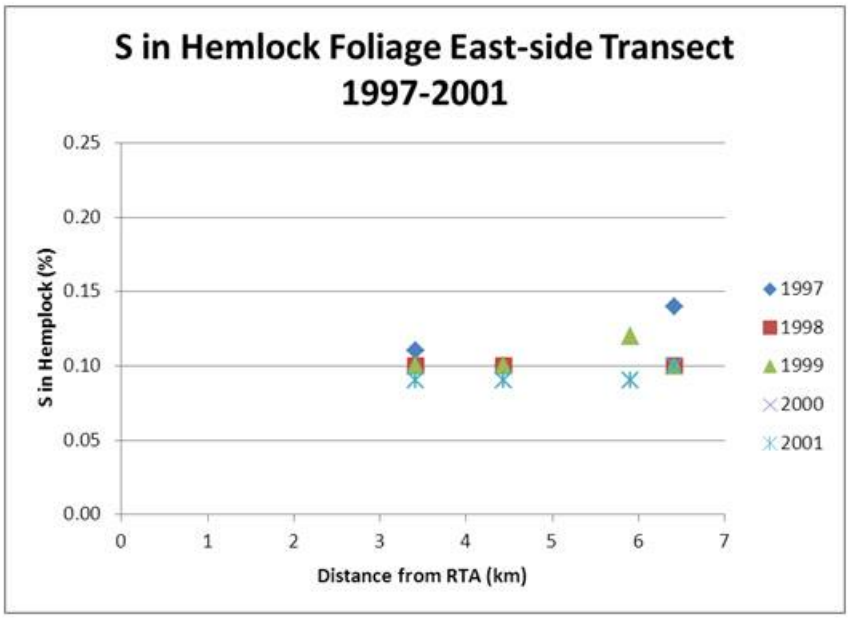


Figure 9.2-2: Percent S in hemlock vs. distance from Kitimat smelter for 1997-2001 (Eastside Transect).

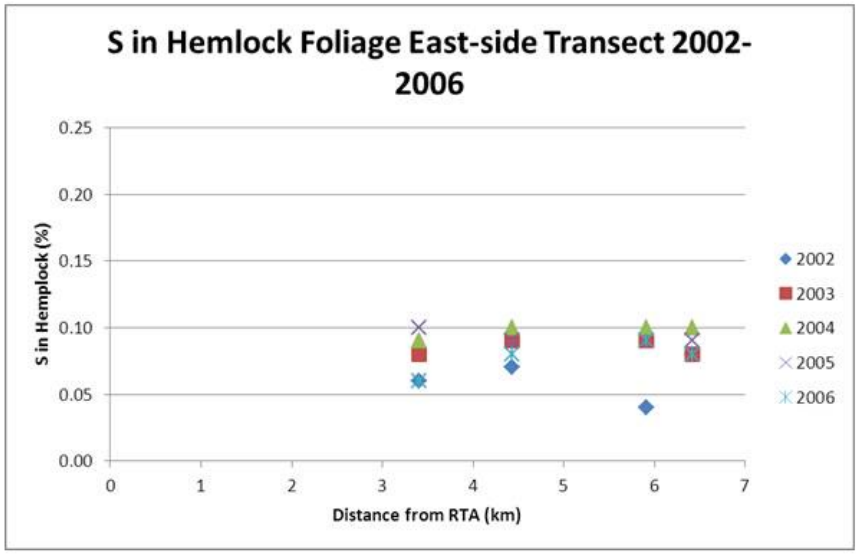


Figure 9.2-3: Percent S in hemlock vs. distance from Kitimat smelter for 2002-2006 (Eastside Transect).

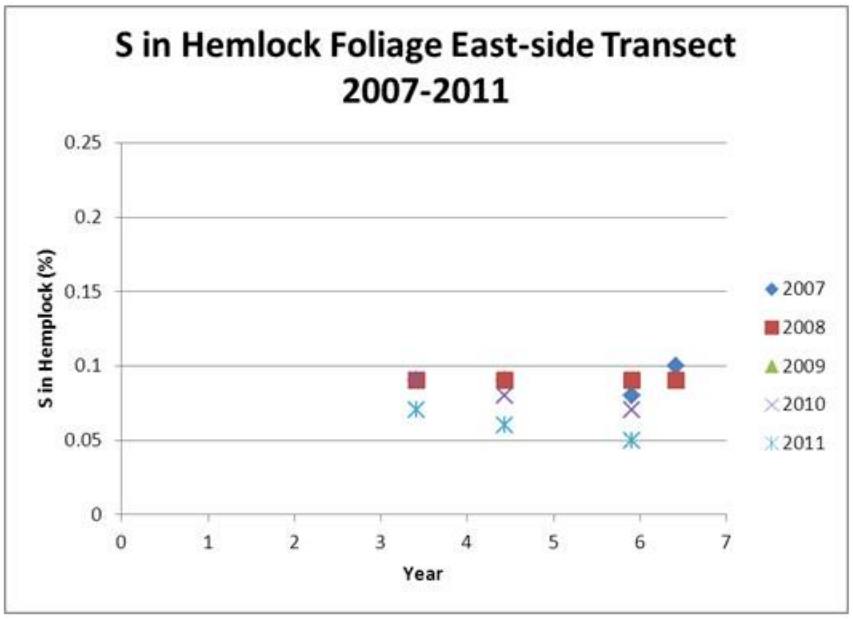


Figure 9.2-4: Percent S in hemlock vs. distance from Kitimat smelter for 2007-2011 (Eastside Transect).

The North Transect (Figure 9.2-5, Figure 9.2-6, Figure 9.2-7 and Figure 9.2-8) does indicate levels of S in vegetation that are likely associated with proximity to the Kitimat smelter. Concentrations decrease with distance, although correlations of S in foliage with distance are generally below the level considered to be evidence of a strong relationship, ranging from -0.42 to -0.72, with most values below -0.6. So while the correlation is weak, the patterns evidenced in the graphs suggest a decline in S concentration with distance.

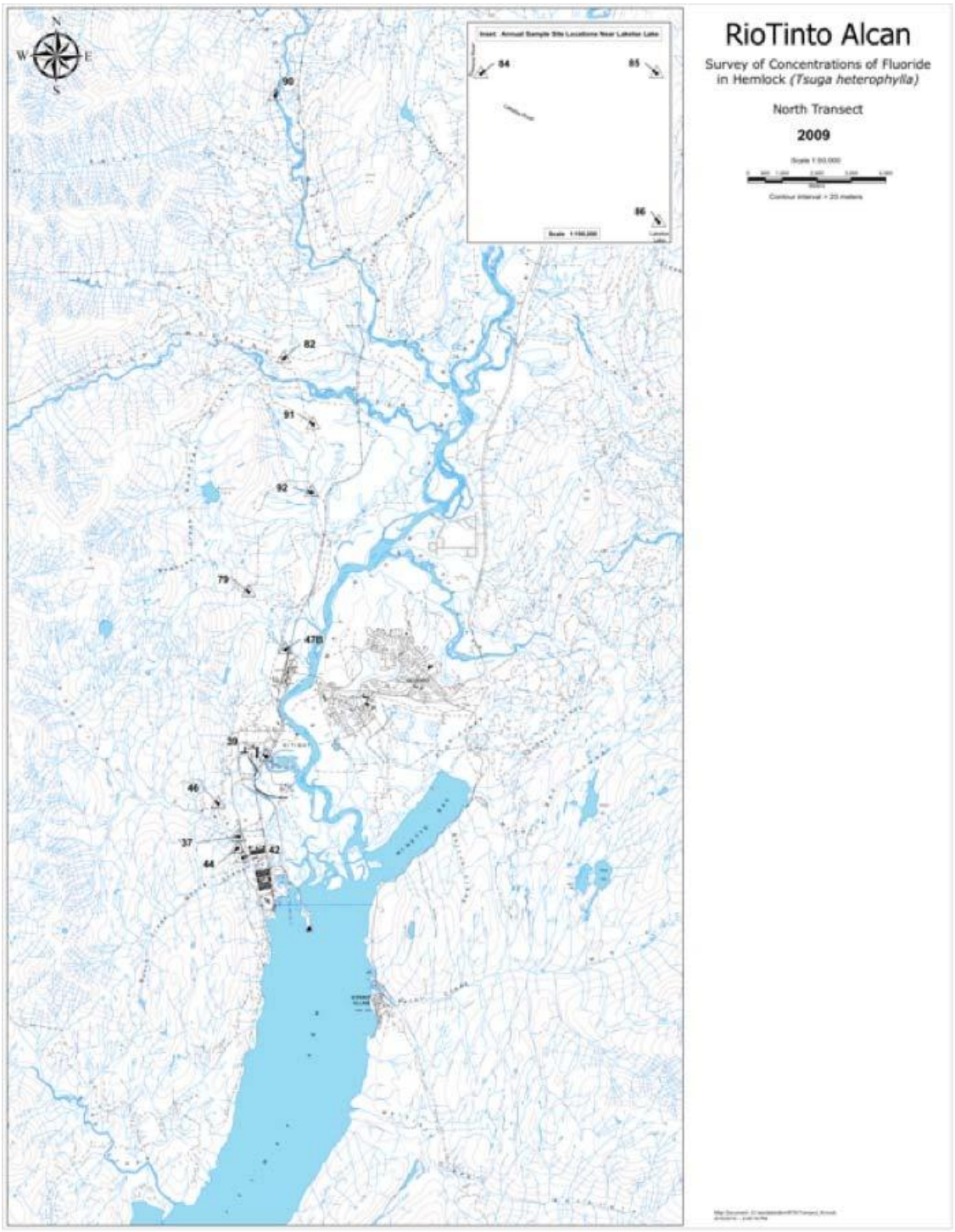


Figure 9.2-5: Location of vegetation monitoring stations on the North Transect.

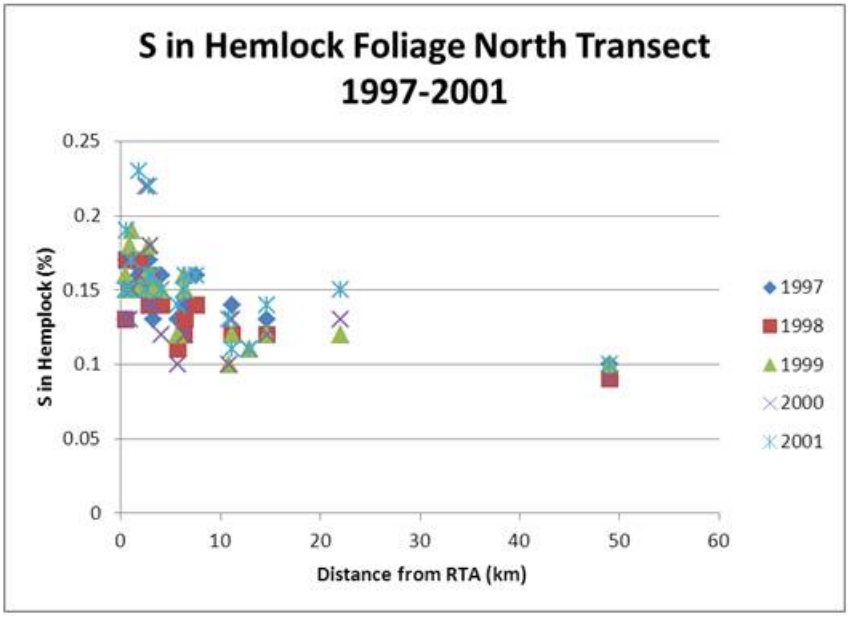


Figure 9.2-6: Percent S in hemlock vs. distance from Kitimat smelter for 1997-2001 (North Transect).

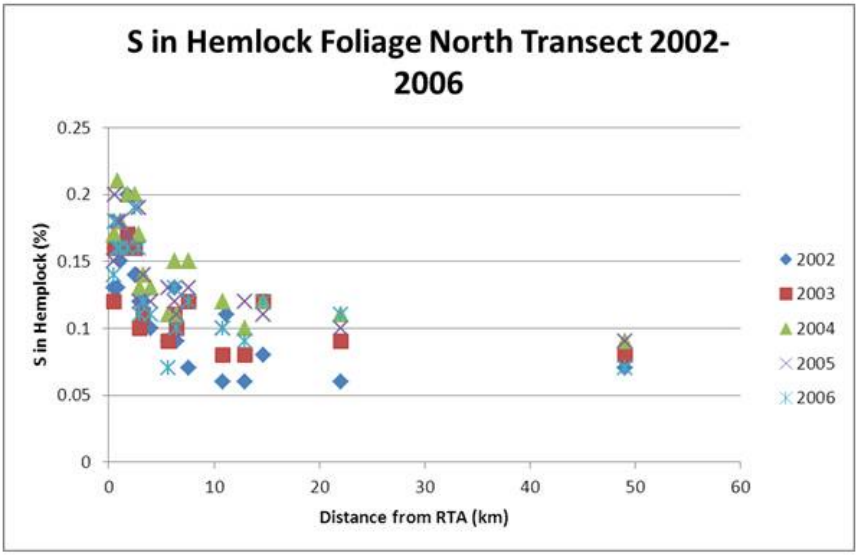


Figure 9.2-7: Percent S in hemlock vs. distance from Kitimat smelter for 2002-2006 (North Transect).

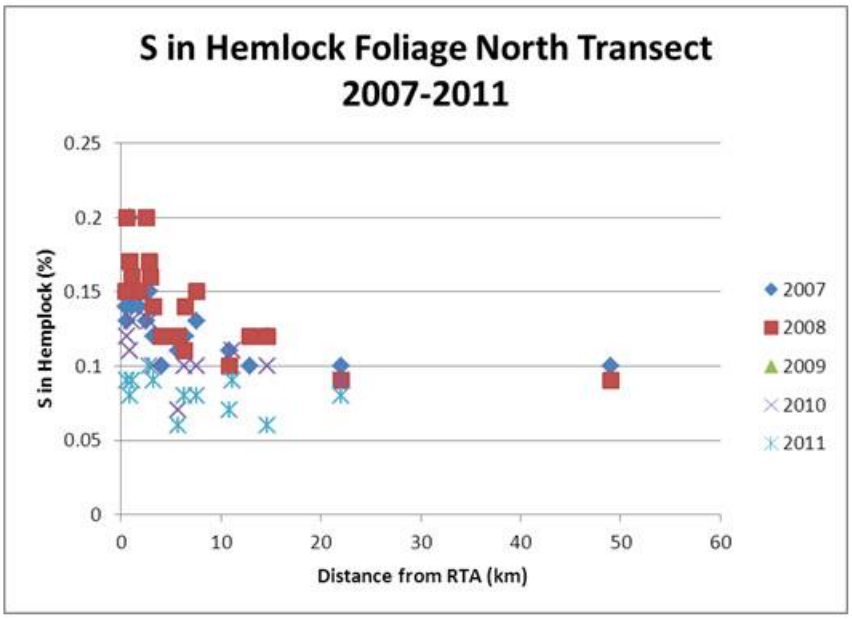


Figure 9.2-8: Percent S in hemlock vs. distance from Kitimat smelter for 2007-2011 (North Transect).

The Northeast Transect (Figure 9.2-9, Figure 9.2-10, Figure 9.2-11 and Figure 9.2-12) shows patterns similar to the Eastside Transect with little apparent relationship between S in foliage and distance from the Kitimat smelter. The concentrations are near 0.10%, a value considered in the literature to be background.

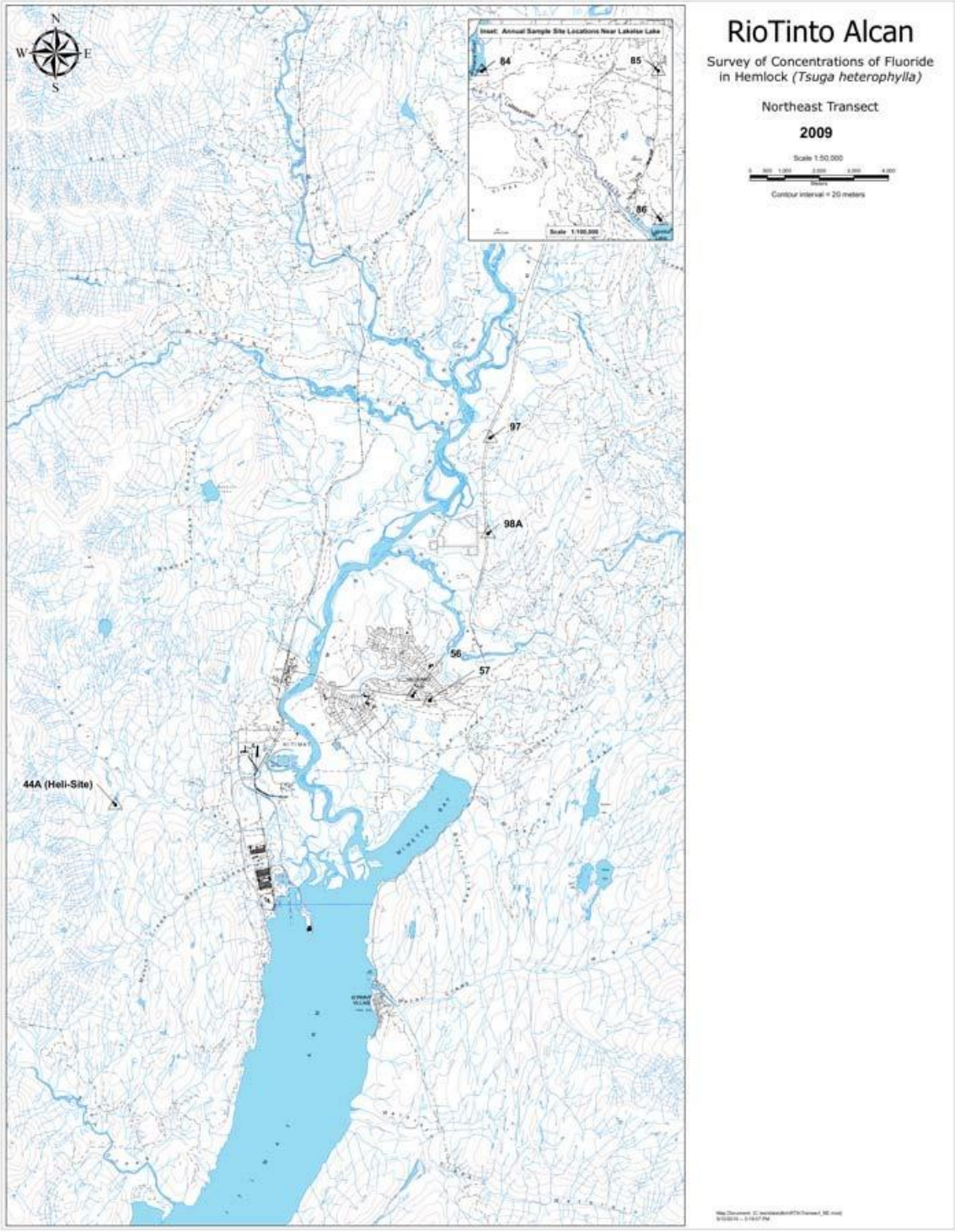


Figure 9.2-9: Location of vegetation monitoring stations on the Northeast Transect.

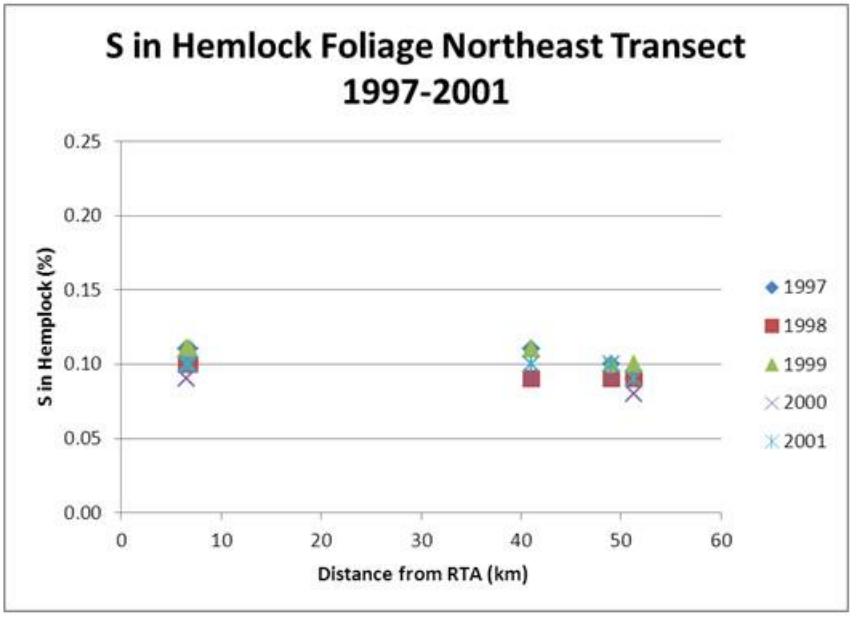


Figure 9.2-10: Percent S in hemlock vs. distance from Kitimat smelter for 1997-2001 (Northeast Transect).

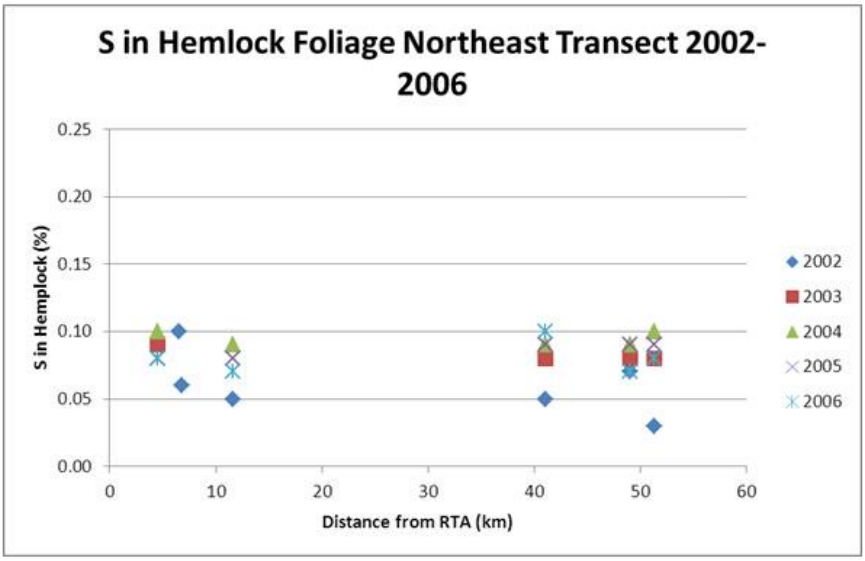


Figure 9.2-11: Percent S in hemlock vs. distance from Kitimat smelter for 2002-2006 (Northeast Transect).

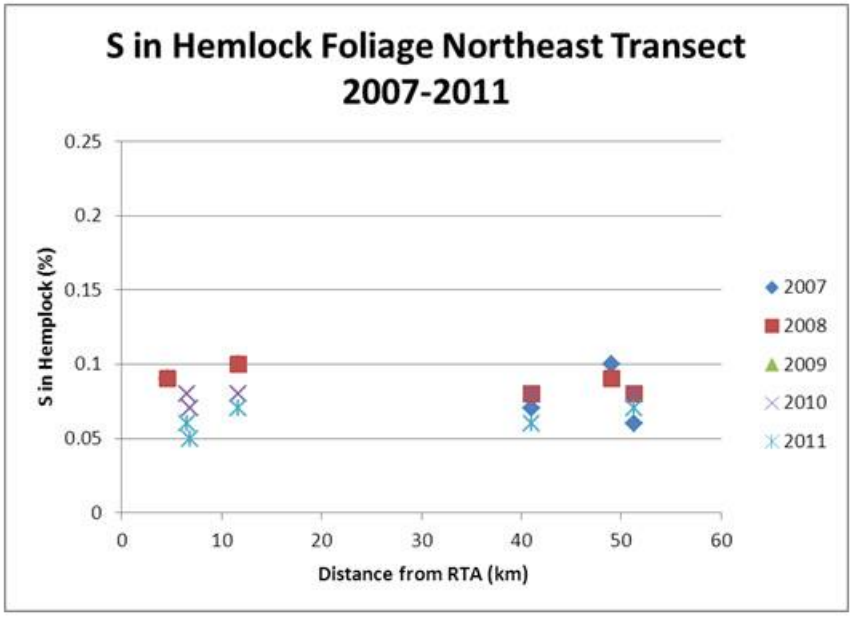


Figure 9.2-12: Percent S in hemlock vs. distance from Kitimat smelter for 2007-2011 (Northeast Transect).

The South Transect (Figure 9.2-13, Figure 9.2-14, Figure 9.2-15 and Figure 9.2-16) is more similar to the North Transect, with concentrations that may reflect emissions from the Kitimat smelter; however, the correlations with distance are not strong. It is possible that soil conditions differ to the south of the Kitimat smelter and that could be reflected in the higher concentrations of S across the extent of the transect.

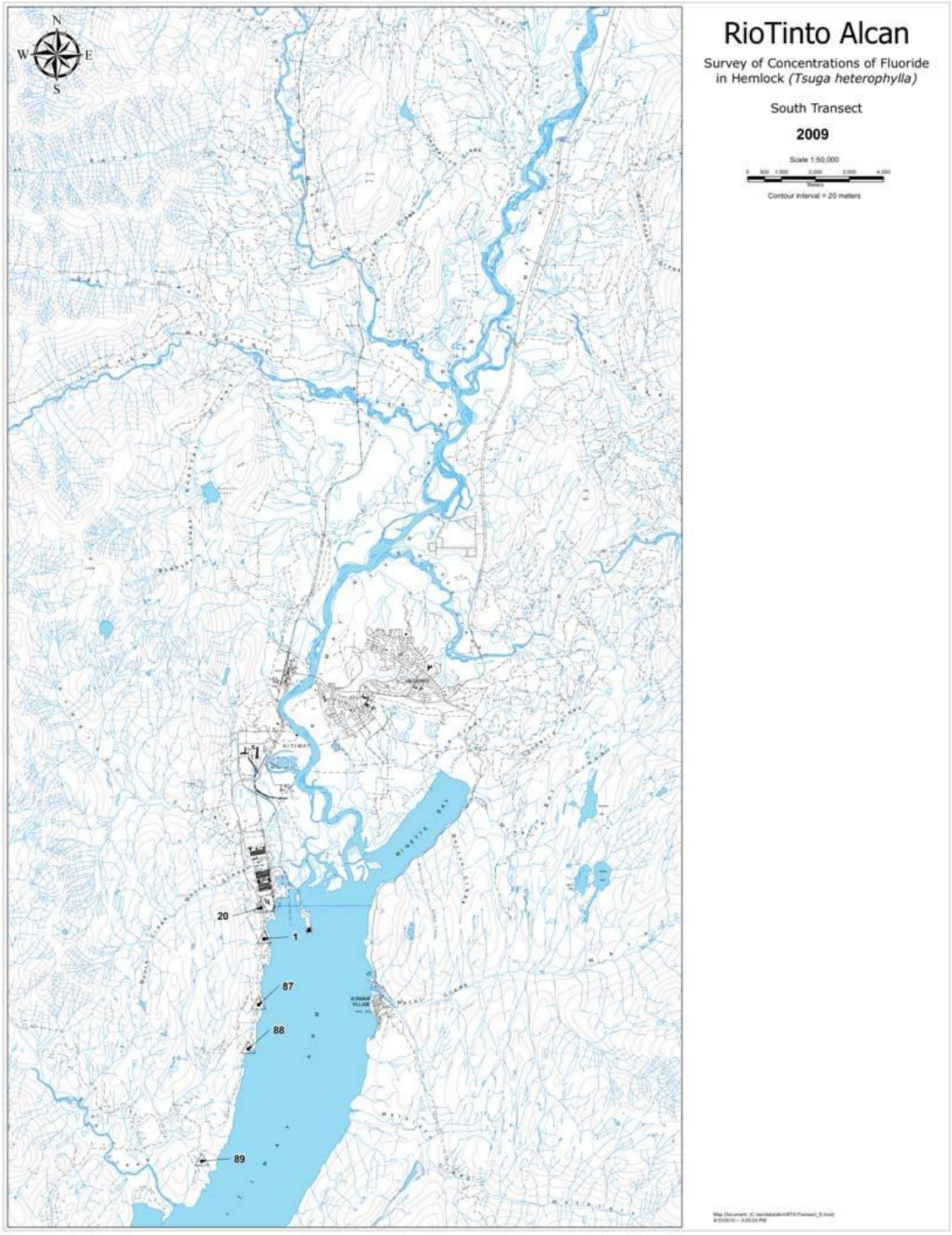


Figure 9.2-13: Location of vegetation monitoring stations on the South Transect.

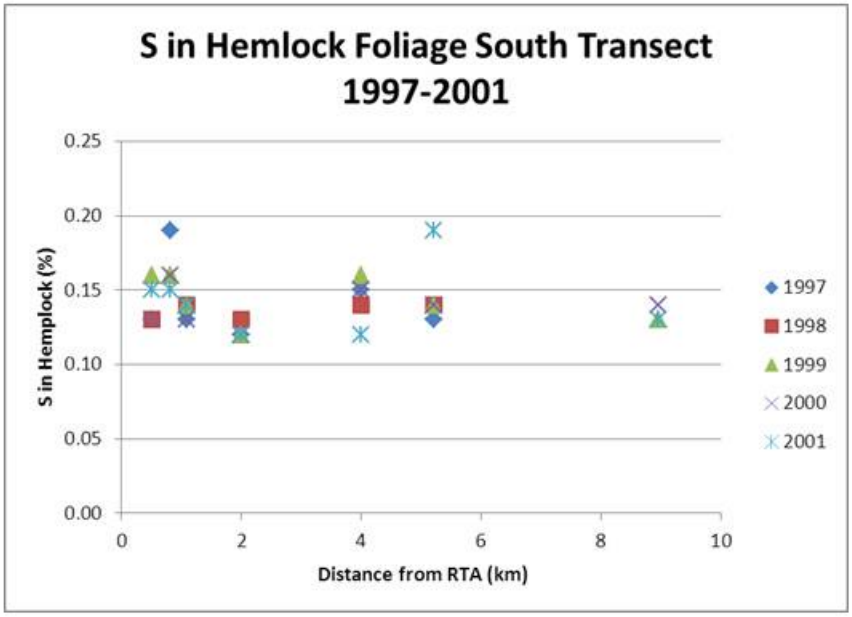


Figure 9.2-14: Percent S in hemlock vs. distance from Kitimat smelter for 1997-2001 (South Transect).

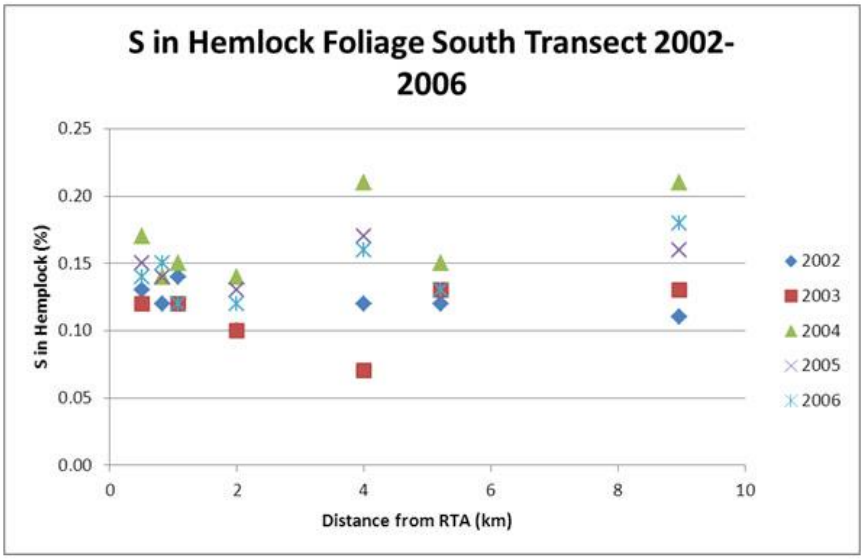


Figure 9.2-15: Percent S in hemlock vs. distance from Kitimat smelter for 2002-2006 (South Transect).

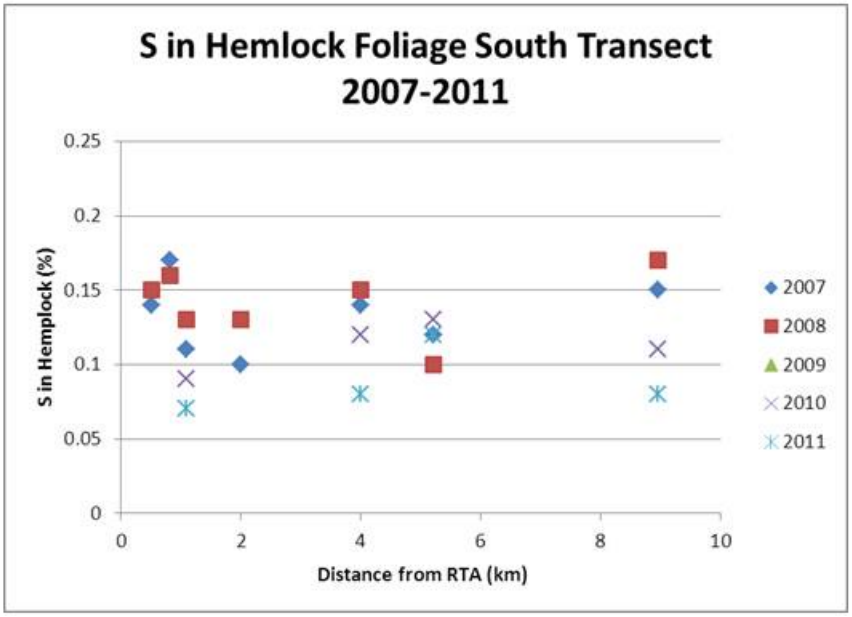


Figure 9.2-16: Percent S in hemlock vs. distance from Kitimat smelter for 2007-2011 (South Transect).

9.2.1.2 Dispersion modelling and thresholds of concern

The results of the analysis indicate that there are relatively few times in which modelled concentrations exceed the thresholds of concern for vegetation, and that, for the most part, the receptors with exceedances are restricted to three locations near KMP (Figure 9.2-17). Most of the exceedances occur at a cliff face on Anderson Creek that, based on helicopter reconnaissance in 2012, is inaccessible for sampling. Table 9.2-3 presents the number of times thresholds of concern are exceeded (at any individual receptor), both under the current conditions, and with KMP assumptions.

Since repeated exposures might have a cumulative impact, we determined the number of repeated exposures over the 653 µg/m^3 (half the SNAAQS 3-hour criterion) threshold. Repeated exposures occurred only under meteorological conditions of 2009 when the model predicted that 6 receptors had a 2nd high 3-hour average greater than 653 µg/m^3. In all cases, both the first and second high 3-hour averages were associated with a single event that began at 9 PM and continued for 6 hours. Thus the exposure was of little concern as it took place at night when plants are not actively taking up atmospheric gases.

Table 9.2-4 presents results for both annual and growing season periods in relation to the Canadian National Ambient Air Quality Objective and Guideline for SO_2. There are a small number of hours that exceed the 1-hour objectives during both time periods. However, the 24-hour objectives are not exceeded during the growing season in any year or under either scenario.

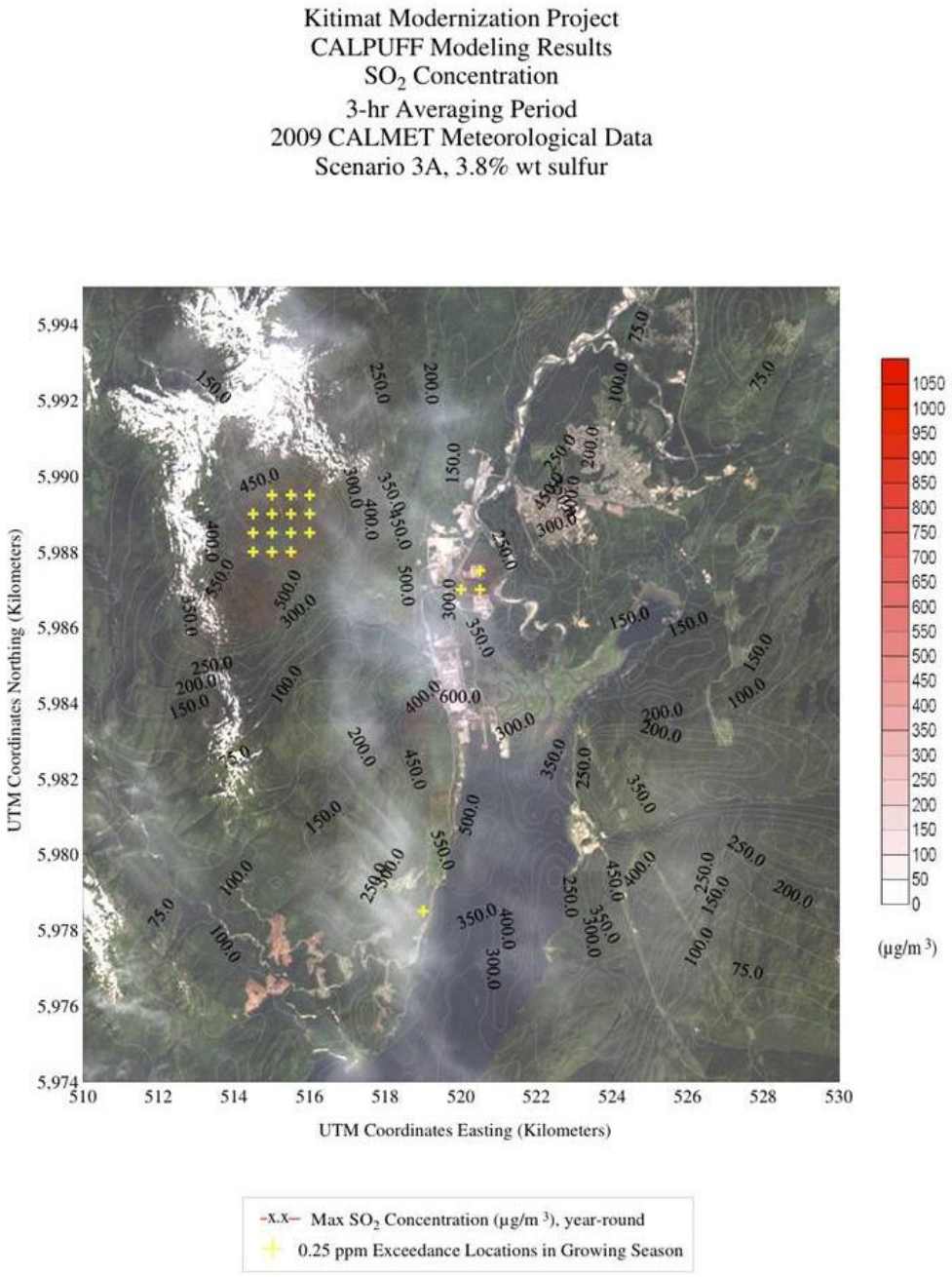


Figure 9.2-17: Maximum 3-hour SO_2 concentrations under KMP and 2009 meteorology, and locations of sites with exceedances above 0.25 ppm (yellow plus signs).

Table 9.2-5 presents the results of modelling and provides concentrations and locations for the 10 highest 1-hour concentrations during the entire year, and during the growing season for each year and each scenario. According to a synthesis by the National Research Council of the U.S. National Academy of Science (NRC 1978), visible injury to the most sensitive species of

plants is possible following exposures of >1 ppm for less than 1-hour or 0.5 ppm to 1 ppm for 1 hour. Concentrations in those ranges occur 12 times over three years (Table 9.2-6).

Table 9.2-3: Number of occurrences at all receptors that exceed thresholds of concern during the growing season.

Averaging Period	**3-hour**		**1-hour**		**24-hour**	
Concentration	**653 µg/m^3**	**1307 µg/m^3**	**491 µg/m^3**	**873 µg/m^3**	**163 µg/m^3**	**329 µg/m^3**
			Number of Receptor-Hours [a]			
Pre-KMP						
2006	135	0	899	61	104	30
2008	151	0	1105	29	125	47
2009	41	0	743	16	83	22
KMP						
2006	1	0	16	3	2	0
2008	0	0	14	4	1	0
2009	18	0	18	5	4	0

[a] The total number of hours at any receptor, including repeated occurrences at the same receptor. There are approximately 11,000 receptors modeled and there are 3,672 hours in the growing period, leading to a total of more than 40,000,000 receptor-hours.

Table 9.2-4: Comparison of modelled SO_2 exposures to the Canadian National Ambient Air Quality Objective and Guideline for SO_2.

SO_2 Exceedance Comparison

Averaging Period	Threshold [a] ($\mu g/m^3$)	Year	Year Round			Growing Season		
			# [b]	Value [c]	Receptor Location (UTM, NAD 27, km)	# [b]	Value [c]	Receptor Location (UTM, NAD 27, km)
1-hour	491	2006	31	754	519.500 E, 5981.500 N	16	1043	517.000 E, 5987.000 N
		2008	34	1039	519.500 E, 5981.500 N	14	632	518.000 E, 5987.500 N
		2009	56	1723	519.500 E, 5981.500 N	18	1058	519.000 E, 5978.500 N
1-hour	873	2006	7	1215	519.132 E, 5983.241 N	3	1482	518.748 E, 5985.238 N
		2008	8	1822	519.132 E, 5983.241 N	4	1068	519.000 E, 5979.000 N
		2009	6	1058	519.000 E, 5978.500 N	5	1477	515.500 E, 5988.500 N
24-hour	163	2006	5	251	519.500 E, 5981.500 N	2	184	517.500 E, 5986.500 N
		2008	5	205	519.500 E, 5981.500 N	1	170	519.145 E, 5979.253 N
		2009	7	249	519.500 E, 5981.500 N	4	193	518.500 E, 5987.500 N
24-hour	329	2006	0	N/A	N/A	0	N/A	N/A
		2008	0	N/A	N/A	0	N/A	N/A
		2009	0	N/A	N/A	0	N/A	N/A

[a] Threshold values associated with Canada's Objectives and Guidelines for SO_2 Maximum Desirable and Maximum Acceptable concentrations.
[b] The number of occurrences for a single receptor to exceed the given threshold for a specified scenario and time frame.
[c] The maximum modelled concentration at the receptor with the greatest number of exceedances in the specified scenario and time frame.

Table 9.2-5: The 10 highest hourly concentrations modelled during the entire year.

Top 10 hours of SO_2 Concentrations						
	Maximum Concentration - All Receptors ($\mu g/m^3$)	Maximum Concentration - Receptor Location (UTM, NAD 27, km)	Maximum Concentration - All Receptors ($\mu g/m^3$)	Maximum Concentration - Receptor Location (UTM, NAD 27, km)	Maximum Concentration - All Receptors ($\mu g/m^3$)	Maximum Concentration - Receptor Location (UTM, NAD 27, km)
No.	2006		2008		2009	
1	2626.3	522.180 E, 5983.612 N	4151.7	519.500 E, 5984.500 N	1963.7	520.000 E, 5985.500 N
2	2358.7	520.000 E, 5985.500 N	3745.2	519.500 E, 5984.500 N	1913.7	522.400 E, 5989.101 N
3	2322.8	519.245 E, 5979.254 N	3376.4	519.500 E, 5985.000 N	1876.4	519.500 E, 5984.000 N
4	2284.1	521.500 E, 5987.000 N	3201.2	520.000 E, 5985.500 N	1734.0	520.500 E, 5987.000 N
5	2254.5	519.130 E, 5983.641 N	2468.1	520.000 E, 5986.000 N	1723.1	519.500 E, 5981.500 N
6	2089.5	519.145 E, 5979.253 N	2003.3	520.000 E, 5983.000 N	1653.3	522.600 E, 5989.201 N
7	1542.4	522.400 E, 5988.701 N	1981.1	520.000 E, 5986.000 N	1651.3	518.945 E, 5979.591 N
8	1483.6	522.500 E, 5988.800 N	1974.9	519.131 E, 5983.541 N	1649.7	515.000 E, 5988.500 N
9	1481.5	518.748 E, 5985.238 N	1843.5	519.000 E, 5983.500 N	1633.3	519.045 E, 5979.252 N
10	1477.7	519.828 E, 5986.523 N	1711.3	519.130 E, 5984.451 N	1578.3	514.500 E, 5988.500 N

Table 9.2-6: The 10 highest hourly concentrations modelled during the growing season.

Top 10 hours of SO_2 Concentrations						
	Maximum Concentration - All Receptors ($\mu g/m^3$)	Maximum Concentration - Receptor Location (UTM, NAD 27, km)	Maximum Concentration - All Receptors ($\mu g/m^3$)	Maximum Concentration - Receptor Location (UTM, NAD 27, km)	Maximum Concentration - All Receptors ($\mu g/m^3$)	Maximum Concentration - Receptor Location (UTM, NAD 27, km)
No.	2006 Growing Season		2008 Growing Season		2009 Growing Season	
1	2089.5	519.145 E, 5979.253 N	3376.4	519.500 E, 5985.000 N	1734.0	520.500 E, 5987.000 N
2	1481.5	518.748 E, 5985.238 N	1416.2	514.000 E, 5988.500 N	1649.7	515.000 E, 5988.500 N
3	1420.0	518.748 E, 5985.238 N	1237.8	519.500 E, 5984.500 N	1633.3	519.045 E, 5979.252 N
4	1160.3	518.000 E, 5985.500 N	1067.7	519.000 E, 5979.000 N	1578.3	514.500 E, 5988.500 N
5	1141.5	522.200 E, 5989.000 N	946.7	519.000 E, 5979.000 N	1458.8	515.500 E, 5987.000 N
6	1042.5	517.000 E, 5987.000 N	926.5	519.000 E, 5979.000 N	1409.1	515.500 E, 5988.000 N
7	1012.0	518.954 E, 5983.644 N	882.9	519.000 E, 5979.000 N	1340.1	520.500 E, 5987.000 N
8	1003.2	518.945 E, 5979.392 N	835.1	519.000 E, 5978.500 N	1308.8	516.000 E, 5989.000 N
9	911.0	518.000 E, 5984.000 N	817.7	514.500 E, 5985.000 N	1282.9	519.000 E, 5983.000 N
10	879.1	522.800 E, 5989.800 N	809.0	514.500 E, 5988.500 N	1209.1	520.000 E, 5984.000 N

9.2.2 Discussion

9.2.2.1 Historical analysis of S in vegetation

The results of the analysis demonstrate that S concentrations in the foliage of western hemlock are within the range of S concentrations reported as background in the scientific literature; however, there are indications that concentrations in needles are higher in the dispersion pattern of the current smelter. S concentrations in western hemlock at areas distant from the Kitimat smelter, or out of the growing season dispersion pattern, average about 0.08 to 0.10%. Concentrations nearer the operation, or along the growing season dispersion pattern, have a greater mean concentration of S, about 0.12-0.17%. Correlations between SO_2 emissions from the Kitimat smelter and S in foliage are generally less than 0.6, indicating a weak relationship between the 2 variables. Sixteen of 67 sampling sites had correlations greater than 0.6, with a maximum correlation of 0.81. By comparison, 26 sites had correlations greater than 0.6 between F emissions and F in foliage, with 8 sites greater than 0.8, versus 2 sites greater than 0.8 in the present analysis. Symptoms of SO_2 injury are not present on vegetation in the vicinity of the Kitimat smelter, an observation that is consistent with the modelling results of the current operation. Symptoms of injury caused by acid rain or acid fog have not been observed on vegetation in the vicinity during the course of the monitoring program (now in its fourth decade). Based on reports in the literature, it is likely that if there are effects of acidification, they will be related to critical loads in soils and not direct exposure. However, the inspection program will continue to assess vegetation for symptoms that might be related to acidic deposition.

Given the weak correlation between S emissions and S in vegetation, the high natural occurrence of S in vegetation, the essential nature of S in plants, and the use of a passive sampling program for SO_2, there seems to be little reason to continue measuring S in vegetation.

Based on the results of the monitoring program, there does not appear to be any direct effect of SO_2 on vegetation currently.

9.2.2.2 Dispersion modelling, thresholds of concern, and projected exposures

The results of the analysis of dispersion modelling indicate that conditions will likely improve with regard to SO_2 exposure of vegetation with the implementation of KMP. Based on the analysis of modelling results, the probability of direct effects of SO_2, even on the most sensitive vegetation, is low. The analysis indicates that the U.S. EPA standard is not exceeded, and that there are only a few places and times where the 3-hour average exceeds the conservative threshold of 653 $\mu g/m^3$ for 3 hours. The Canadian Maximum Acceptable objectives for 24 hours are not exceeded. There are a very few times that the Maximum Desirable objective is exceeded and those are likely associated with 1 or 2 individual events at clustered receptors.

Further, modelling does not suggest the occurrence of repeated episodes where exposure concentrations are in the range that is likely to cause direct effects on plants. The results of the Critical Load analysis for soils indicate that the probability of indirect effects on vegetation through deposition of sulphate to the soils is low. The only exceedance of Critical Load occurs in an area that has been highly disturbed by mechanical processes (clearing, industrial use, etc.) for decades.

9.2.2.3 Likelihood and consequence of KMP emissions with respect to direct effects of SO_2 on vegetation

Given the results of the analysis, it is expected that the effects of SO_2 emissions on vegetation will be restricted to those described in the Very Unlikely and Minor categories (Table 9.2-7). It is highly unlikely that the categories of Almost Certain, Likely, and Possible, and Serious, Major, and Catastrophic will occur. The major uncertainty associated with this projection is the accuracy of the dispersion modelling. If actual ground level concentrations occur that match a higher level of likelihood in the risk assessment matrix for vegetation, then more substantial effects might be anticipated. However, given the years of monitoring program results, and the current exposure conditions (likely greater than expected under KMP), it will still be unlikely that measureable and wide-spread direct effects on vegetation will be observed.

It is unclear where lichens might fall in the classification since nothing is known about the sensitivity of local species to SO_2, and the valley has been industrialized for some decades. We do know that listed lichen species were present long after industry came to the area, at least on the east side of Minette Bay. It is not known if the listed species have persisted, since the last reported collection was in 1991.

We conclude that effects of KMP on vegetation are very unlikely and would be of minor consequence. Within the risk assessment framework, we consider the impact to be **low** (green) – an acceptable impact requiring routine monitoring. We believe this is true, even though soils are in the moderate (yellow) category due to an area of high exceedance near KMP. The vegetation in that highly disturbed area is not typical of surrounding ecosystems and is of low ecological importance or value.

Table 9.2-7: Assessment prediction for vegetation impacts.

	Consequence				
Likelihood	1 – Minor Occasional symptoms of injury due to SO_2 on leaves of the most sensitive species in the immediate vicinity of KMP.	2 – Medium Symptoms of SO_2 injury extending beyond immediate vicinity of KMP Chronic symptoms (chlorosis/necrosis) indicating potential growth effects	3 – Serious Severe & repeated symptoms of SO_2 injury on more than the most sensitive species, including species of economic or social importance Symptoms of SO_2 injury at remote monitoring locations	4 – Major Defoliation of trees and shrubs of high public importance at multiple locations due to SO_2	5 – Catastrophic Death of trees, shrubs, and forbs of high public importance at multiple locations due to SO_2 exposures
A – Almost Certain Exposure of sensitive vegetation to >2,600 µg/m^3 for 1-hour or more during daylight hours of the growing season Exposure of sensitive vegetation to 1,300µg/m^3 for >3 hours on more than one occasion during daylight hours of the growing season.					
B – Likely Exposure of the most sensitive vegetation to 1,300µg/m^3 for 3 hours during daylight hours of the growing season					
C – Possible Exposure of the most sensitive vegetation to 650µg/m^3 for >8 hours during daylight hours of the growing season					
D – Unlikely Exposure of the most sensitive vegetation to 650µg/m^3 repeated daily during daylight hours of the growing season					
E – Very Unlikely Exposure of vegetation to less than 1,300µg/m^3 for 3 hours or 650µg/m^3 for 8 hours during daylight hours of the growing season	X				

9.2.2.4 Seasonality of exposures and sensitivity of lichens

The International Cooperative Programme (ICP) on Modelling and Mapping of Critical Loads and Levels and Air Pollution Effects, Risks and Trends (found at http://www.unece.org/env/lrtap/workinggroups/wge/mapping.html) reports that annual means of 10-30 µg/m^3 are appropriate to protect lichens, forests, and agricultural crops from effects of SO_2. The ICP specifies wintertime means as well, since winter cereal crops are widely grown in Europe, can be active under European winter conditions, and can take up SO_2 (WHO 2000). That is not the case for the Kitimat area where the growing season and dormant season are pronounced. Air dispersion modelling results presented in Table 7.6-10 project that the maximum offsite annual mean concentration will be 35 µg/m^3, nearly within the range of concentrations deemed protective by ICP. Given that wintertime exposures are likely to be of little concern to higher plants in forest ecosystems (trees, shrubs, and forbs), and based on the results of growing season analyses presented above, it is unlikely that long-term, low concentration exposures will be problematic.

WHO (2000) also discuss the sensitivity of lichens to SO_2 and points out that since lichens are not dependent on uptake of gases through stomata, they may be susceptible whenever metabolically active. Again, due to the pronounced winter season in Kitimat, the metabolic activity of lichens is likely limited primarily to the growing season used in this analysis. Even so, WHO suggests an annual mean of 10 µg/m^3 will protect lichens from effects of SO_2. Isopleths of projected SO_2 annual mean concentrations show that exposures meet the 10 µg/m^3 level once away from the vicinity of KMP that is bounded on the south by the current vegetation inspection site #89 and to the north by a location just north of the Service Centre. There is variability from year to year, primarily in north-south extent. In no case does it appear that exposures greater than an annual average of 10 µg/m^3 extend into the alpine or sub-alpine areas.

In the adaptive management phase, the vegetation inspection and monitoring program will continue to assess the presence of lichens and mosses at inspection locations.

The current vegetation monitoring and inspection program will be continued, so as to confirm the analysis presented above, and to document the condition of vegetation, including the effects of insects, disease, abiotic stressors, and emissions from KMP.

9.3 SOILS STUDY

9.3.1 Results – critical loads and exceedance

9.3.1.1 Soil data

Soils were moderately acidic ranging from pH (H_20) 4.8 (rock types CA and SO) to 5.4 (VA) for weighted-average site pH (Table 9.3-1), and low in clay content (<10%), ranging from sandy

loam to silty-loam in texture (Table 9.3-1). Composite soils for each bedrock category contained between 6.4% (VC) and 17.5% (OG) organic matter (LOI) and soil bulk density ranged between 0.64 g/cm^3 (OG) and 1.05 g/cm^3 (SO; Table 9.3-1).

Table 9.3-1: Physical characteristics and pH of composite pit samples (weighted-average of individual depth analysis) summarized by the 11 bedrock categories in the Kitimat Valley. See Table 8.5-1 for abbreviations of bedrock categories.

Measurement	**Bedrock category**										
	CA	G0	GD	GR	LM	OG	QD	QM	S0	VA	VC
Depth (cm)	50	50	46	50	50	50	50	50	50	50	50
Bulk density (g/cm^3)	0.90	0.70	0.90	0.89	0.99	0.64	0.95	0.79	1.05	0.93	1.03
Loss-on-ignition (%)	8.8	14.7	9.2	9.6	7.4	17.5	8.2	12.8	6.2	8.6	6.4
pH H_2O	4.8	5.2	5.1	5.2	5.2	5.1	5.0	4.9	4.8	5.4	5.3
pH $CaCl_2$	3.7	3.8	3.9	4.1	4.0	4.0	4.2	3.7	3.8	4.0	4.0
Pebbles (%)	0.00	0.05	0.00	0.00	0.11	0.67	0.71	0.88	0.02	0.24	1.20
Sand (%)	35	53	27	46	46	50	46	62	38	49	61
Silt (%)	61	41	65	49	45	46	47	34	56	46	34
Clay (%)	4.3	6.2	7.7	5.7	9.1	3.0	6.3	3.1	6.4	4.8	4.0

Soils sampled (n = 51) from all sites in the eleven bedrock categories were dominated by silicate (SiO_2), aluminum (Al_2O_3) and iron (Fe_2O_3) oxides, accounting for more than 70% of the oxides present in each bedrock category (Table 9.3-2). Sodium oxide (Na_2O) was the dominant base cation oxide (ranging from 2.1 to 3.0%) in soil from the majority (9) of the 11 bedrock categories. Calcium oxide content was the dominant oxide in GO and OG and ranged from 1.1 to 2.6% (Table 9.3-2). Magnesium oxide values were between 1.1 and 1.8% and K_2O was between 1.1 and 2.7% for soils sampled from the 11 bedrock categories (Table 9.3-2).

Table 9.3-2: Oxide content composite pit samples (weighted-average of individual depth analysis) summarized by the 11 bedrock categories in the Kitimat Valley. See Table 8.5-1 for abbreviations of bedrock categories.

Chemical	Bedrock category										
(%)	CA	GO	GD	GR	LM	OG	QD	QM	SO	VA	VC
SiO_2	56	53	57	56	58	53	57	55	61	56	58
TiO_2	0.83	0.61	0.74	0.76	0.81	0.57	0.82	0.47	0.84	0.85	0.85
Al_2O_3	15	12	13	15	14	13	15	13	14	15	15
Fe_2O_3	6.5	7.1	5.3	6.2	6.9	4.2	5.8	4.9	5.9	6.3	6.9
MnO	0.09	0.25	0.07	0.08	0.07	0.09	0.10	0.07	0.07	0.11	0.09
MgO	1.8	1.4	1.1	1.3	1.7	1.1	1.2	1.4	1.4	1.6	1.7
CaO	1.6	2.6	1.5	1.6	1.5	2.7	1.4	1.1	1.3	1.2	1.3
K_2O	1.3	1.6	1.5	1.5	1.1	1.8	1.5	2.7	1.4	1.5	1.2
Na_2O	2.1	2.3	2.6	2.3	2.1	2.5	2.7	3.0	2.2	2.2	2.2
P_2O_5	0.20	0.13	0.21	0.16	0.26	0.17	0.15	0.08	0.24	0.20	0.23
LOI	14	19	16	15	13	21	14	17	11	14	12

Soil from all 11 bedrock categories contained quartz and the aluminum-silicate minerals, muscovite, K-feldspar, plagioclase, clinochlore and actinolite, which is consistent with the oxide analysis (Table 9.3-3). Other common minerals observed in soil included hematite (8/11 bedrocks), kaolinite (9/11 bedrocks) and magnetite (5/11 bedrocks), although these secondary clay minerals do not contain base cations and hence do not buffer against acidity or affect the base cation weathering rate and critical load calculations. The other base cation-containing minerals identified in soils in the study region were the Ca^{2+}-containing minerals calcite (present at CA and OG), laumontite (also present at CA and OG), stilpnomelane (contains K^+ and Mg^{2+} and was present at 6 sites) and paragonite (contains Na^+ and was present only at VC; Table 9.3-3).

Table 9.3-3: Measured qualitative mineralogy for each rock type from composite soil samples; x indicates presence and a blank cell is absent. See Table 8.5-1 for abbreviations of bedrock categories.

Mineral	Chemical Formula	Bedrock category										
		CA	G0	GD	GR	LM	OG	QD	QM	S0	VA	VC
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	X	X	X	X	X	X	X	X	X	X	X
Andalusite	Al_2SiO_5				X							
Calcite	$CaCO_3$	X					X					
Clinochlore	$(Mg,Fe^{2+})_5Al(Si_3Al)O_{10}(OH)_8$	X	X	X	X	X	X	X	X	X	X	X
Glaucophane	$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$								X			

Mineral	Chemical Formula	Bedrock category										
		CA	G0	GD	GR	LM	OG	QD	QM	S0	VA	VC
Hematite	a-Fe_2O_3	X	X		X	X		X		X	X	X
Kaolinite	$Al_2Si_2O_5(OH)_4$	X	X		X	X		X	X	X	X	X
K-Feldspar	$KAlSi_3O_8$	X	X	X	X	X	X	X	X	X	X	X
Laumontite	$Ca_4[Al_8Si_{16}O_{48}]_{18}H_2O$	X					X					
Lepidocrocite	γ-$Fe^{3+}O(OH)$								X			
Magnetite	Fe_3O_4		X	X	X	X		X				
Muscovite	$KAl_2AlSi_3O_{10}(OH)_2$	X	X	X	X	X	X	X	X	X	X	X
Paragonite	$NaAl_2AlSi_3O_{10}(OH)_2$											X
Plagioclase	$NaAlSi_3O_8 – CaAl_2Si_2O_8$	X	X	X	X	X	X	X	X	X	X	X
Pyrite	FeS_2						X		X	X		
Quartz	SiO_2	X	X	X	X	X	X	X	X	X	X	X
Stilpnomelane	$K(Fe^{2+},Mg,Fe^{3+})_8(Si,Al)_{12}(O,OH)_{27}$			X	X	X	X	X		X		

We grouped the estimated mineral classes (determined by A2M from measured oxide content and observed qualitative mineralogy) to be consistent with data input required by the PROFILE model to estimate weathering rates. The dominant minerals for soils within every bedrock category were quartz (range in average 21 to 43%) and plagioclase (range in average 17 to 39%). It should also be noted that there is a considerable range in the possible content of all base cation-containing minerals; for example, the possible plagioclase content of the CA bedrock type ranges from 15.4 to 57.5% (Table 9.3-4). Consequently, all possible mineralogy combinations for soil in each bedrock type were used in PROFILE (n = 980 weathering estimates for the study area). The other dominant mineral classes present in soil at all sites include muscovite (range in average 8 to 25%), K-feldspar (range in average 6 to 13%), hornblende (range in average 6 to 20%), Fe-chlorite (range in average 7 to 11%) and small amounts of apatite (range in average 0.3 to 0.9%). Calcite was estimated to be present in small amounts at two bedrock types (CA and OG; Table 9.3-4).

Table 9.3-4: Percent mineralogy (average (avg) and range (minimum to maximum)) estimated using A2M and summarized for soils sampled within each bedrock type (Quartz not shown). See Table 8.5-1 for abbreviations of bedrock categories.

Rock Type	Apatite		Calcite		Fe-Chlorite		Hornblende		K-Feldspar		Muscovite		Plagioclase	
	Avg	Range	Avg	Range	Avg	Range	Avg	Range	Avg	Range	Avg	Range	Avg	Range
CA	0.6	0.3-1.1	2	0.1-4.2	8.7	0.2-19.8	10.3	0.6-29.7	8.2	0.7-10.2	11.6	4.8-13.9	30.9	15.4-57.5
G0	0.5	0.3-0.7			10.2	0.1-26.7	7.5	0.6-16.8	6.6	1.4-12.4	13	1.5-17.3	34.4	29.6-40.6
GD	0.5	0.3-1.0			6.2	0.1-18.4	9.1	2.8-17.9	10.1	0.8-17.1	11.5	2.7-15.7	30.5	22.4-42.6
GR	0.4	0.3-0.5			6.7	0.1-19.7	8.9	0.3-22.6	9.4	2.0-13.9	13.8	6.4-19.0	29.9	19.6-45.3
LM	0.9	0.3-1.6			9.4	0.1-22.4	10	1.1-42.6	6.6	2.3-8.9	8.8	0.7-12.1	27.6	14.3-49.6
OG	0.5	0.4-0.7	1.1	0.0-2.8	8	0.2-17.9	7.6	0.2-15.3	6.8	0.2-14.1	15.3	0.1-19.4	39.2	30.1-51.8
QD	0.4	0.2-0.7			7.1	0.1-19.4	9.4	2.5-27.8	9	2.6-13.7	12.9	5.9-18.7	29.8	23.2-43.1
QM	0.3	0.0-0.5			11.3	0.1-53.0	20.2	1.6-42.1	13.9	1.0-29.0	9.1	0.6-13.4	23.9	0.5-42.5
S0	0.6	0.2-1.1			7.7	0.1-17.6	6.8	1.6-15.2	8.3	1.7-11.0	11.7	4.5-15.0	21.9	10.5-35.8
VA	0.6	0.4-0.7			8.7	0.5-19.4	8.9	3.1-20.6	9.2	4.0-11.5	12.5	5.4-15.7	24.7	18.1-39.7
VC	0.8	0.4-1.5			9.6	0.1-20.7	6.8	1.0-21.9	7	0.9-10.0	25.4	5.4-39.6	17.3	0.1-42.2

9.3.1.2 Base cation weathering rates

In general, BC weathering was dominated by Ca^{2+} and Na^{+}, and average base cation weathering rates for soils within each bedrock category ranged between 0.105 (OG) and 0.288 eq/m^3/a (CA; Table 9.3-3), although the range in weathering rates estimated for the soil pits varied considerably among bedrock categories (Table 9.3-5). Base cation weathering rates based on the average, temperature-modified, for each bedrock category ranged between 33.4 and 173.8 meq/m^2/a (Figure 9.3-1). The average weathering rate for alpine complexes and till veneer surficial soils (78.1 meq/m^2/a) was significantly lower compared with the average for other surficial materials (135.0 meq/m^2/a; $p<0.01$ unpaired t-test). Base cation weathering rates for soils in the majority of the study area were between 50 and 150 meq/m^2/a, which is considered to be moderately sensitive to acidic deposition (Figure 9.3-1). The areas with the lowest weathering rates (25 to 50 meq/m^2/a) were generally located to the south of Kitamaat Village (south-east portion of study area) and at higher elevation regions south-west of Terrace (Figure 9.3-1).

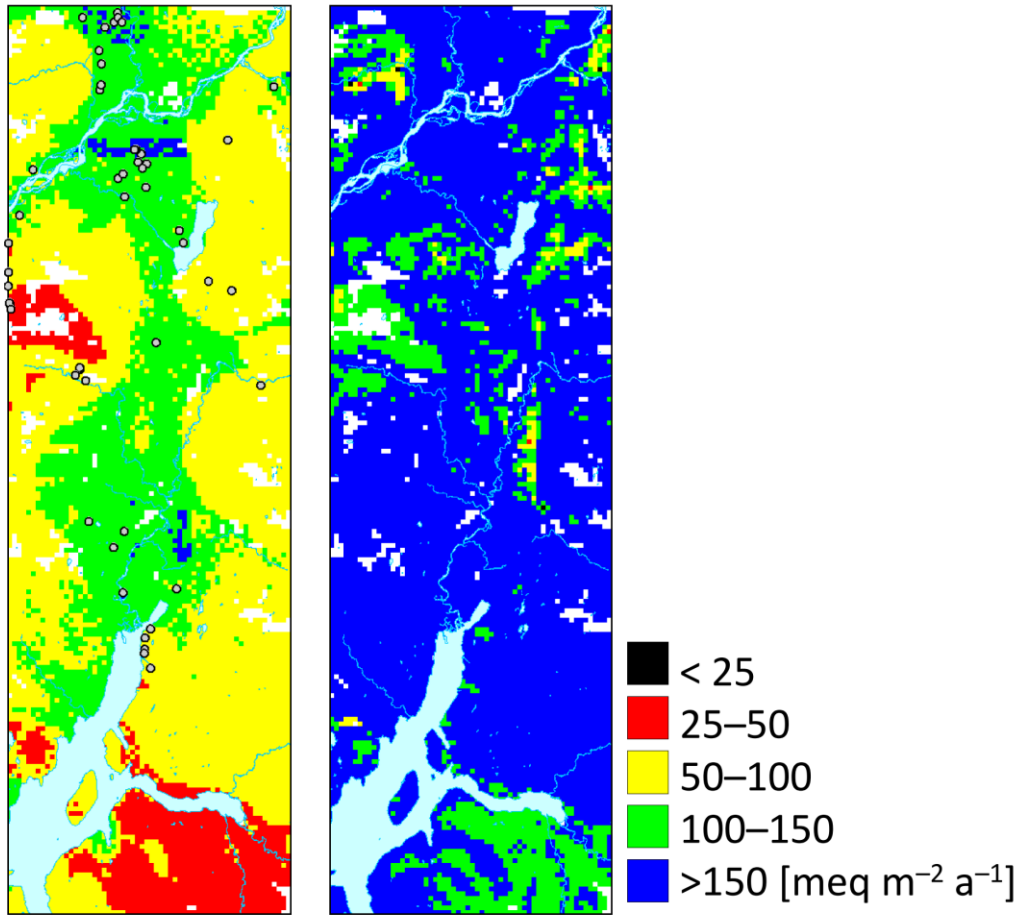


Figure 9.3-1: Base cation weathering rates estimated for each rock-type (left) based on multiple soil sampling sites for each category, and critical loads of acidity for the study area (right).

Table 9.3-5: Base cation weathering rates (average and range (minimum to maximum): eq/m^3/a) for each site within each bedrock category estimated using PROFILE and all possible mineral combinations determined by A2M.

Bedrock Category	Calcium		Magnesium		Potassium		Sodium		Base Cations (sum)	
	Avg	Range	Avg	Range	Avg	Range	Avg	Range	Avg	Range
CA	0.113	0.033–0.335	0.062	0.044–0.088	0.018	0.014–0.021	0.095	0.080–0.095	0.288	0.196–0.554
G0	0.055	0.051–0.059	0.026	0.019–0.037	0.009	0.008–0.010	0.038	0.033–0.038	0.128	0.119–0.142
GD	0.048	0.036–0.063	0.028	0.013–0.041	0.012	0.009–0.020	0.069	0.057–0.069	0.157	0.144–0.170
GR	0.071	0.038–0.116	0.041	0.032–0.049	0.016	0.013–0.020	0.078	0.072–0.078	0.206	0.174–0.248
LM	0.105	0.033–0.268	0.067	0.052–0.106	0.014	0.009–0.017	0.09	0.055–0.090	0.275	0.168–0.441
OG	0.056	0.034–0.071	0.015	0.013–0.017	0.007	0.006–0.007	0.029	0.025–0.029	0.105	0.086–0.121
QD	0.056	0.028–0.116	0.041	0.033–0.054	0.013	0.011–0.018	0.087	0.074–0.087	0.196	0.164–0.254
QM	0.039	0.016–0.059	0.044	0.004–0.086	0.011	0.003–0.026	0.051	0.015–0.051	0.146	0.132–0.152
S0	0.063	0.042–0.095	0.052	0.046–0.059	0.018	0.014–0.022	0.1	0.054–0.100	0.234	0.157–0.300
VA	0.058	0.036–0.110	0.048	0.040–0.061	0.016	0.013–0.019	0.088	0.077–0.088	0.21	0.172–0.285
VC	0.046	0.020–0.087	0.043	0.033–0.060	0.012	0.007–0.016	0.054	0.042–0.054	0.155	0.110–0.249

9.3.1.3 Terrestrial critical loads

Critical loads were estimated for all areas classified as forested mineral soils in the study area (69% of the study area (1,991 km^2); Figure 9.3-2). Sampling sites were generally located within the low-elevation areas (average elevation 208 m; range 18-661 m) as these are where the more accessible sites were located (Figure 9.3-2).

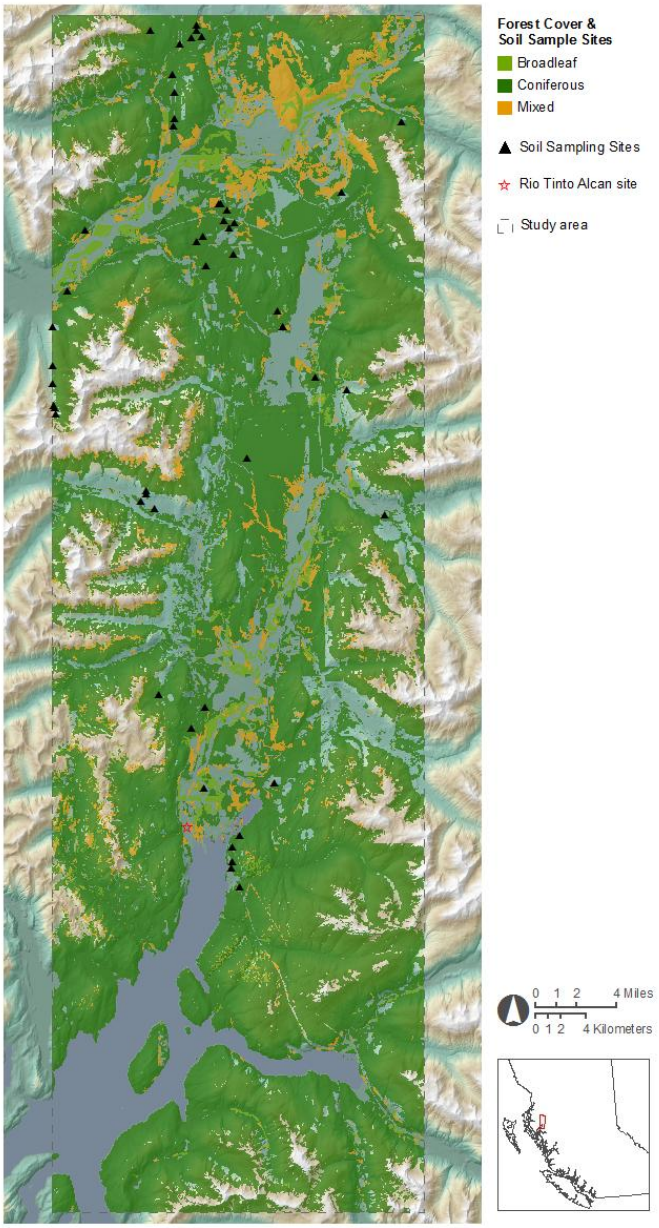


Figure 9.3-2: Soil sampling sites and forest cover types in the study area.

Because critical loads are highly dependent upon base cation weathering rates, critical loads of acidity were also lowest (100 to 150 meq/m^2/a) in these regions, although there were other areas (mostly in the northern and eastern part of the study area) that had critical loads within this category (Figure 9.3-1). In general, because of the high runoff (and high $ANC_{le(crit)}$, see equation {8.5-3}) and relatively low harvest removals, much of the study region is considered to have moderate to high critical load and as such, moderate to low sensitivity to acidic deposition.

Removal of base cations by forestry (Bc_u) averaged about 7 meq/m^2/a, compared with average weathering of 88 meq/m^2/a. This estimate of Bc_u assumes that all of the AAC would be harvested, which is three times more than is currently harvested. An overestimate of Bc_u leads to an underestimate of critical loads, which is precautionary.

Critical Load Exceedance

Under the post-KMP deposition scenario (SO_2 modelled emission rate of 42 t/d; see Section 7.6), the highest total S deposition areas (>100 meq/m^2/a) were restricted to the area immediately to the north of the facility (Figure 9.3-3). There is a larger area that receives S deposition between 25 and 100 meq/m^2/a that extends further up the valley and to the north of Lake Else (Figure 9.3-3). However, only a small area (0.25 to 0.41 km^2) is predicted to receive S deposition in excess of the critical load (Figure 9.3-4); this area is immediately adjacent to the facility and receives the greatest modelled S deposition (>150 meq/m^2/a). Critical load exceedance estimates were generally insensitive to assumptions regarding the gibbsite dissolution constant; for example, estimated areal exceedance under post-KMP S deposition was 0.25 km^2 for –pKgibb = 8.0, 0.41 km^2 for –pKgibb = 8.5, 0.41 km^2 for –pKgibb = 9.0, and 0.77 km^2 for –pKgibb = 9.5.

The average weathering rate per rock-type (average of soil sampling sites per rock type (n = 4 to 6)) does not account for the lower estimates of weathering (see Table 9.3-3) that can potentially occur anywhere within the mapped rock type. As such, the approach may be considered an 'optimistic view' of critical loads. To account for spatial uncertainty in weathering, we also assumed that it was possible to get the lowest estimated weathering rate anywhere within each bedrock type region. Under this approach (see Appendix 9.3-1), exceedance of critical load increased slightly (2.19 km^2) predominantly in the region adjacent to the facility; there was also an increase in the area receiving deposition close to critical load (6.58 km^2 non-exceeded 0 to 10 meq/m^2/a). Nonetheless, exceedance was restricted to just two of the bedrock categories (CA and QD) located adjacent to the facility and directly under the modelled deposition plume (Appendix 9.3-1). The critical load map (Figure 9.3-1) was based on the median base cation weathering rate estimated from 4-6 soil pit measurements located within each bedrock geology type. In some areas, the surficial geology can be distinct from the underlying bedrock (surficial materials other than alpine complex and till) although, in general, weathering rates in these areas are higher (Appendix 9.3-1). Our sampling campaign

effectively captured the sensitive surficial deposits in the study area (Clague 1983; Fulton 1996), if we assume that the lowest estimated weathering rate obtained from the 51 sampling sites (33.8 meq/m^2/a (OG003); see Appendix 9.3-1) can occur anywhere in the study region (highly conservative estimate), exceedance of the critical load increases to 30.98 km^2 (<1.6% of the mapped area). This represents the worst-case scenario irrespective of underlying bedrock and surficial geology maps.

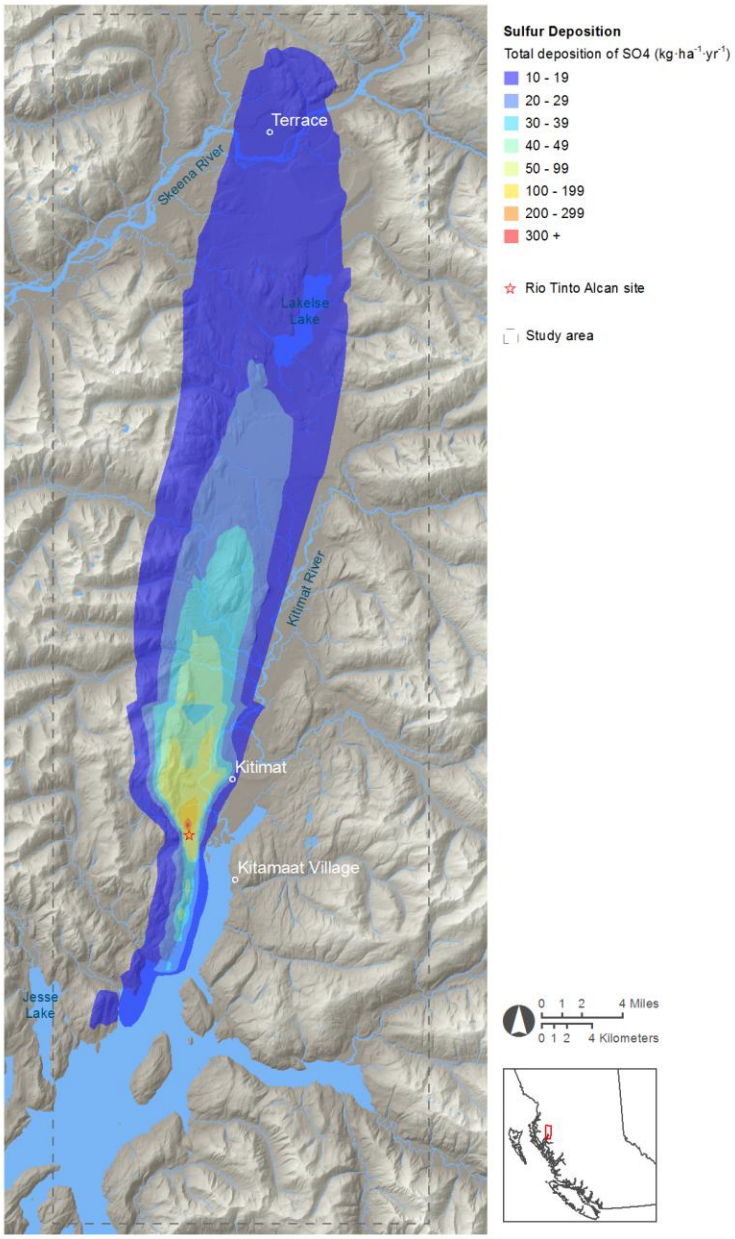


Figure 9.3-3: Modelled total deposition of SO_4 (kg/ha/yr), post-KMP.

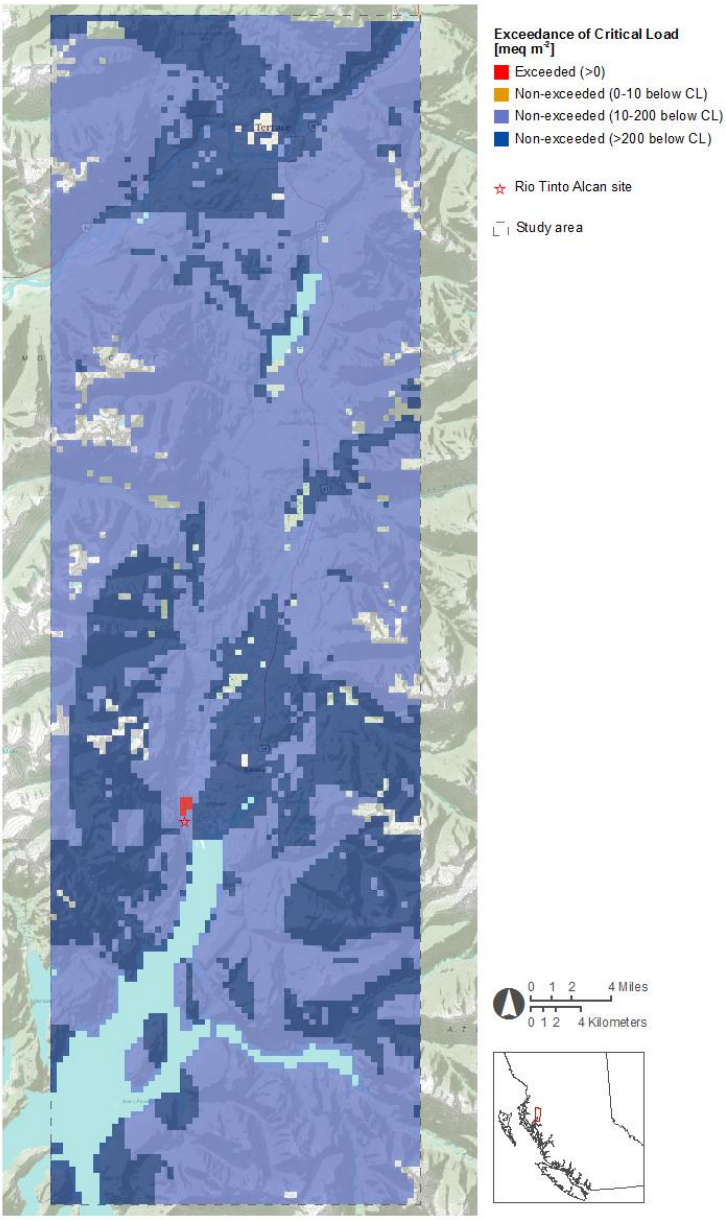


Figure 9.3-4: Exceedance of maximum critical load of sulphur (right) based on the average weathering per bedrock type.

9.3.2 Discussion

Average base cation weathering rates, stratified by the 11 dominant bedrock categories in the study area indicate that the region is moderately sensitive to acidic (S) deposition. However the high critical leaching limit (owing to high runoff (soil percolation)) and low base cation removal via forest harvesting results in moderate to high critical loads for the study area. Under

modeled post-KMP deposition, exceedance of the critical load for acidity is restricted to a small area immediately adjacent and downwind of the facility. The exceeded area is slightly increased when accounting for potential uncertainty in the regionalisation of weathering rates ('uncertainty' scenario based on lowest estimated weathering rate for each rock type rather than average; see Appendix 9.3-1). Areas showing exceedance are predicted to have Bc:Al <1.0 indicating potential damage to tree roots from elevated aluminum in soil solution.

9.3.2.1 Application of risk assessment framework

Using the average weathering rate for each bedrock category a small area (0.25 to 0.41 km^2) is predicted to receive acidic deposition in excess of the critical load; however exceedance is almost certain owing to the magnitude of modelled deposition in the regional close to the smelter. Under the risk assessment framework described in Section 8.1, this would be coded as **moderate** (yellow), i.e., <5% of mineral forest soils are exceeded under deposition >10 meq/m^2/a above the critical load (Table 9.3-6 and Table 9.3-7, 'minor consequence, with almost certain likelihood'). Assuming that the lowest measured weathering rate for each bedrock category could occur anywhere (see Appendix 9.3-1), exceedance of critical load increased slightly (2.19 km^2) predominantly in the region adjacent to the facility. There was also an increase in the area receiving deposition close to critical load (6.58 km^2 with deposition 0 to 10 meq/m^2/a below the critical load) and the code remains **moderate** (yellow). If the lowest estimated weathering rate across all sites (n = 51) is assigned to the entire study area (highly conservative approach) the exceeded area increases to <1.6 %, remaining **moderate** (yellow) under the risk assessment framework.

Table 9.3-6: Application of risk assessment framework to results of the soil critical load assessment.

	Consequence				
Likelihood	1 – Minor <5% mapped area	2 – Medium 5–10% of mapped area	3 – Serious >10–15% of mapped area	4 – Major >15–25% of mapped area	5 – Catastrophic >25% of mapped area
A – Almost Certain Deposition is ≥ 10 meq m^{-2} a^{-1} above CL	**0.01–0.02% of mapped area**	Not Applicable to KMP Outcomes			
B – Likely Deposition is 0 to 10 meq m^{-2} a^{-1} above CL					
C – Possible Deposition is 10 to 0 meq m^{-2} a^{-1} below CL	**49.92% of mapped area**				
D – Unlikely Deposition is 10 to 20 meq m^{-2} a^{-1} below CL	**22.87% of mapped area**				
E – Very Unlikely Deposition is more than 20 meq m^{-2} a^{-1} below CL	**27.20 % of mapped area**				

Table 9.3-7: Summary of risk assessment for forest mineral soil.

Level of Impact	Percent of soil Affected
Low: No impact or acceptable impact; routine monitoring	99.98–99.99% of mapped area
Moderate: Acceptable impact but in need of closer scrutiny; moderate monitoring	0.01–0.02% of mapped area
High: Unacceptable impact; contingency/response action; intensive monitoring	None
Critical: Extremely unacceptable impact; critical response action; very intensive monitoring	None

The overall conclusion is that the impact of KMP on soils is predicted to be **moderate** (yellow) – an acceptable impact but in need of closer scrutiny, with moderate monitoring.

9.3.2.2 Uncertainties and recommendations

1. Uncertainty: As with all critical load studies, base cation weathering rates are a source of uncertainty. In this study critical loads for acidity (S) were estimated using a limited number (4-6) soil pits assigned to each bedrock category; the resultant critical load exceedance does not take into account the fact that in some areas the surficial geology is distinct from the underlying bedrock. Although our sampling campaign likely captured all the sensitive soils and surficial geologies within the study area, the use of a summarized weathering rate per bedrock category will potentially result in some areas where weathering rates are underestimated. The potential for underestimation of weathering rates appears to be most critical for two regions where exceedance occurred.

Recommendation:

- Additional soil sampling and analysis of the two most critical bedrock categories, and the orthogneiss metamorphic bedrock category in the unsampled southern portion of the study domain (maximum 10-15 samples) to expand the weathering estimates. Two locations: (1) in quartz diorite bedrock type south of Lakelse Lake, co-located with lakes that had very low base cation concentrations (highest priority)(see Section 9.4); (2) in calc-alkaline bedrock type near the smelter to support current weathering estimates that were based on extrapolation from other sites (lower priority as unlikely to change conclusion of high exceedance). Additional sampling of the orthogneiss metamorphic bedrock category should be carried out in the south-west region consistent with high post-KMP modelled deposition (Figure 8.5-1).

2. Uncertainty: Critical load estimates in this study are steady state estimates and provide no indication as to *when* the current buffering capacity (base cation pool) will be exceeded.

Recommendation:

- Additional measurements of the exchangeable base cation pools for comparing pool sizes with deposition in exceeded areas; and samples collected in regions with low base cation lakes.

3. Uncertainty: Deposition (base cation and S) values in the study region are uncertain. Base cation deposition data have not been included in the calculations as they were not available. Inclusion of base cation data will increase the critical load. Further, there are uncertainties with modelled S deposition estimates produced by CALPUFF that should be addressed simultaneously.

Recommendations:

- Better estimates of base cation and S deposition are needed. At least two wet deposition sites should be established in the study area (one close to facility and one in a low deposition area (Lakelse Lake)).
- Modelled deposition should be compared to observed deposition.

9.4 SURFACE WATER STUDY

9.4.1 Results and risk assessment

The surface water assessment includes many different lines of evidence, which are presented below in sequence. Table 9.4-8 synthesizes all of these different lines of evidence, showing both field and modelling results for each sampled lake and stream site. Each of these sites can be located on Figure 8.6-1. For convenience, both Table 9.4-8 and Figure 8.6-1 are also included at the back of this report.

This section discusses a series of classifications of interest:

- sites with current ANC <0 (acidic) or current ANC <50 (vulnerable to episodes);
- sites dominated or influenced by different anions, providing clues to the factors responsible for acidification;
- sites with varying levels of exceedance of their critical load (CL), estimated using the SSWC model; and
- sites with current pH_t <6, estimated historical pH_0 <6, and an expected future change in pH >0.1 pH units (with original pH_0 and eventual steady-state pH_∞ estimated using a modified version of the ESSA/DFO model).

The number of sites fitting into each of these categories varies, and a given lake may fulfill some but not all of these attributes in a manner that at first seems counter-intuitive (e.g., some lakes with current pH_t <6 are not expected to exceed their CL, while others are; some lakes exceed their CL but are not expected to have a future change in pH >0.1 pH units; some lakes without CL exceedance are expected to show a pH change >0.1 pH units). All of these important attributes can be viewed in Table 9.4-8, and the colour coding helps to see the inter-relationships among the different outcomes of field and modelling work. Figure 9.4-18 graphically illustrates the overlapping attributes of each lake with a current pH_t <6.

9.4.1.1 Data quality

9.4.1.1.1 Analysis of field blanks, replicate samples and spiked samples

This section summarizes the detailed analysis described in Limnotek (2012b) (Appendix 8.6-1). The analysis of field blanks was used to determine incidence of contamination. With the exception of ammonium (which always shows up in blanks because it can be sequestered from the air by absorption), analyte concentrations in the blanks were 6 to 840 times lower than corresponding concentrations in the stream and lake samples, indicating negligible contamination. Ammonium in the blanks was at concentrations half of those in the stream and lake samples, but is of little consequence because it is too low to affect the cation-anion balance. Both field and lab replicate samples showed high precision (<25 % difference in replicates) among all tests except for total aluminum, total and dissolved iron, and ammonium. None of these three substances were significant contributors to the overall charge balance. The average percent recovery in spiked samples was 99.5 % and it ranged from 91 % to 106 % among all analytes. These results show very high accuracy in both of the labs.

9.4.1.1.2 Analysis of charge balance and predicted vs. measured conductivity

These two tests of data quality integrate all of the cumulative analytical errors in all measured parameters. The analysed samples showed an excellent charge balance (Figure 9.4-1) and very strong relationship between predicted and measured conductivity (Figure 9.4-2). These results provide a very high level of confidence in the field and laboratory procedures, and the quality of the data they generated.

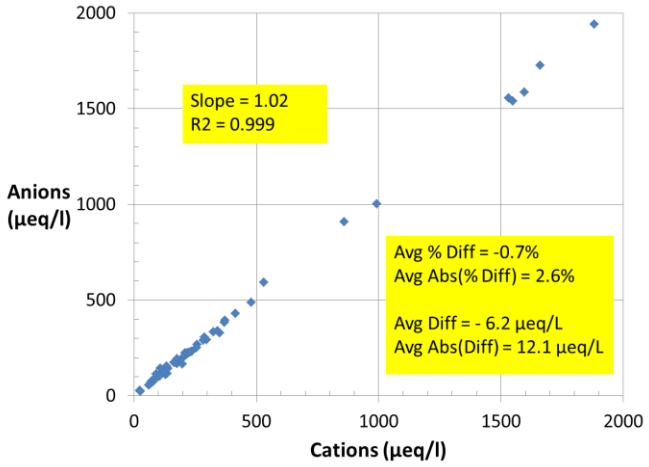


Figure 9.4-1: Analysis of charge balance. Y-axis is the sum of all major anions (negatively charged ions); X-axis the sum of all major cations (positively charged ions).

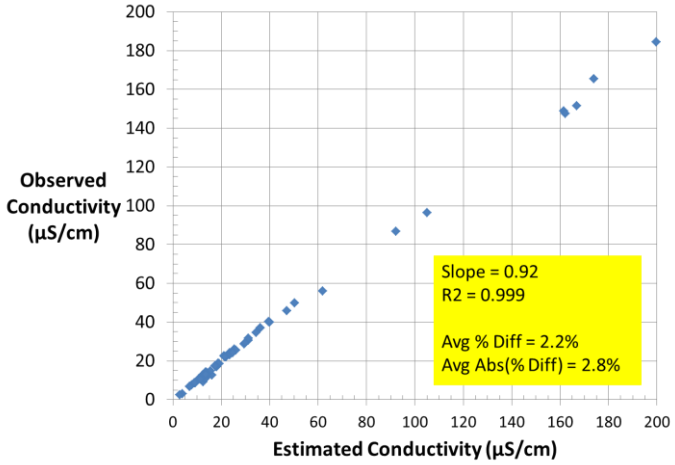


Figure 9.4-2: Analysis of estimated conductivity (based on laboratory measurements of the concentrations of all ions, and literature values for the conductivity of each ion) vs. conductivity observed in field measurements.

9.4.1.1.3 Determination of critical ANC

Figure 9.4-3 shows the best fit of the Small and Sutton (1986) equation to the lab pH and Gran ANC data for surface samples from the 41 lake sites. The fitted equation is:

$$pH = 5.25 + \frac{1}{\ln 10}\operatorname{arcsinh}\left[\frac{(Gran\ ANC) - 0.002}{9.564}\right] \quad \{9.4\text{-}0\}$$

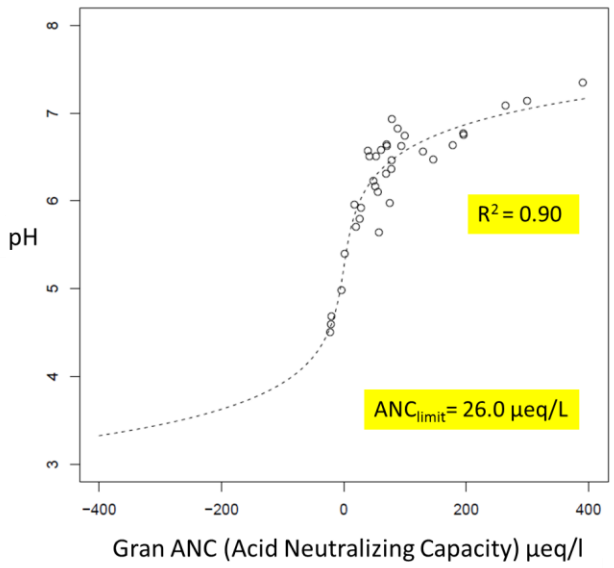


Figure 9.4-3: Application of Small and Sutton (1986) equation to Gran ANC and lab pH data from the 41 lake and 20 stream sites. An ANC_{limit} of 26 µeq/L, corresponds to a pH of 6.0.

Analyses of pH residuals from Figure 9.4-3 vs. DOC showed that 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) (not shown). This is consistent with theoretical expectations (Hemond 1990). The ANC_{limit} of 26.0 µeq/L derived from the fitted equation was within the range of 20 to 40 µeq/L found in other acidification studies within North America and Scandinavia (Henriksen et al. 2002). The titration curve is very helpful for understanding the responses of different sites to KMP. Sites on the steepest part of the curve are likely to show the largest relative shift in pH, whereas those sites on the more gently sloping sections are much less sensitive.

9.4.1.2 Level 0 analyses of acid sensitivity

The following three sections present results of analyzing the data from the 41 sampled lakes and 20 sampled stream sites. As noted in Section 8.6.1, the water sampling focused on the regions with the highest level of sulphate deposition and most acid-sensitive bedrock types. Therefore**, statistics estimated from the sampled sites alone overestimate the sensitivity to acidification of the overall study area.**

9.4.1.2.1 Acid neutralizing capacity in sampled lakes and streams

The distribution of ANC values for sampled lakes and streams is shown in Table 9.4-1 and Figure 9.4-4. The sample included 4 acidic lakes (ANC <0). The likely causes of this condition are

discussed with the analysis of anion composition in Section 9.4.1.1.3. There were no acidic streams amongst the sampled sites.

Eight of the 41 sampled lakes (about 20% of those sampled and including the 4 acidic lakes), currently have an ANC value less than the ANC_{limit} of 26 µeq/L, and therefore can be expected to have a pH close to 6.0. About 30% of the lakes (12 out of 41) had an ANC <50 µeq/L and therefore could potentially experience acidic episodes during storm and snowmelt events (Driscoll et al. 2001). The remaining 70% of the lakes have an ANC >50 µeq/L and therefore are relatively insensitive to acidic deposition. Of the 20 sampled streams, 19 of them (95%) have an ANC >50 µeq/L and are relatively insensitive to acidic deposition.

Table 9.4-1: Distribution of lake and stream ANC values by category.

ANC Category	# Lakes	% Lakes	# Streams	% Streams
<0	4	10 %	0	0 %
0-26	4	10 %	0	0 %
>26-50	4	10 %	1	5 %
>50-200	20	49 %	12	60 %
>200	9	22 %	7	35 %
TOTAL	41	100 %	20	100 %

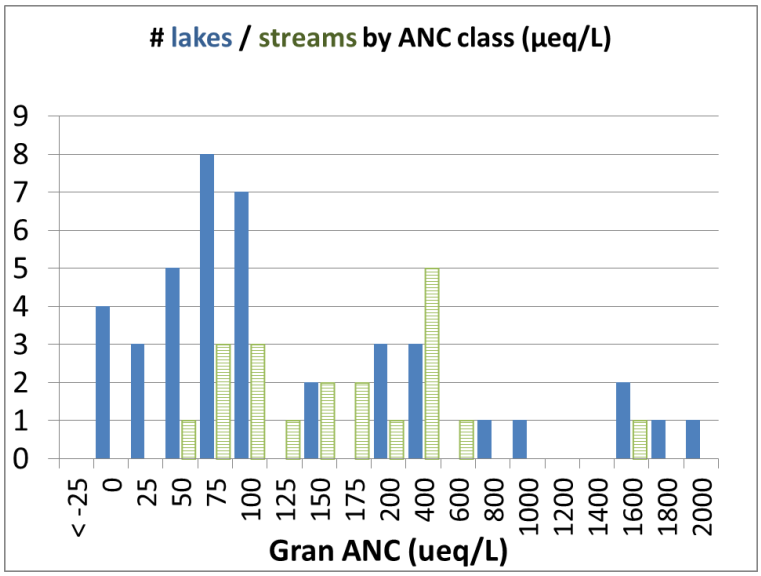


Figure 9.4-4: Distribution of Gran Acid Neutralizing Capacity amongst sampled lakes (blue solid bars) and streams (green cross-hatched bars). The number on the x-axis shows the maximum value of the ANC interval (e.g., "25" indicates waters with ANC between 0 and 25 µeq/L). Note that the ANC interval is 25 up to 200 µeq/L, and then increases to 200 µeq/L.

9.4.1.2.2 pH Levels in sampled lakes and streams

As shown in Table 9.4-2 and Figure 9.4-5, 11 of the 41 sampled lakes (27 %) had a lab pH less than 6.0, though three of these lakes had pH values very close to 6.0 (5.97, 5.96, 5.92). There were eight lakes with a pH <5.9 and ANC <26 µeq/L, consistent with the use of 26 µeq/L as a critical ANC value for identifying lakes with a pH near 6.0. None of the streams had a pH <6.0. As shown in Figure 9.4-6, the 11 lakes with pH <6 are in four clusters: two in the northernmost part of the study area, five southwest of Lakelse Lake (including one in the far west of the study area), two north of the smelter, and two in the most southwestern part of the study area. The subsequent section on anion composition discusses the likely causes of pH values <6.0.

Table 9.4-2: Distribution of sampled lakes and streams by pH category.

pH Category	# Lakes	% Lakes	# Streams	% Streams
<4.5	1 [a]	2 %	0	0 %
>4.5 to 5	3	7 %	0	0 %
>5 to 5.5	1	2 %	0	0 %
>5.5 to 6	6	15 %	0	0 %
>6 to 6.5	7	17 %	2	10 %
>6.5 to 7	15	37 %	9	45 %
>7 to 7.5	4	10 %	8	40 %
>7.5	4	10 %	1	5 %
TOTAL	41	100 %	20	100 %

[a] Lake 056 has a pH value of 4.499.

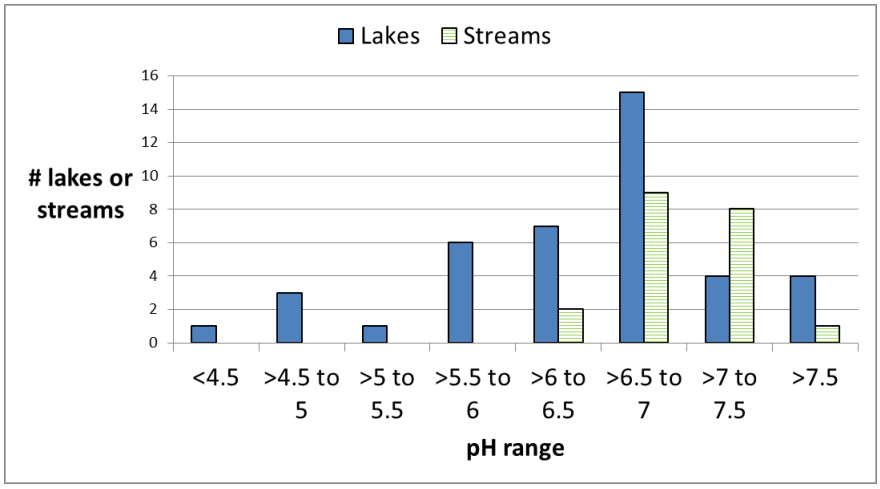


Figure 9.4-5: Distribution of pH among sampled lakes (blue solid bars) and streams (green cross-hatched bars).

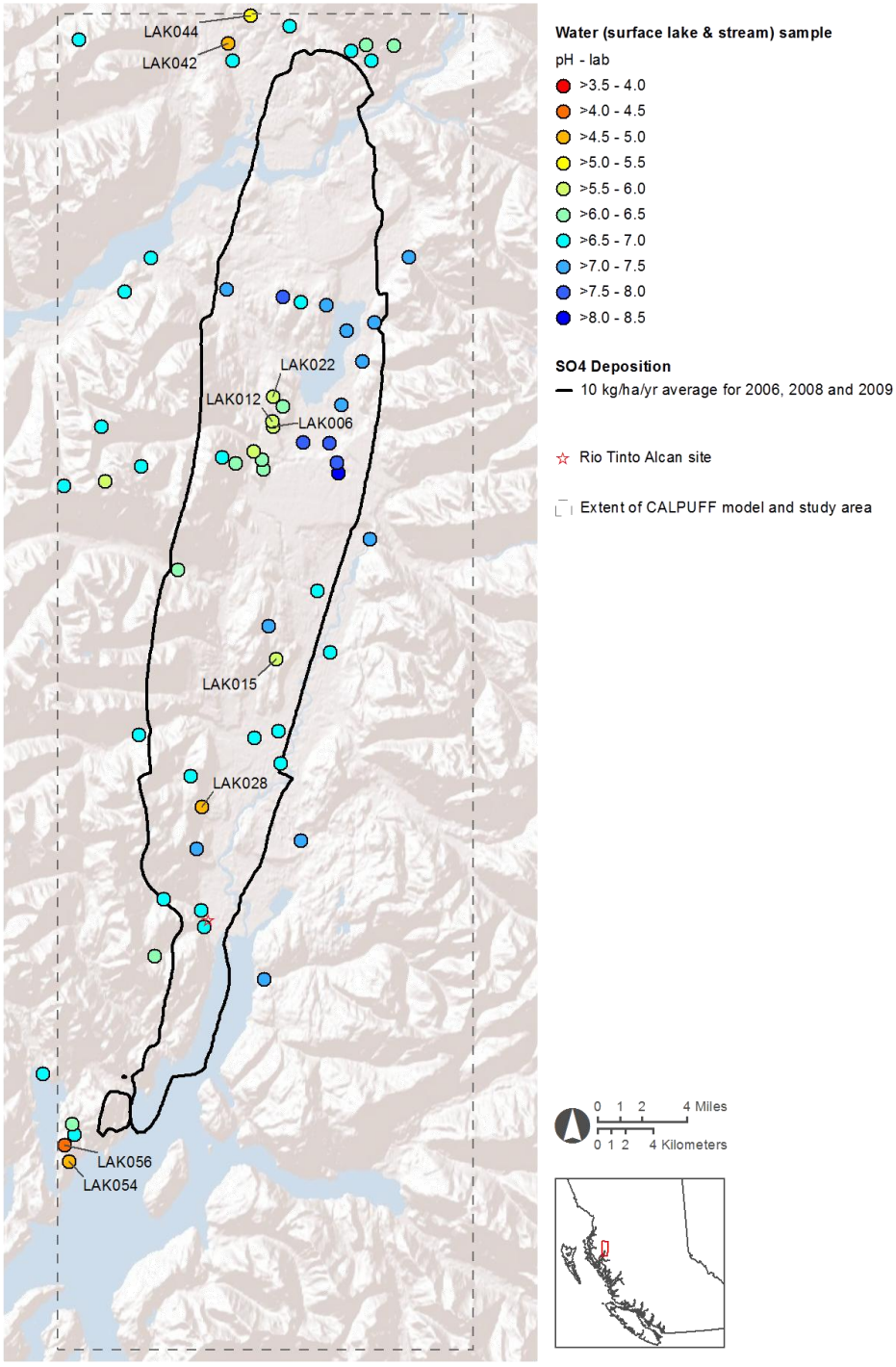


Figure 9.4-6: Spatial distribution of lab pH values across the study region. Lakes with a pH <6 are in four clusters: 2 in the northernmost part of the study area, 5 southwest and west of Lakelse Lake, 2 north of the smelter, and 2 in the most southwestern part of the study area.

Data from geochemical surveys available from the government of British Columbia (Figure 9.4-7) indicate that virtually all streams in the region have a pH >6, and most >6.5. While these data are an aggregation of different surveys and do not represent a random sample of all streams, they do provide a comforting confirmation from a much larger sample of data points that stream pH values are generally well above the 6.0 threshold for biological effects. Many of these geochemical samples are from high elevation sites outside of the 20 stream sites that our team sampled in 2012.

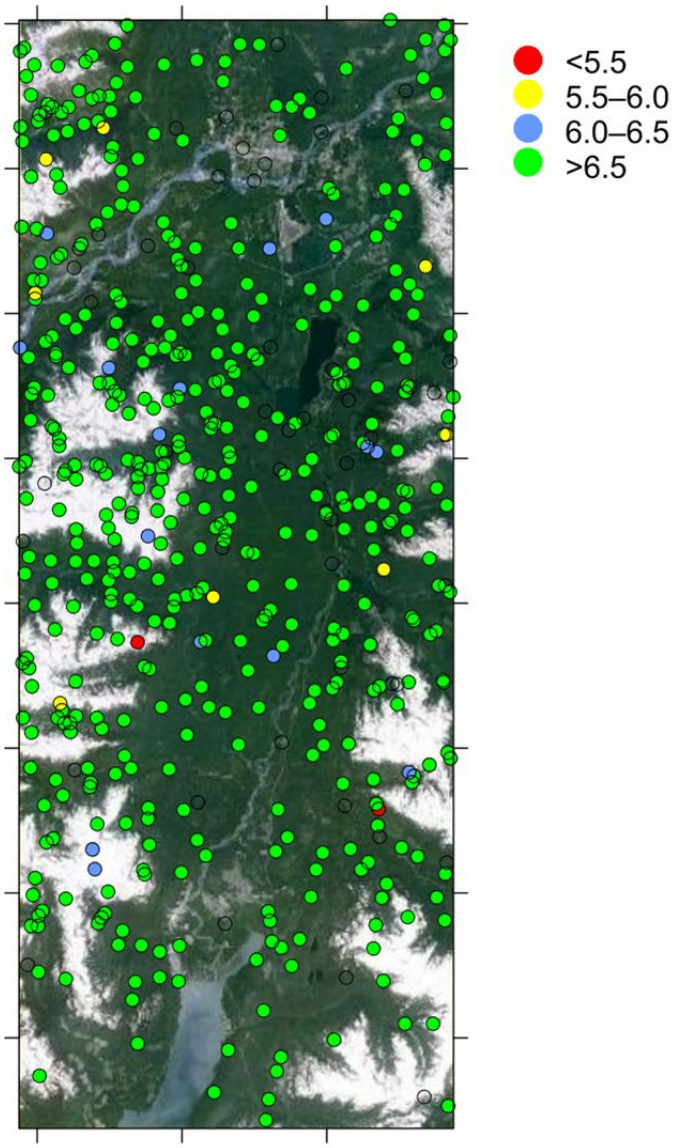


Figure 9.4-7: Spatial distribution of pH values from geochemical surveys. Source: B.C. Government. http://www.empr.gov.bc.ca/Mining/Geoscience/Geochemistry/RegionalGeochemistry/Pages/default.aspx

9.4.1.2.3 Anion composition

These analyses help to determine potential causes of acidification (Marmorek et al. 1989). 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%. A lake can be dominated by one anion and influenced by another, or have up to three influential anions. The key findings (Table 9.4-3, Table 9.4-4, and Table 9.4-8; Figure 9.4-8 and Figure 9.4-9) are as follows:

- Streams had higher % bicarbonate content than lakes, lower % organic content and a similar mean and range of % sulphate levels (Table 9.4-3). Due to their low organic content, streams end up along the left side of the triangle in Figure 9.4-8.
- Thirty of the 41 lakes, and 19 of the 20 streams (altogether 80% of the sampled sites) were *bicarbonate-dominated*, which is expected for lakes with a pH >6 that have not been acidified. Only two of these lakes had a pH <6. Bicarbonate-dominated lakes and streams end up on the upper half of the triangle in Figure 9.4-8.
- Two lakes (Lake 027 (pH 6.64) and Lake 028 (pH 4.98)) were *sulphate-dominated*. A third lake (Lake 044) was dominated by the combination of SO_4, F, Cl, and NO_3, but was only *sulphate-influenced*. Only two of these lakes (Lake 028 and Lake 044) had a pH <6.
- Three lakes (Lakes 042, 054 and 056) were *organic-dominated* (bottom of Figure 9.4-8 on the right side). These three lakes all had a pH <6 (red triangles in Figure 9.4-8). Another seven lakes (Lakes 006, 012, 022, 023, 028, 044, 055) were *organic-influenced* and all but one (Lake 055) had a pH <6.
- Four lakes and one stream showed various combinations of anion influence without any dominance (middle part of Figure 9.4-8), and all had pH <6 (these lakes are listed in Table 9.4-4). The acidifying effect of sulphate (from either atmospheric deposition or watershed sources) is additive to naturally produced organic acids.
- Three of the four acidic lakes (ANC <0) are *organic-dominated* (Lakes 042, 054, 056) and the fourth is *sulphate-dominated* (Lake 028).
- Table 9.4-4 (conclusions in rightmost column) and Figure 9.4-9 can be used to infer the likely causes of acidification of the 11 lakes with a pH <6:
    - Nine of the 11 lakes with current pH <6 are either organically dominated (3) or influenced (6), indicating that organic acids have significantly contributed to their low pH through natural acidification. This organic influence is apparent from the green 'pie slices' in Figure 9.4-9 and the green shading under "anion composition" in Table 9.4-8.
    - Consistent with this high level of organic influence, retrospective analyses using the modified ESSA/DFO model (presented in Section 9.4.1.3.5 and summarized at the right side of Table 9.4-8 under "pH"), estimate that eight of the 11 lakes

with current pH_t <6 had an original, pre-industrial pH_0 <6 (Lakes 012, 015, 023 – West Lake, 028, 042, 044, 054, 056), and that the other three lakes (Lakes 006 – End Lake, 022, 047) had estimated pH_0 values very close to 6 (6.02, 6.11, and 6.00, respectively).

- One lake (Lake 028, about 8 km north of the smelter) shows *strong evidence* of *smelter effects*, based on its high percentage of sulphate (51%), its location in the plume, and its relatively high fluoride content (18%);
- Five lakes show *possible smelter influence on top of a historical base of natural organic acidification*: Lakes 006 (End Lake), 022 and 023 (West Lake), all southwest of Lakelse Lake; Lake 044 (far north of the study area, which also has relatively high chloride indicative of marine influence) and Lake 015 (about 20 km north of the smelter, which also has indications of watershed S sources);
- Four lakes are *primarily acidified to below pH 6 due to organic acids* and have variable sulphate content (Lakes 012, 042, 054 and 056). Lakes 054 and 056 may have also acidified partly due to *marine sources of chloride and sulphate*; and
- Lake 047, an alpine lake, has acidified due to a *mix of organic, sulphate and chloride effects*.

Table 9.4-3: Summary of analyses of anion composition. {D} = dominated; {I} = influenced. The total number of lakes/streams either dominated or influenced (51/22) exceeds the number sampled (41/20) because a lake/stream can be influenced by more than one anion.

Waterbody		**Anion**					
		HCO_3	**Cl**	**SO_4**	**ORG**	**F**	**NO_3**
Lakes	Average %	60 %	5 %	15 %	17 %	3 %	0 %
	Minimum %	0 %	1 %	2 %	0 %	0 %	0 %
	Maximum %	95 %	26 %	51 %	81 %	18 %	3 %
	# >50 % {D}	30		2	3		
	# >25 % {I}	5	1	4	6		
Streams	Average %	80 %	3 %	13 %	3 %	1 %	1 %
	Minimum %	47 %	1 %	4 %	0 %	0 %	0 %
	Maximum %	94 %	7 %	44 %	7 %	1 %	2 %
	# >50 % {D}	19					
	# >25 % {I}	1		2			

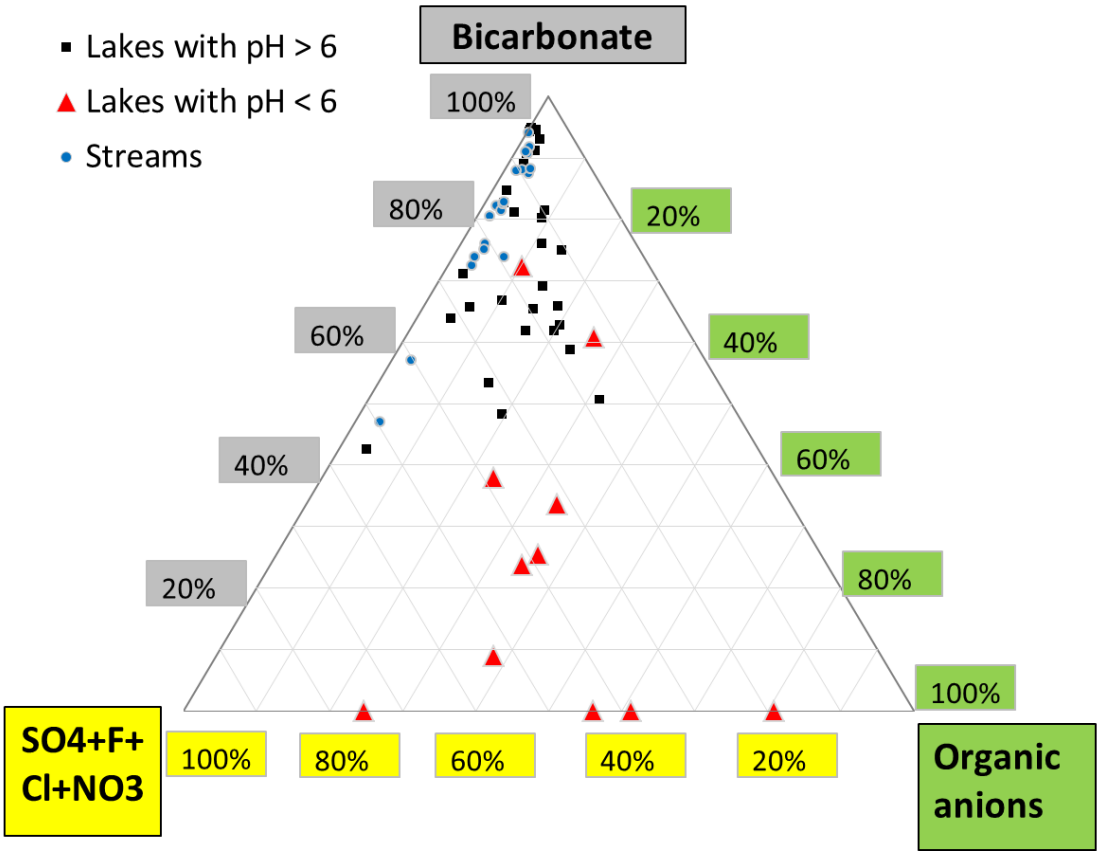


Figure 9.4-8: Ternary diagram of anion composition of the sampled lakes and streams. Points closest to a corner are dominated by the anion at that corner. Acidification (whether natural or anthropogenic) moves points down the triangle, as bicarbonate is replaced by other anions that accompany hydrogen.

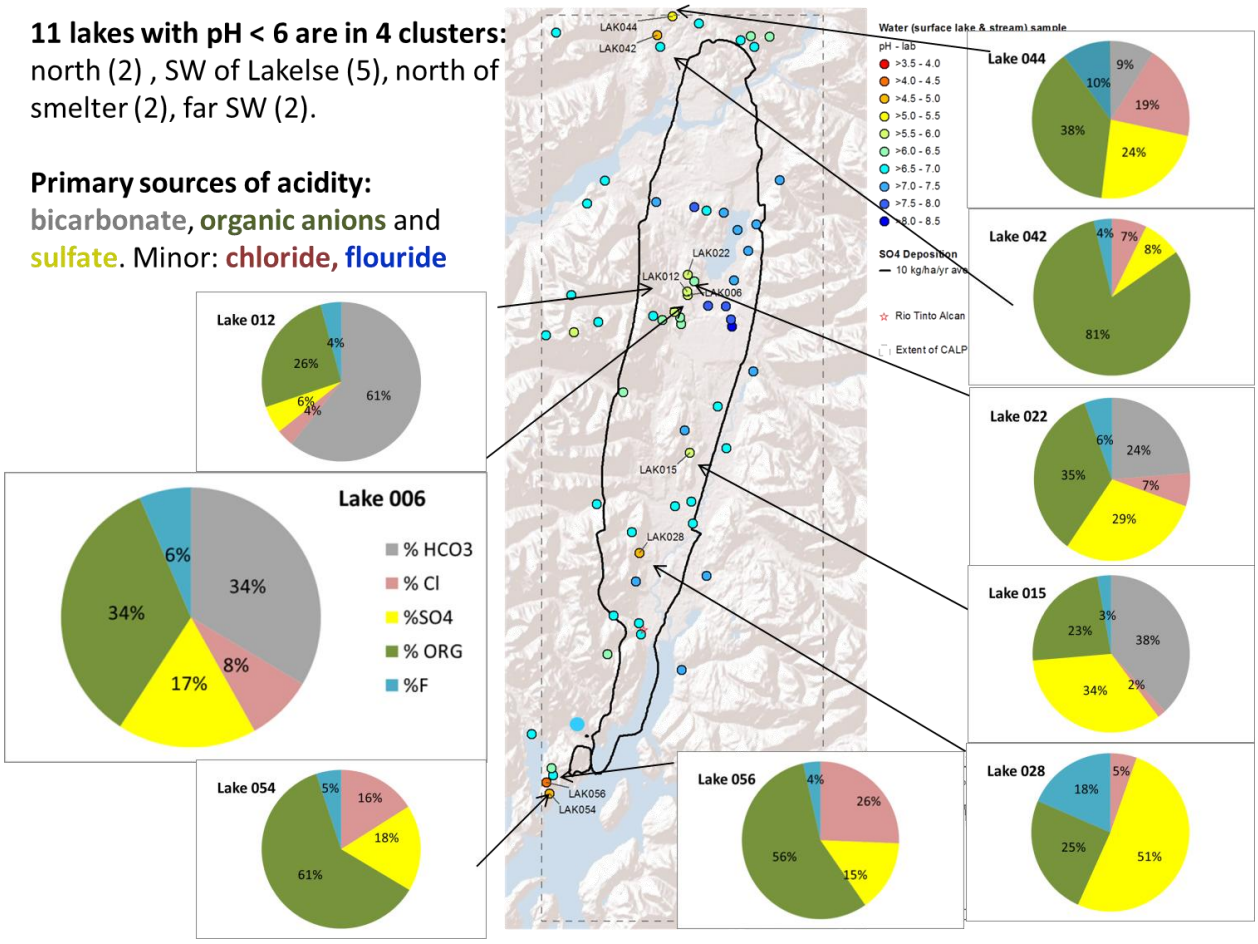


Figure 9.4-9: Spatial distribution and anion composition of nine of the 11 lakes with a pH <6 (data shown in Table 9.4-4 and Table 9.4-6).

Table 9.4-4: Analysis of the anion composition of 11 lakes with a pH <6, and probable causes of their pH status.

COND=conductivity. Bold lettering indicates anion dominance (>50%); italics indicate anion influence (>25%). Unusually low oxygen levels in Lakes 012 and 042 might have contributed to low pH levels due to high levels of CO_2 associated with biological decomposition of organic matter. Expected [SO_4] was estimated from pre-KMP deposition divided by runoff, as explained in Section 8.6.3.4. Lakes with a ratio of observed [SO_4]:expected [SO_4] >2 (e.g., particularly Lake 015, and potentially Lakes 054 and 056) may have watershed sources of sulphur (indicated by {W}), or may have an underestimate of S deposition. Lakes primarily acidified by organic acids are indicated by {O} in last column: Lakes 012, 042, 054, 056. Organic-influence lakes are indicated by {o}. Lakes 044, 054 and 056 likely have strong contributions of marine sulphur sources, based on their relatively high chloride content, indicated by {M}. Lake 028 shows strong evidence of smelter effects, based on its high SO_4 content, its location, and its relatively high fluoride content (indicated by {S}). Lakes 006, 015, 022, 023 and 044 show possible smelter influence {s} in addition to natural organic acidification, based on their SO_4 percentage and location relative to the plume; Lake 015 also shows of evidence of watershed S sources.

Name	COND (lab)	O2	pH (lab)	% HCO3	% Cl	%SO_4	% ORG	%F	%NO_3	ratio of observed [SO_4]: expected [SO_4]	Primary causes of pH <6
LAK006	7	8.6	5.79	*34 %*	8 %	17 %	*34 %*	6 %	0 %	0.5	{s}{o}
LAK012	13	1.4	5.64	**61 %**	4 %	6 %	*26 %*	4 %	0 %	0.3	{O}
LAK015	23	11.0	5.97	*38 %*	2 %	*34 %*	23 %	3 %	0 %	3.1	{W}{s}
LAK022	11	8.2	5.92	24 %	7 %	*29 %*	*35 %*	6 %	0 %	1.3	{s}{o}
LAK023	8	8.8	5.70	25 %	6 %	*25 %*	*36 %*	7 %	0 %	0.8	{s}{o}
LAK028	12	10.1	4.98	0 %	5 %	**51 %**	*25 %*	18 %	0 %	1.4	{S}{o}
LAK042	12	1.3	4.68	0 %	7 %	8 %	**81 %**	4 %	0 %	0.6	{O}
LAK044	3	8.9	5.40	9 %	19 %	24 %	*38 %*	10 %	0 %	0.6	{s} {M}{o}
LAK047	3	11.5	5.96	**72 %**	7 %	8 %	10 %	1 %	3 %	0.9	mix
LAK054	9	6.9	4.59	0 %	16 %	18 %	**61 %**	5 %	0 %	2.0	{O} {M}{W}
LAK056	13	7.6	4.50	0 %	*26 %*	15 %	**56 %**	4 %	0 %	2.2	{O} {M}{W}

Observed [SO_4] (measured in 2012) was more than twice expected [SO_4] (estimated from pre-KMP deposition divided by runoff) at 44 of the 61 sites, presumably reflecting either watershed sulphate sources and/or underestimates of sulphate deposition. Lowering estimates of pre-KMP deposition by 27.2% to account for recent declines in emissions (see Section 8.6.3.4) increases the number of sites with a ratio of observed [SO_4]:expected [SO_4] >2 from 44 to 48 sites but does not change any of the conclusions regarding the primary causes of pH values <6.

9.4.1.2.4 Other relevant observations from water quality data

Aluminum and dissolved organic carbon

Aluminum is of interest because of both toxic effects on fish, and hypothesized effects on human health (see Section 3.4). Levels of both dissolved aluminum and dissolved organic carbon (DOC) increased as pH decreased, consistent with other studies (Baker et al. 1991). This pattern is expected due to greater solubility of aluminum at low pH, and increased acidity (lower pH) with higher contributions of organic anions. It is likely that most of the aluminum in lower pH sites was complexed with organic anions, which renders it less toxic to fish (Baker et al. 1990). Lakes in the study area have higher levels of both aluminum and DOC than streams for a given pH.

The maximum concentration of dissolved aluminum across all sample sites was 0.42 mg/L, in Lake 042 with a lab pH of 4.68 and DOC of 13.16 mg/L (also the highest concentration found). Someone who drank 2 litres of water per day from Lake 042 would consume 0.84 mg/day of aluminum. McDonald (1984) cites evidence that humans on average consume 22 mg/day of aluminum (plus 35 to 208 mg for each antacid or buffered aspirin they consume). Hence, someone drinking 2 litres of water from Lake 042 with pH 4.68 would be obtaining 2.6% of their normal intake of aluminum (i.e., 0.84 / 22). McDonald (1984) concluded that drinking water aluminum concentrations generally did not represent a risk to human health, and the current concentrations of dissolved aluminum yield the same conclusion for the Kitimat study area.

Variability in lake chemistry with depth

Density stratification was present in the seven lakes sampled over multiple depth layers, with lower oxygen and pH levels in deep-water than in surface samples, and higher levels of ammonium and total dissolved solids (Figure 9.4-10 and Table 9.4-5). These patterns are consistent with normal lake chemistry (Wetzel 2001). As discussed in the methods (Section 8.6.2.3), data from five low pH lakes in Ontario showed that surface water samples from a period of summer stratification in August yielded a similar critical ANC to samples taken in late October and November after lakes had been vertically mixed.

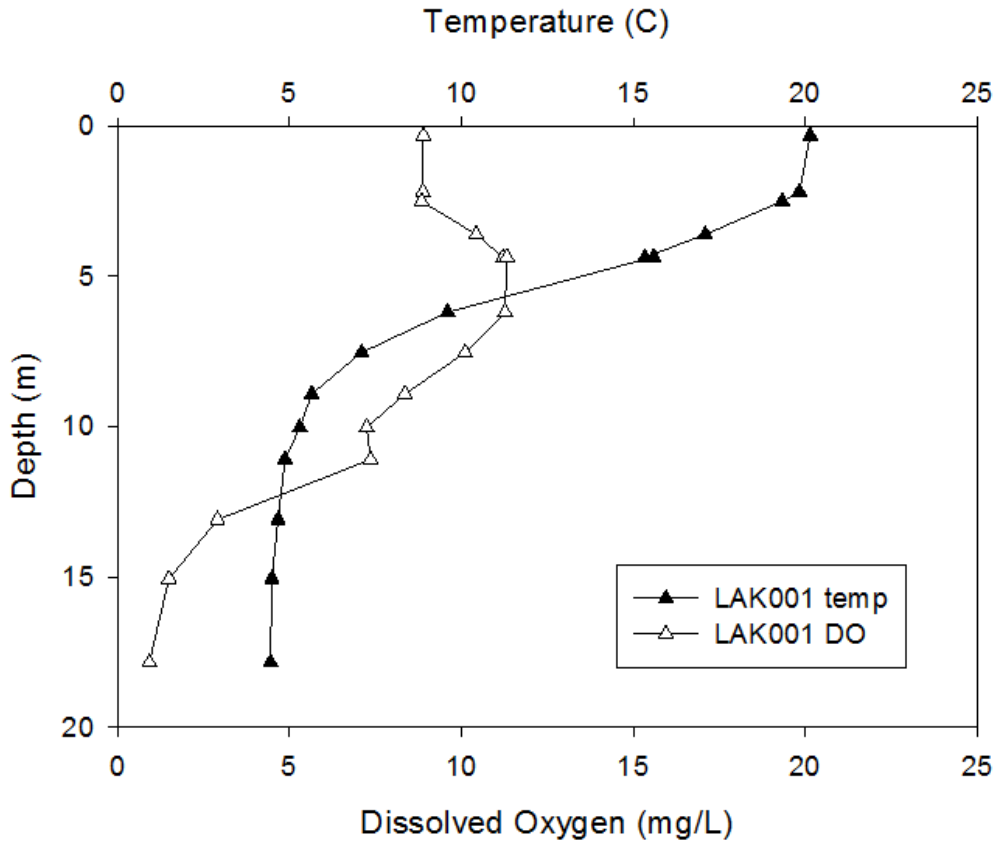


Figure 9.4-10: Example of density stratification (Lake 001).

Table 9.4-5: Average concentration and range by analyte in lakes sampled at surface and 2 m off bottom (n=6). Data set does not include Jesse Lake, which was too deep to get gear down to 2 m off bottom.

Analyte	Epilimnion (surface)	Hypolimnion (2m off bottom)
DO (mg/L)	9.3 (8.4 – 10.6)	5.4 (2.2 – 10.4)
pH	6.9 (5.7 – 7.5)	6.2 (5.1 – 6.9)
DOC (mg/L)	2.6 (1.1 – 4.5)	2.8 (1.7 – 4.6)
NH_4-N (µg/L)	3.0 (0.6 – 4.9)	5.0 (1.0 – 18.1)
TDS (mg/L)	22 (2 – 58)	27 (4 – 75)

9.4.1.3 Level 1 analyses of critical loads and exceedance

9.4.1.3.1 Critical loads

The frequency and spatial distributions of critical loads for the sampled lakes and streams, estimated from the SSWC model, are shown in Figure 9.4-11 and Figure 9.4-12, respectively. The CL values for each lake and stream are shown in the middle of Table 9.4-8. Key points are as follows:

- 46 of 61 sites (75%) have very low sensitivity (CL>100 meq/m^2/yr), five sites have low sensitivity (CL= 60 to 100 meq/m^2/yr), three have moderate sensitivity (CL= 40 to 60 meq/m^2/yr), two are sensitive (CL=20 to 40 meq/m^2/yr), and five are highly sensitive (CL=0 to 20 meq/m^2/yr);
- This *bimodal distribution of critical loads is a key attribute of the study area.* The vast majority of sites (51 out 61, 84%) have very low or low sensitivity to acidification, while a small fraction (seven out of 61; 11%) are sensitive or highly sensitive.
- Critical loads are generally higher in the Kitimat study area than in the New England Governors/Eastern Canadian Premiers region (NEG/ECP) reported in Dupont et al. (2005):
    - 75% of critical loads are greater than 100 in the Kitimat study area (blue dots in Figure 9.4-12; very low sensitivity), as compared to 26% of the 2,053 lakes in NEG/ECP (Dupont et al. 2005); and
    - five lakes (8% of those sampled) in the Kitimat study area have critical loads that are less than 20 (red dots in Figure 9.4-12; highly sensitive), as compared to 14% of the lakes in NEG/ECP (Dupont et al. 2005).

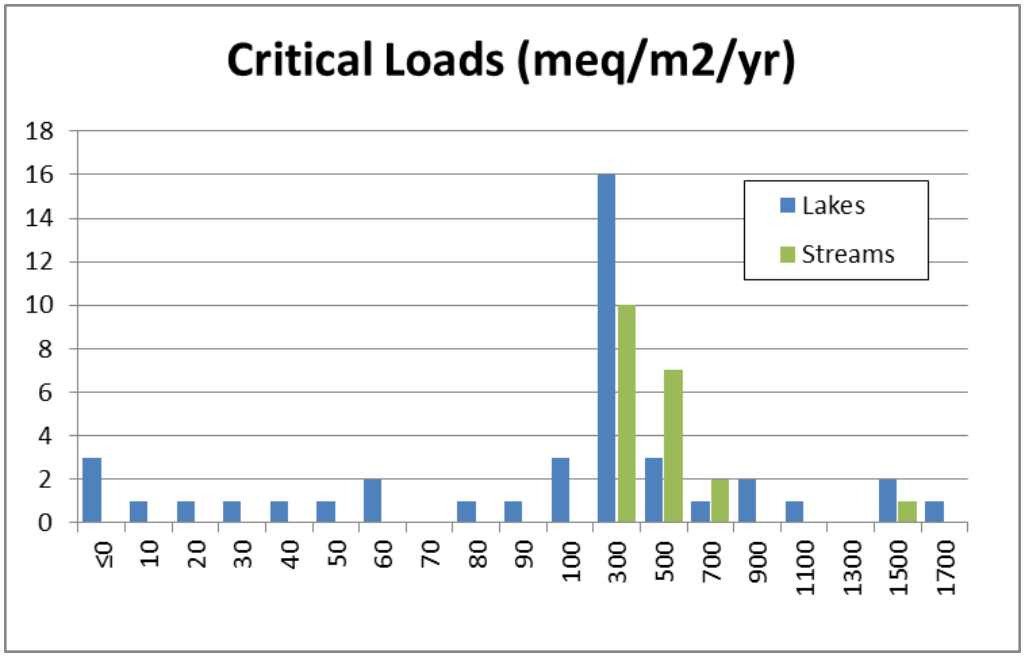


Figure 9.4-11: Frequency distribution of critical loads for the sampled lakes and streams. The label below each interval is the maximum value for that critical load category (e.g., 10 is for CL >0 and ≤10). Y-axis indicates number of lakes or streams in each category. The 3 lakes in the lowest category have CL = 0.

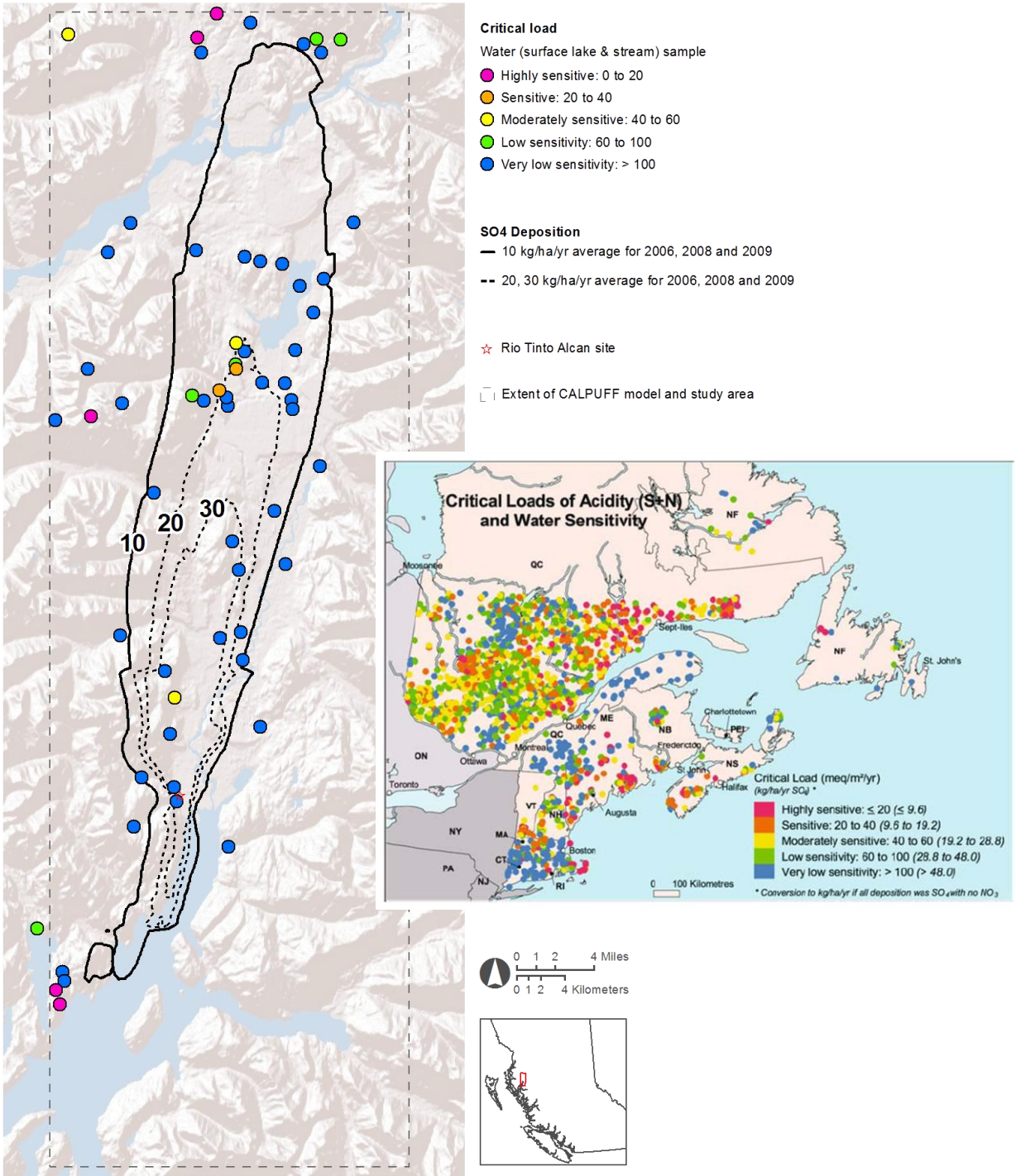


Figure 9.4-12: Spatial distribution of critical loads for the sampled sites in Kitimat study region; inset map for comparison is from Dupont et al. (2005) and uses the same critical load categories and colours.

Variation in critical loads with bedrock geology

Lake and stream sites were assigned to an Acid Sensitivity Classes of bedrock geology (ASC) based on their location. There was a high variation in critical loads within each ASC (Figure 9.4-13), which may be due to the fact that some lake and most stream watersheds cover more than one ASC bedrock type, or that there is high variation in critical loads within an ASC. Nevertheless, the median values for ASC 1 and 2 (the most acid sensitive bedrock types) were lower than for the ASC 3 and 4 (Figure 9.4-13; Table 9.4-6).

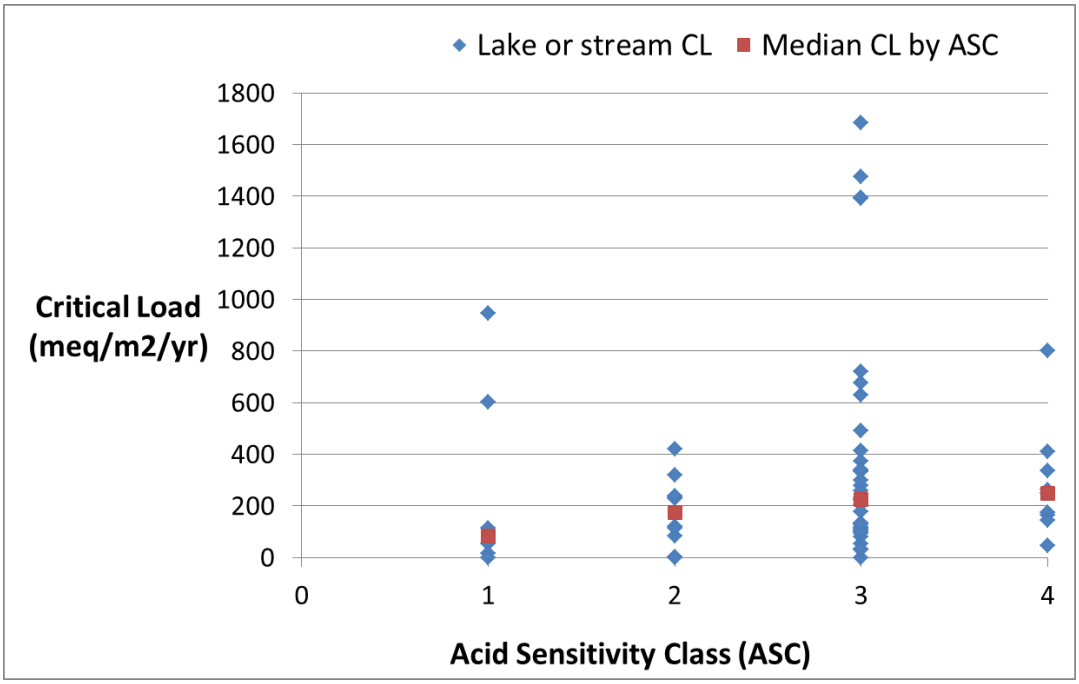


Figure 9.4-13: Variation in critical load by Acid Sensitivity Class.

Table 9.4-6: Statistics on lake and stream critical load values (meq/m^2/yr) by Acid Sensitivity Class (ASC). A critical load of 21 meq/m^2/yr can neutralize 21 meq/m^2/yr of total sulphate deposition (=10 kg/ha/yr) without exceedance.

ASC	n	Min	Max	Median	Mean	# <21	SE
1	6	0	945	83	288	2	161
2	10	0	421	173	175	2	43
3	36	0	1682	223	374	1	73
4	9	46	802	248	287	0	74
Overall	**61**	**0**	**1682**	**220**	**320**	**5**	**48**

9.4.1.3.2 Exceedances

The frequency and spatial distributions of exceedances (EX) for the sampled sites, estimated from the SSWC model, are shown in Figure 9.4-14 and Figure 9.4-15, respectively. Figure 9.4-15 includes all lakes predicted to have an exceedance and/or a change in pH of greater than 0.1 pH units (predicted pH change, based on the modified ESSA/DFO model, is presented in Section 9.4.1.3.5). Table 9.4-7 shows how many lakes and streams fit into each combination of critical load and exceedance categories, and Figure 9.4-16 shows the changes in exceedance for eight lakes under no deposition, pre-KMP conditions and post-KMP conditions. Exceedance estimates for all lakes are shown in Table 9.4-8 under "Critical Load, Deposition and Exceedance".

Using the risk assessment likelihood categories introduced in Section 8.6.4, the key points are as follows:

- 32 lakes and all 20 stream sites have an exceedance below -20, and are therefore *very unlikely* to exceed their critical load (78% of sampled lakes; 99% of the sampled lake area);
- one lake (Lake 022) is *unlikely* to exceed its critical load (predicted deposition is 10-20 meq/m^2/yr below CL, EX = -12);
- two lakes (Lakes 043 and 023) are *likely* to exceed their critical load (predicted deposition is 0-10 meq/m^2/yr above CL; see Figure 9.4-15);
- six lakes are *almost certain* to exceed their critical load (predicted deposition is more than 10 meq/m^2/yr above CL EX >10; see Figure 9.4-15);
- the modified ESSA/DFO model predicted that Lakes 012 and 022 would have more than a 0.1 unit decrease in their pH (-0.13 and -0.39 respectively), though the SSWC model predicts that deposition will not exceed their CL (exceedance values of -37 and -12, respectively). The difference between these two model predictions reflects the fact that the SSWC model is most strongly affected by current base cation concentrations and deposition, whereas the modified ESSA/DFO model is driven by current ANC, the estimated F-factor, and deposition; and
- the total area of the eight lakes with exceedances equals 1% of the sampled lake area (6 are <2 ha in area while the other two lakes are seven and 10 ha in size).

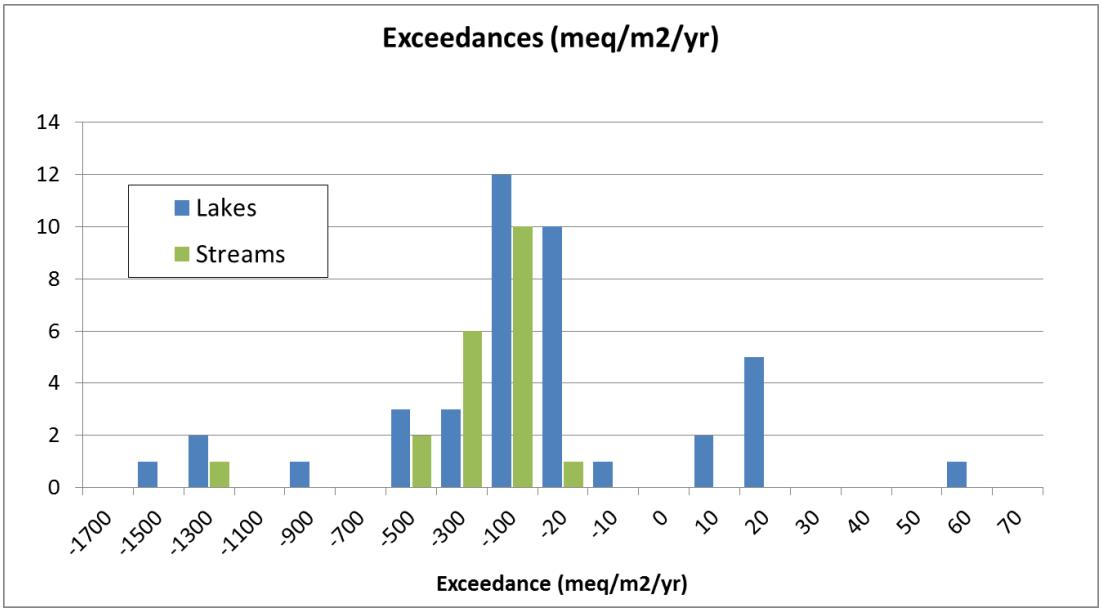


Figure 9.4-14: Frequency distribution of critical load exceedances (acidic deposition minus critical load) for the sampled lakes and streams. A positive value indicates that acidic deposition exceeds the critical load. A negative value indicates that acidic deposition is less than the critical load. The label below each interval is the maximum value for that exceedance category (e.g., 10 is for exceedance >0 and ≤10). Y-axis values indicate number of lakes or streams in each category.

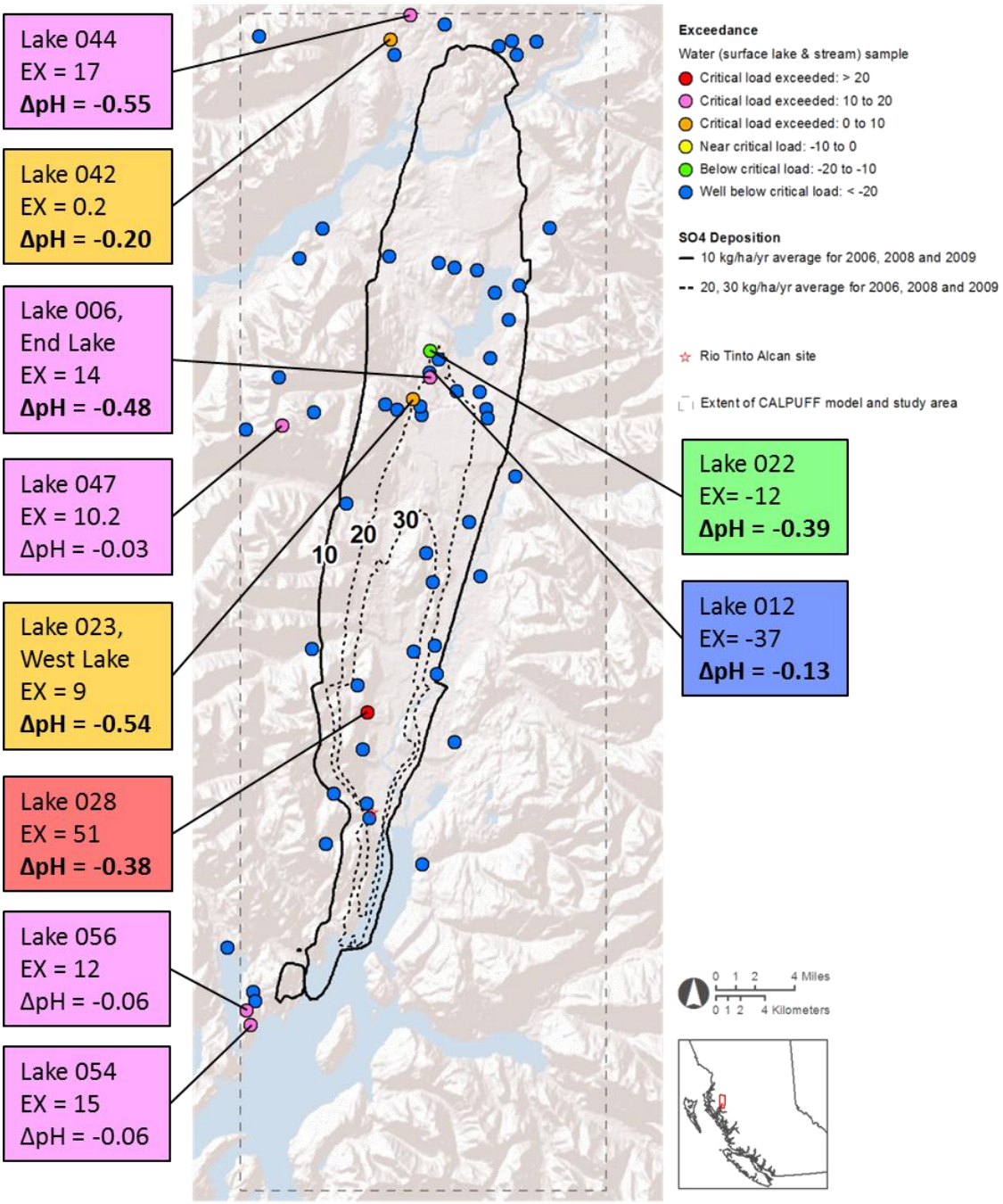


Figure 9.4-15: Spatial distribution of 10 sampled lakes which are of concern: 8 with predicted critical load exceedances (EX >0), and 7 with predicted pH changes greater than 0.1 pH unit (ΔpH) in **bold** type. EX = exceedance. See Figure 9.4-18 for overlap in lake attributes. The exceedance categories and colours are consistent with Dupont et al. (2005).

Table 9.4-7: Lakes and streams by both critical load and exceedance categories.

Critical Load Sensitivity Classes (meq/m²/yr) \ Exceedance Classes (meq/m²/yr)	Critical load exceeded: > 20	Critical load exceeded: 10 to 20	Critical load exceeded: 0 to 10	Near critical load: -10 to 0	Below critical load: -20 to -10	Well below critical load: <-20
Highly sensitive: 0-20		4	1			
Sensitive: 20 to 40		1	1			
Moderately sensitive: 40 to 60	1				1	1
Low sensitivity: 60 to 100						5
Very low sensitivity: > 100						26 / 20

- 6 lakes almost certain to show exceedance
- 2 lakes likely to
- 1 lake unlikely to
- 32 lakes & 20 streams very unlikely to

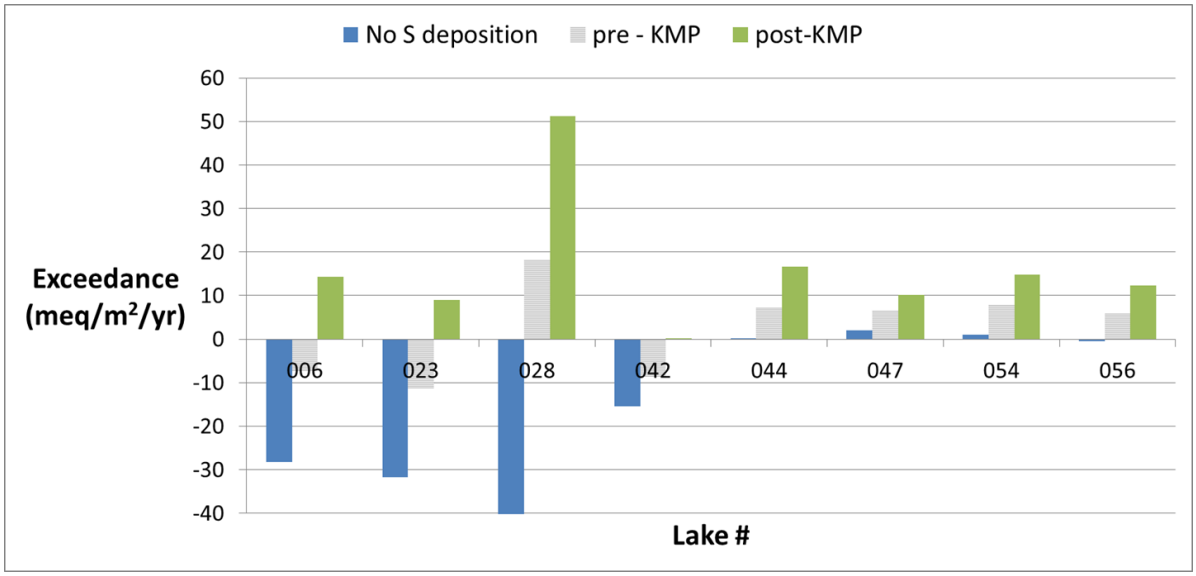


Figure 9.4-16: Changes in exceedance for 8 lakes under no deposition, pre-KMP conditions and post-KMP conditions. Lake 042 has EX=0.2. The four lakes on the right are all very acid-sensitive (CL = 0 to 1) and three of them are dominated by organic acids (Lakes 047, 054 and 056).

9.4.1.3.3 Characteristics of lakes with exceedance

Table 9.4-8 summarizes characteristics of all sampled lakes, including the eight lakes with exceedances. As illustrated in Figure 9.4-18, only five of the eight lakes with CL exceedances are predicted to show a pH change >0.1 pH units (Lakes 006 (End Lake), 023 (West Lake), 028, 042, 044). These five lakes, plus two others predicted to also show a pH change >0.1 pH units but without CL exceedance (Lakes 012 and 022), are the seven highest priority lakes for future study in the AM phase (as shown at the right side of Table 9.4-8).

Here are the characteristics of the eight lakes with CL exceedance:

- all eight lakes with critical load exceedances have a pH <6, and seven of these eight lakes are estimated to have also had an original pre-industrial pH_0 <6;
- three lakes are currently dominated by organic acids and four are influenced by organic acids;
- one of the lakes is sulphate-dominated and one is sulphate-influenced;
- seven of the eight lakes are at elevations between 149 and 265 m, while the eighth lake (Lake 047) is an alpine lake at 1,446 m and was ice covered during the August sampling period);
- all eight lakes with exceedances have relatively low concentrations of total dissolved solids (TDS) ranging from 2 to 8 mg/L, compared to the average (23 mg/L) and median (11 mg/L) TDS for the 41 sampled lakes; TDS divided by mean depth (the "morphoedaphic" index) is generally correlated with levels of fish production (Ryder 1965, 1982);
- six of the eight lakes are <2 ha in area, while Lake 006 (End Lake, 10.3 ha) and Lake 023 (West Lake, 6.8 ha) are larger (total area of the 8 lakes is 26.5 ha);
- there is a wide range of watershed to lake area ratios, from 4.95 (Lake 044) to 83.5 (Lake 054), and this attribute therefore appears unrelated to their low critical loads;
- while the mean or maximum depths of each lake are not known, the depth at the sampling point is an indication of the minimum depth, which ranged from 0.5 m in Lake 047 to 15.5 m in Lake 028 [22];
- all eight lakes can be easily sampled for water chemistry by helicopter, as was done in 2012; and
- two of the eight lakes have good accessibility for fish sampling (End Lake and West Lake), two have fair accessibility (Lakes 042 and 044 are within 200 m of a road, allowing

[22] Other minimum depths are 5.7 m in Lake 006 (End Lake), 2.7 m in Lake 023 (West Lake), 12 m in Lake 042, 15 m in Lake 044, 5.1 m in Lake 054 and 6.6 m in Lake 056.

an inflatable boat to be packed in), while Lakes 022, 028, 054 and 056 are not safely accessible by any means for fish sampling (helicopter, road, or hiking).

Empirical observations of fish presence are only available from the B.C. Fisheries Information Summary System for Lake 006 (End Lake, containing rainbow trout) and Lake 023 (West Lake, containing coho, Chinook, stickleback and cutthroat trout). The B.C. Watershed Atlas infers that Lakes 042, 054 and 056 should be accessible to freshwater fish based on stream gradients, though there are no empirical observations recorded in the Atlas for these lakes; current fish production may be relatively low in these three lakes given the high concentration of organic acids and low pH values. The alpine Lake 047 is not accessible to fish, and the accessibility of Lakes 028 and 044 is not known.

The fish species identified in the Fisheries Information Summary System for West Lake were consistent with a 1986 survey by the B.C. MOE Fisheries Branch in Smithers (MOE 1986). Other relevant observations from this document include: (1) the shallow depth of the lake (estimated at 2.5 m in 1986) might make it vulnerable to winter fish kill; (2) the forest surrounding the lake had been clear cut right to the shoreline; (3) the lake was all littoral zone with good insect production; and (4) no fish were caught in minnow traps set in the lake outlet (Cecil Creek).

Table 9.4-8: Measured attributes of the sampled lakes and streams and associated model outputs.

Fold out to see the table on the other side; the table footnotes are on the next (facing) page.

Table 9.4-8. Measured attributes of the sampled lakes and streams and associated model outputs.

IDENTIFICATION		SITE ATTRIBUTES							ANION COMPOSITION [3]					CRITICAL LOAD, DEPOSITION & EXCEEDANCE [4]				pH (original, present, post-KMP) [6]				CONSIDERATIONS FOR AM PLAN		
Lake/Stream ID	Name	Elevation	Lake Area	Watershed Area	Runoff	Acid Sensitivity Class (ASC) [1]	Fish Habitat [2]	Gran ANC	HCO_3	Cl	SO_4	ORG	F	Critical Load	SDEP [5] (pre-KMP)	SDEP [5] (post-KMP)	Exceedance	Estimated original pH	Measured current pH	Predicted future steady-state pH	Predicted Δ pH (2012 to future)	Priority level for monitoring [7]	Accessibility for water sampling [9]	Accessibility for fish sampling
		m	ha	ha	m			µmeq/L	%	%	%	%	%	meq/m²/yr	meq/m²/yr	meq/m²/yr	meq/m²/yr	pH_0	pH_t	pH_∞				
LAK001	Hai L.	203	9.8	54	0.8	1	Yes - Infer.	792.6	91%	1%	5%	3%	0%	602.8	15.3	33.6	-569.0	7.56	7.56	7.56	0.00	-		
LAK002	Herman L.	226	7.5	143	0.8	1	Yes - Obs.	93.7	62%	3%	13%	20%	2%	113.1	15.5	34.4	-78.4	6.66	6.62	6.56	-0.06	-		
LAK003		296	10.9	118	1.4	3	Yes - Obs.	263.9	64%	2%	28%	5%	1%	492.0	36.0	68.5	-423.2	7.08	7.08	7.08	0.00	-		
LAK004		594	1.7	95	1.2	3	Yes - Infer.	146.1	75%	2%	7%	14%	2%	202.6	16.0	31.4	-170.8	6.48	6.47	6.46	-0.01	-		
LAK005		303	1.3	18	0.9	3	Unknown	55.3	48%	4%	23%	20%	5%	113.7	23.1	46.9	-66.5	6.18	6.10	6.01	-0.10	-		
LAK006	End L.	151	10.2	91	0.9	3	Yes - Obs.	25.7	34%	8%	17%	34%	6%	28.4	20.7	42.4	14.2	6.02	5.79	5.31	-0.48	High	Heli.	Good
LAK007	Clearwater Ls.	152	2.6	367	1.0	3	Yes - Obs.	1437.6	95%	2%	3%	0%	0%	1390.0	16.8	35.9	-1353.7	7.98	7.98	7.98	0.00	-		
LAK008		146	1.8	300	0.9	3	Unknown	1802.6	94%	1%	5%	0%	0%	1682.4	21.9	46.7	-1635.3	7.92	7.92	7.92	0.00	-		
LAK011		920	1.3	52	1.2	3	Non-habitat	70.1	80%	2%	8%	9%	1%	99.2	14.8	28.9	-70.2	6.65	6.62	6.58	-0.04	-		
LAK012		151	2.3	90	0.9	3	Yes - Infer.	57.0	61%	4%	6%	26%	4%	79.1	19.9	41.5	-37.4	5.74	5.64	5.51	-0.13	High	Heli.	Fair
LAK013		276	2.2	49	0.8	3	Yes - Infer.	859.8	89%	1%	8%	2%	0%	720.3	14.7	33.4	-686.8	7.43	7.43	7.43	0.00	-		
LAK014	Ena L.	171	11.3	108	0.9	3	Yes - Obs.	77.8	62%	4%	15%	16%	3%	111.0	20.1	42.7	-68.1	6.51	6.46	6.38	-0.07	-		
LAK015		224	2.8	84	1.3	3	Yes - Infer.	75.0	38%	2%	34%	23%	3%	225.4	32.6	62.0	-161.7	5.98	5.97	5.96	-0.01	- [8]		
LAK016		247	2.6	41	0.9	3	Unknown	68.7	53%	4%	23%	15%	5%	115.5	21.9	44.3	-70.9	6.37	6.31	6.24	-0.07	-		
LAK017		129	1.0	26	1.1	3	Yes - Infer.	195.3	81%	6%	2%	9%	1%	231.3	17.4	32.4	-198.2	6.78	6.77	6.77	0.00	-		
LAK018	Clearwater Ls.	154	7.9	170	1.0	3	Yes - Infer.	1467.1	95%	1%	3%	0%	0%	1473.4	15.7	33.5	-1438.8	8.08	8.08	8.08	0.00	-		
LAK022		162	5.7	40	0.8	3	Yes - Infer.	27.8	24%	7%	29%	35%	6%	53.9	19.5	41.5	-12.2	6.11	5.92	5.54	-0.39	High	Heli.	No
LAK023	West L.	211	6.8	40	0.9	3	Yes - Obs.	19.8	25%	6%	25%	36%	7%	31.9	20.3	40.7	9.0	5.96	5.70	5.16	-0.54	High	Heli.	Good
LAK024	Lakelse L.	100	1374.4	37982	1.1	3	Yes - Obs.	299.5	83%	7%	7%	3%	0%	336.8	9.9	22.1	-314.5	7.14	7.14	7.14	0.00	-		
LAK027	Bowbyes L.	419	19.5	190	1.7	4	Yes - Infer.	69.8	43%	1%	51%	4%	1%	247.6	62.2	87.1	-160.4	6.65	6.64	6.64	0.00	-		
LAK028		267	1.0	12	1.6	4	Unknown	-4.0	0%	5%	51%	25%	18%	46.1	63.7	96.8	51.2	5.77	4.98	4.60	-0.38	High	Heli.	No
LAK030		376	4.5	66	1.8	4	Yes - Infer.	390.6	71%	2%	21%	3%	3%	801.6	72.8	116.9	-677.2	7.35	7.35	7.35	0.00	-		
LAK032		121	1.7	61	0.6	1	Unknown	1634.6	95%	1%	3%	1%	0%	944.7	7.1	16.2	-928.2	6.99	6.99	6.99	0.00	-		
LAK034		292	8.6	73	0.7	3	Yes - Infer.	99.4	69%	3%	11%	15%	3%	125.1	8.0	18.8	-105.9	6.76	6.74	6.71	-0.03	-		
LAK035		687	2.3	106	0.9	3	Yes - Infer.	48.3	63%	4%	12%	20%	1%	91.6	6.8	16.6	-74.8	6.26	6.23	6.17	-0.05	-		
LAK037		354	6.5	271	1.0	3	Yes - Infer.	60.7	65%	4%	13%	15%	3%	134.7	7.9	19.1	-115.3	6.60	6.58	6.54	-0.03	-		
LAK038		505	2.8	28	0.9	3	Yes - Infer.	129.0	66%	2%	12%	18%	2%	178.8	8.0	19.4	-159.2	6.57	6.56	6.55	-0.01	-		
LAK039		686	3.6	60	1.0	3	Yes - Infer.	77.5	59%	5%	10%	24%	3%	98.5	7.7	18.7	-79.5	6.39	6.36	6.33	-0.03	-		
LAK041		1150	1.6	63	1.4	1	Non-habitat	41.5	81%	2%	11%	5%	0%	53.9	2.2	5.2	-47.5	6.52	6.51	6.49	-0.01	-		
LAK042		171	1.5	37	0.6	1	Yes - Infer.	-20.4	0%	7%	8%	81%	4%	15.9	6.7	15.7	0.2	4.92	4.68	4.48	-0.20	High	Heli.	Fair
LAK044		219	2.0	10	0.6	1	Unknown	1.3	9%	19%	24%	38%	10%	0.0	7.0	16.6	16.7	5.80	5.40	4.86	-0.55	High	Heli.	Fair
LAK045		1279	1.6	52	2.3	2	Non-habitat	78.4	93%	2%	2%	2%	0%	226.5	2.8	4.7	-219.7	6.93	6.93	6.93	0.00	-		
LAK047		1476	1.6	43	2.4	2	Non-habitat	17.0	72%	7%	8%	10%	1%	0.0	4.5	8.2	10.2	6.00	5.96	5.94	-0.03	Low	Heli.	n/a
LAK049		1278	20.8	211	2.3	2	Non-habitat	87.9	91%	2%	5%	2%	0%	234.3	5.6	10.3	-221.7	6.83	6.82	6.82	0.00	-		
LAK050		1345	1.1	33	2.2	2	Non-habitat	52.6	85%	2%	10%	2%	1%	113.6	3.9	7.3	-101.9	6.52	6.51	6.51	0.00	-		
LAK051		145	1.9	94	0.9	2	Yes - Infer.	195.5	67%	1%	21%	10%	0%	236.6	5.2	11.2	-225.1	6.75	6.75	6.75	0.00	-		
LAK053	Jesse L.	57	1166.6	20001	1.8	2	Yes - Obs.	39.1	66%	8%	19%	6%	0%	83.0	5.9	10.5	-71.7	6.59	6.57	6.55	-0.01	-		
LAK054		170	1.5	125	1.6	3	Yes - Infer.	-21.3	0%	16%	18%	61%	5%	0.0	7.0	13.8	14.8	4.67	4.59	4.53	-0.06	Low	Heli.	No
LAK055		138	13.9	129	1.7	2	Yes - Infer.	51.3	51%	9%	8%	32%	1%	120.3	6.7	12.7	-107.2	6.17	6.16	6.15	-0.01	-		
LAK056		247	1.8	27	1.6	2	Yes - Infer.	-22.4	0%	26%	15%	56%	4%	1.2	6.5	12.9	12.4	4.56	4.50	4.44	-0.06	Low	Heli.	No
LAK057		107	1.4	148	1.7	2	Yes - Infer.	177.7	76%	4%	9%	11%	1%	420.7	6.7	12.7	-406.9	6.63	6.63	6.63	0.00	-		
STR001	Anderson Cr. u/s	130		2702	2.2	3	Yes - Infer.	62.4	76%	2%	18%	3%	0%	220.4	12.6	16.0	-203.5	6.77	6.77	6.77	0.00	-		
STR002	Anderson Cr. d/s	146		3741	2.1	3	Yes - Obs.	94.2	57%	2%	37%	3%	1%	330.6	21.4	25.5	-301.9	6.91	6.91	6.91	0.00	-		
STR003	Clearwater Cr.	152		454	0.9	3	Yes - Obs.	1418.6	94%	2%	4%	0%	0%	1395.7	16.7	35.8	-1359.0	7.87	7.87	7.87	0.00	-		
STR004	Furlong Cr.	127		1104	1.2	3	Yes - Obs.	338.2	87%	2%	5%	4%	1%	413.7	6.8	16.1	-391.5	7.06	7.06	7.06	0.00	-		
STR005	Hatchery Cr.	148		3052	1.5	3	Yes - Obs.	165.8	88%	2%	6%	2%	1%	258.6	5.1	11.7	-244.9	7.01	7.01	7.01	0.00	-		
STR006	Hirsch Cr.	93		35292	2.1	4	Yes - Infer.	186.4	88%	1%	9%	2%	0%	409.5	1.4	1.9	-406.8	7.11	7.11	7.11	0.00	-		
STR007	Humphrys Cr.	93		3072	2.1	3	Yes - Infer.	127.4	88%	2%	5%	3%	0%	277.6	2.7	4.8	-270.9	6.89	6.89	6.89	0.00	-		
STR008	Kitimat R. u/s	89		82143	1.4	4	Yes - Obs.	138.8	82%	1%	14%	2%	0%	262.6	3.4	6.8	-254.4	7.05	7.05	7.05	0.00	-		
STR009	Kitimat R. d/s	112		157136	1.6	3	Yes - Obs.	160.6	80%	4%	13%	2%	0%	299.3	13.9	23.6	-273.4	6.98	6.98	6.98	0.00	-		
STR010	Lakelse R. u/s	121		49868	1.2	4	Yes - Obs.	271.6	81%	7%	8%	3%	0%	334.2	10.6	22.7	-310.1	7.07	7.07	7.07	0.00	-		
STR011	Lakelse R. d/s	127		57352	1.1	2	Yes - Obs.	276.4	83%	7%	7%	3%	0%	317.7	10.4	22.2	-293.7	6.98	6.98	6.98	0.00	-		
STR012	Little Wedeene R. u/s	429		11014	2.1	4	Yes - Infer.	98.9	83%	2%	12%	3%	0%	163.0	6.9	9.3	-150.4	6.58	6.58	6.58	0.00	-		
STR013	Little Wedeene R. d/s	127		18282	2.0	4	Yes - Obs.	73.1	72%	2%	20%	3%	1%	174.7	18.2	25.2	-146.4	6.60	6.59	6.58	0.00	-		
STR014	Moore Cr. u/s	186		246	1.9	3	Yes - Infer.	39.4	74%	4%	13%	7%	1%	103.3	6.5	11.0	-89.6	6.47	6.45	6.44	-0.01	-		
STR015	Moore Cr. d/s	122		1353	1.7	3	Yes - Infer.	107.6	47%	3%	44%	3%	1%	372.5	12.3	20.0	-343.9	6.80	6.80	6.80	0.00	-		
STR016	Schulbuckhand Cr.	179		3301	1.4	3	Yes - Obs.	418.9	92%	1%	5%	2%	1%	627.3	6.7	14.8	-610.6	7.10	7.10	7.10	0.00	-		
STR017	Wedeene R. u/s	103		21286	1.8	3	Yes - Obs.	52.9	74%	3%	19%	3%	0%	131.5	6.4	10.8	-117.2	6.47	6.46	6.45	-0.01	-		
STR018	Wedeene R. d/s	165		31571	1.7	4	Yes - Obs.	80.1	75%	2%	17%	4%	0%	144.7	17.3	29.7	-111.4	6.74	6.73	6.72	-0.01	-		
STR019	Williams Cr.	106		16975	1.3	3	Yes - Obs.	257.6	91%	1%	6%	2%	0%	339.0	4.7	11.1	-327.3	7.26	7.26	7.26	0.00	-		
STR020	Wathl Cr.	33		12151	2.3	3	Yes - Obs.	293.3	91%	1%	6%	1%	0%	675.0	1.0	1.3	-671.8	7.36	7.36	7.36	0.00	-		

Footnotes for Table 9.4-8:

1. Acid Sensitivity Class (ASC) is based on the bedrock geology. A lower ASC number means higher bedrock sensitivity to acidification. Refer to Section 4.3.2 for details.
2. Fish habitat classifications for each lake and stream are taken from the B.C. Watershed Atlas (GeoBC 2012). Lakes/streams are classified as fish habitat (observed or inferred; blue text), non-habitat (red text) or unknown (purple text).
3. Anion composition analyses – refer to Section 8.6.3.3 for methods and Section 9.4.1.2.3 for results. The coloured shading indicates if a lake/stream is "influenced" (≥25%, lighter shading) or "dominated" (≥50%, darker shading with bold font) by a particular anion.
4. Critical load and exceedance analyses – refer to Section 8.6.3.4 for methods and Section 9.4.1.3 for results. The coloured shading indicates the critical load class or exceedance class, using the same classification schemes as the maps and tables in the report.
   For critical loads, the classes are:
   - Highly sensitive (0 to 20 meq/m^2/yr; red)
   - Sensitive (20 to 40 meq/m^2/yr; orange)
   - Moderately sensitive (40 to 60 meq/m^2/yr; yellow)
   - Low sensitivity 60 to 100 meq/m^2/yr; green)
   - Very low sensitivity (>100 meq/m^2/yr; blue)

   For exceedances, the classes are:
   - Critical load exceeded (>20 meq/m^2/yr; red)
   - Critical load exceeded (10 to 20 meq/m^2/yr; purple)
   - Critical load exceeded (0 to 10 meq/m^2/yr; orange)
   - Near critical load (-10 to 0 meq/m^2/yr; yellow)
   - Below critical load (-20 to -10 meq/m^2/yr; green)
   - Well below critical load (<-20 meq/m^2/yr; blue)
5. SDEP = wet + dry deposition of sulphate.
6. Estimated original pH and predicted future pH – refer to the end of Section 8.6.3.4 for methods and Section 9.4.1.3.5 for results.
7. Considerations for the adaptive management (AM) plan are discussed in Section 10.0. The 10 lakes identified as candidates for monitoring in the AM plan show exceedances of their critical loads and/or predicted changes in pH of greater than 0.1 pH units. The three lakes identified as low priorities for monitoring (Lakes 047, 054 and 056) demonstrate exceedances of their critical loads, which are close to zero. However, their predicted changes in pH are less than 0.1 pH units (0.03, 0.06 and 0.06 respectively).
8. Lake 015 has a current pH less than 6 but has not been selected as a candidate for the AM plan because the exceedance analysis showed that it will be well below its critical load and its future pH is only predicted to change by 0.01 pH units, therefore it does not appear to be sensitive to KMP.
9. Heli. = Helicopter. Sites with good or fair accessibility for fish sampling will also be accessible by foot for water sampling, which may be of benefit for sampling individual episodic events but is likely less efficient than helicopter when sampling all lakes being monitored.

9.4.1.3.4 Exceedance sensitivity analysis

The number of sites with critical load exceedances is quite insensitive to variation in deposition estimates (Table 9.4-9). As we varied the post-KMP deposition estimates from 50% to 200% of their predicted values (a broad range used for emissions modelling; A. Henolson, Trinity Consultants, September 2012, pers. comm.), the number of sites with exceedance (bottom row in Table 9.4-9) changed from five to 10 (out of 61), as compared to the eight lakes reported above under the most likely post-KMP deposition levels. Additionally, the number of sites with deposition more than 20 meq/m^2/yr below their critical loads (very unlikely to show exceedance, blue row in Table 9.4-9) changed very little, from 53 to 50 sites. The predictions of exceedance are quite insensitive to wide variations in deposition estimates, because of the bimodal distribution of critical loads discussed in Section 9.4.1.3.1; a few lakes are sensitive to acidification, while most lakes (plus all sampled stream and river sites) are very insensitive to acidification and could withstand deposition levels twice as high as KMP without exceeding their critical load.

Table 9.4-9: Results of sensitivity analysis to variation in sulphate deposition from one half to twice its predicted level. The number of sites in each exceedance category is shown across the deposition scenarios.

EXceedance (meq/m^2/yr)	**Sulphate Deposition Level**						
	0.5 KMP	0.75 KMP	1.0 KMP	1.25 KMP	1.5 KMP	1.75 KMP	2.0 KMP
EX >20	0	1	1	3	5	6	7
EX = 10 to 20	0	2	5	4	2	3	2
EX = 0 to 10	5	3	2	1	2	0	1
EX = -10 to 0	2	2	0	1	0	1	0
EX = -20 to -10	1	0	1	0	1	0	1
EX = <-20	53	53	52	52	51	51	50
Total # sites	61	61	61	61	61	61	61
# sites with EX >0	**5**	**6**	**8**	**8**	**9**	**9**	**10**

9.4.1.3.5 Predicted steady state ANC and pH using a modified ESSA/DFO model

The key results (Figure 9.4-15, Figure 9.4-17, and Table 9.4-8) are as follows:

- 34 lakes and 20 streams (54 of 61 sites) are predicted to have a pH change <0.1 unit. Of these 54 sites, 43 sites are predicted to have a pH change <0.02 pH units. Therefore

most lakes and all streams will not be expected to have any significant change in pH or biological condition. They line up on the 1:1 line in the Figure 9.4-17.

- Seven lakes are predicted to have a pH decline >0.1 unit (shown in red in Figure 9.4-17). These lakes have an ANC which puts them on the steep part of the pH-ANC titration curve so an ANC decline causes a bigger change in pH. These lakes *could* show some biological change if the predicted pH change actually occurs (depends on the actual F vs. the predicted F, as well as actual deposition vs. predicted deposition). Both current levels of organic acids and any change in DOC over time will affect the ultimate pH level. Five of these lakes showed exceedances using the SSWC model.
- Results from the ESSA/DFO approach are generally consistent with SSWC model results (see Table 9.4-8). Five of the eight lakes which show exceedances using the SSWC model also show pH declines >0.1 unit using the ESSA/DFO approach (Lakes 006, 023, 028, 042, 044). These lakes have a wide range of predicted deposition levels under KMP (42.4, 40.7, 96.8, 15.7 and 16.6 meq/m^2/yr, respectively), but the lakes with the lowest deposition levels also have the lowest F-factors and therefore greatest sensitivity to acidification (*F*=0.12 for Lake 042 and *F*= 0.04 for Lake 044). The coherence of both modelling approaches (SSWC and ESSA/DFO) gives stronger weight to potential negative impacts in these five lakes. Lake 042 is dominated by organic anions (DOC = 13.2 mg/L; organic anions = 81 %), and was estimated to have an original pH_0 of 4.8 in the absence of any sulphate deposition.
- Lakes 054 and 056, which did show exceedance using the SSWC (EX = 14.8 and 12.4 meq/m^2/yr) have current pH values of 4.59 and 4.5, and are at the low end of the titration curve. Lakes 054 and 056 have high DOC levels and are dominated by organic anions (DOC = 6.7 and 8.5 mg/L; organic anions = 61% and 56%, respectively). They are predicted to receive relatively low levels of sulphate deposition under KMP (13.8 and 12.9 meq/m^2/yr) and are predicted to change by less than 0.1 pH unit using the modified ESSA/DFO approach. These two lakes were estimated to have an original pH_0 of 4.65 and 4.62 (respectively) in the absence of any sulphate deposition.
- Lake 047 (current pH of 5.96) is a high alpine lake (1447m elevation), very sensitive to acidification (CL=0; F-factor of 0.21), and predicted to have an exceedance of 10.2 meq/m^2/yr with the SSWC model (including 2 meq/m^2/yr from NO_3 leaching and 8.2 meq/m^2/yr from sulphate deposition). However Lake 047 is predicted to have a pH change <0.1 pH units (-0.03 units) using the modified ESSA/DFO approach, due to the relatively low levels of sulphate deposition, and its position on a less steep part of the titration curve.
- Lakes 012 and 022, did not show exceedances under KMP using the SSWC model (EX = -37.4 and -12.2 meq/m^2/yr), but are predicted to show pH declines of 0.13 and 0.39 using the modified ESSA/DFO approach. Lakes 012 and 022 are currently at pH 5.64 and 5.92, have relatively high DOC levels (4.65 and 5.34 mg/L), are sensitive to acidification

(F-factors of 0.4 and 0.3), and are predicted to receive moderately high levels of deposition with KMP (both at 41.5 meq/m^2/yr). A further indication of the consistency between SSWC and modified ESSA/DFO methods is that Lake 012 is predicted to show exceedance under 2*KMP levels of deposition, and Lake 022 shows exceedance under 1.5* KMP (see sensitivity analysis in Section 9.4.1.3).

- Of the 11 lakes with a current lab pH_t <6, eight of them are predicted retrospectively to have had an original pH_0 <6 with no sulphate deposition, due their low base cations and the influence of organic anions: Lake 012 (pH_0 =5.74); Lake 015 (pH_0 = 5.98); Lake 023 (pH_0 = 5.96); Lake 028 (pH_0 =5.77); Lake 042 (pH_0 =4.92); Lake 044 (pH_0 =5.80); Lake 054 (pH_0 =4.67); Lake 056 (pH_0 =4.56). The other three lakes are predicted retrospectively to have had a pH just above or equal to 6: Lake 006 (pH_0 = 6.02); Lake 022 (pH_0 = 6.11); and Lake 047 (pH_0 = 6.00).

9.4.1.3.6 Effects of recent declines in SO_2 emissions on model predictions

We assessed the impact on model estimates of declines in SO_2 emissions from the Kitimat smelter over the period 2006 to 2011. As discussed at the end of Section 8.6.3.4, declining emissions during 2006-2011 would be expected to cause opposite effects in the two models: an underestimate of critical loads in the SSWC model (i.e., overestimating exceedance and acidification risk); and an overestimate of both steady state pH (pH_∞) and original pH (pH_0) in the ESSA/DFO model (i.e., underestimating acidification risk). We explored the sensitivity of pH predictions to this uncertainty by lowering the estimate of pre-KMP deposition by 27.2% (see Section 8.6.3.4), which causes increased critical loads, increased future change in deposition under KMP (i.e., bigger difference between post-KMP and pre-KMP deposition), and decreased historical deposition. In summary, this uncertainty does not significantly change the results of the study or its conclusions on the sensitivity of surface waters to KMP.

- Lowering the estimated pre-KMP deposition had negligible effects on critical loads and exceedances, and did not change the exceedance class of any site. For example, Lakelse Lake, with a high CL of 337 meq/m^2/yr, shifts to a slightly higher CL of 339.5 meq/m^2/yr, and its exceedance value drops from -314.5 to -317.2 (still very unlikely to have its CL exceeded). For the eight lakes with predicted exceedance under KMP, lowering the pre-KMP deposition by 27.2% changed exceedances as follows: Lake 006 (no change, remains at 14); Lake 023 (exceedance decreased from 9.0 to 8.5); Lake 028 (exceedance decreased from 51.2 to 43.7); Lakes 042, 044, 045 and 054 (no change, exceedances remain at 0.2, 16.7, 10.2, and 14.8 respectively); and Lake 056 (exceedance decreased from 12.4 to 12.1).
- Lowering the estimated pre-KMP deposition had negligible effects on pH predictions for most sites: predictions of pH_∞ decreased by less than 0.03 pH

units at 54 of the 61 sampled sites; and decreased by more than 0.1 pH units at only four sites. There was no effect on the number of lakes predicted to decline by 0.1 pH units or more (i.e., still seven lakes). Of these seven lakes (Lakes 006, 012, 022, 023, 028, 042, 044), a 27.2% reduction in pre-KMP deposition lowered pH_∞ by 0.21, 0.04, 0.15, 0.21, 0.13, 0.03 and 0.05 pH units, respectively.

- Lowering the estimate of pre-KMP deposition lowers the estimates of original pH (pH_0). All of the 10 lakes which are predicted to have either a CL exceedance or a future decrease in pH >0.1 pH units are then inferred to have had an original pH_0 <6. In other words, all 10 of these lakes would be considered to be naturally acidified to varying degrees prior to any industrial emissions, though still affected by the smelter. Under the procedures of Jeffries et al. (2000), none of these 10 lakes would be included in impact estimates.

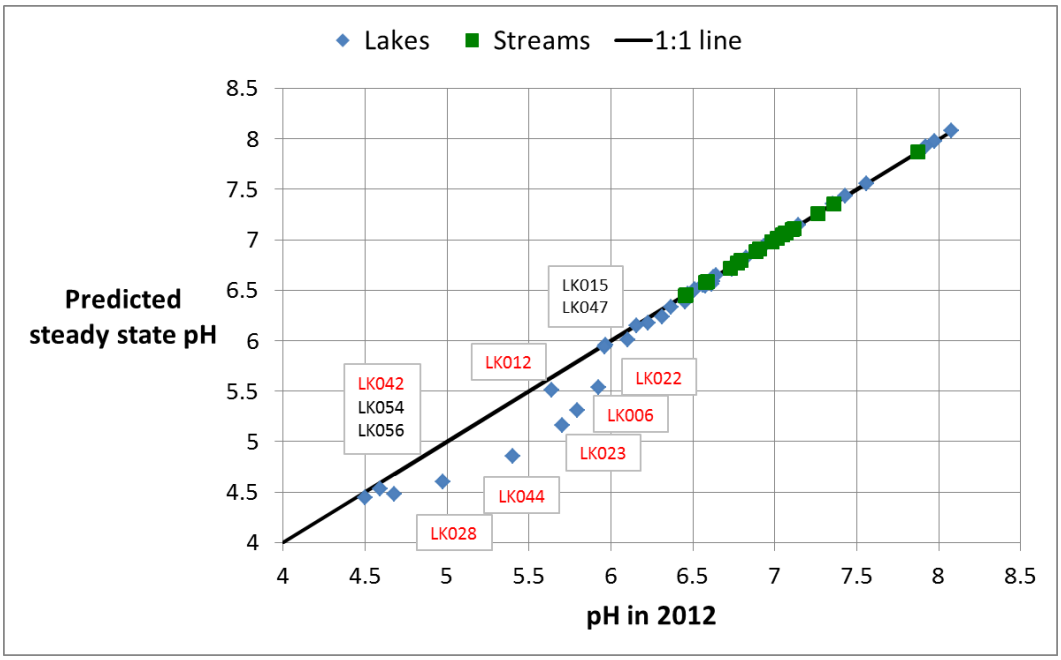


Figure 9.4-17: Predicted steady state pH vs. pH in 2012. All lakes with pH <6 are labelled. Lakes with a predicted pH change >0.1 unit are shown with red labels. Lakes with black labels showed exceedances using SSWC but are predicted to change by less than 0.1 pH units.

9.4.1.4 Synthesis of Level 0 and Level 1 Results

Key attributes from the previous sections of the report include:

- sites with measured current pH_t <6;
- sites with estimated historical pH_0 <6;

- sites with a predicted future change in pH >0.1 pH units; and
- sites which are predicted to exceed their critical load (CL);

None of the sampled streams fulfilled any of these four attributes, so our focus is on the sampled lakes. Figure 9.4-18 helps to clarify which of the 11 lakes with current pH_t <6 have which attributes. Table 9.4-10 (a subset of Table 9.4-8) illustrates the relative priorities for future monitoring of the 10 lakes with either CL exceedance or predicted pH change greater than 0.1 pH units (the two triggers for future monitoring, with a greater weight on pH change). Five lakes (centre of Figure 9.4-18) have both of these triggers: Lakes 006 (End Lake), 023 (West Lake), 028, 042, and 044. They have the highest priority for continued monitoring. Lakes 012 and 022 were not predicted to exceed their CL (first trigger), but are predicted to have more than a 0.1 pH unit change (second trigger), and are therefore also of high priority for continued monitoring. Lakes 047, 054 and 056 are predicted to exceed their CL, but are not expected to change by more than 0.1 pH units and therefore are of lower priority for continued monitoring. Lake 015, though currently with a pH <6 (5.97) is not predicted to exceed its CL or change by more than 0.1 pH unit (predicted change is -0.01 units), and is therefore not a priority for future monitoring (meets neither trigger). Altogether there are seven to 10 lakes potentially of interest for future monitoring – seven high priority and three low priority.

Figure 9.4-18 also illustrates that six of the eight lakes with predicted exceedances have an estimated original pH_0 <6, due to natural acidification (all six are either dominated or influenced by organic acids; Table 9.4-8). Equally important to our assessment of impact are the sites NOT shown on Figure 9.4-18, because deposition is less than their CL and/or their predicted pH change is less 0.01 units. This includes 31 of the 41 sampled lakes (including Lakelse Lake and Lake 015), and all of the sampled streams.

Table 9.4-10: Ten lakes under consideration for future monitoring in the AM phase. This table is a subset of the information contained in Table 9.4-8, and uses the same colour coding of exceedance categories (also used in Figure 9.4-15). Lake 047 is labeled as "n/a" under "Accessibility of fish sampling" because it is an alpine lake that is inaccessible to fish.

LAKE IDENTIFICATION		Triggers			CONSIDERATIONS FOR AM PLAN			Comments
Lake/Stream ID	Name	Exceedance meq/m^2/yr	Predicted future steady-state pH_∞	Predicted Δ pH (2012 to future)	Priority level for monitoring	Accessibility for water sampling	Accessibility for fish sampling	
LAK006	End L.	14.2	5.31	-0.48	High	Heli.	Good	critical load exceeded and pH change >0.1
LAK012		-37.4	5.51	-0.13	High	Heli.	Fair	critical load not exceeded but pH change >0.1
LAK022		-12.2	5.54	-0.39	High	Heli.	No	critical load not exceeded but pH change >0.1
LAK023	West L.	9.0	5.16	-0.54	High	Heli.	Good	critical load exceeded and pH change >0.1
LAK028		51.2	4.60	-0.38	High	Heli.	No	critical load exceeded and pH change >0.1
LAK042		0.2	4.48	-0.20	High	Heli.	Fair	critical load exceeded and pH change >0.1
LAK044		16.7	4.86	-0.55	High	Heli.	Fair	critical load exceeded and pH change >0.1
LAK047		10.2	5.94	-0.03	Low	Heli.	n/a	steady state pH_∞ very close to 6, pH change <0.1
LAK054		14.8	4.53	-0.06	Low	Heli.	No	naturally acidified pre-KMP, pH change <0.1
LAK056		12.4	4.44	-0.06	Low	Heli.	No	naturally acidified pre-KMP, pH change <0.1

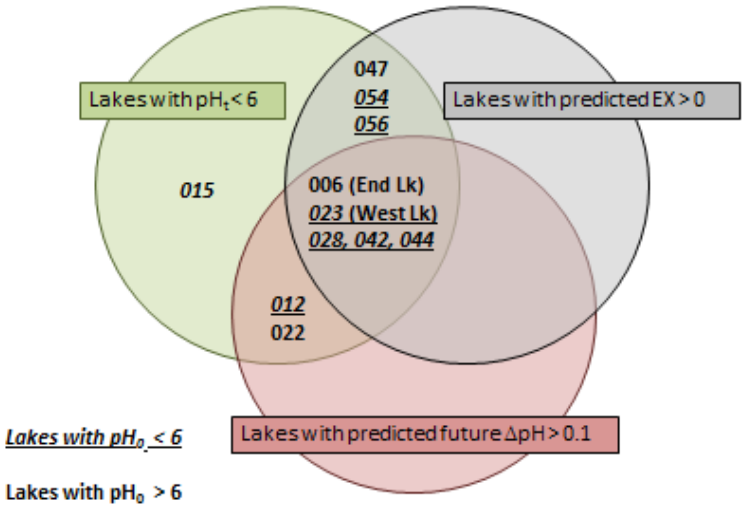


Figure 9.4-18: Overlap in the attributes of the eleven lakes with current pH_t <6.

9.4.2 Discussion

The preceding sections have summarized results for the 41 sampled lakes and 20 sampled stream sites. All of the stream sites and 31 of the 41 lake sites (including Lakelse Lake) were insensitive to acidification at the deposition levels expected under KMP (and even under twice that level of deposition). Ten lakes were found to have either CL exceedance and/or a projected pH change greater than 0.1 pH units. The sensitivity of these lakes to acidification is partly a function of natural acidification from wetlands: nine of these 10 lakes are either dominated or influenced by organic anions. As shown in Table 9.4-8, the 10 lakes of concern were estimated to originally have been either below or very close to pH 6 in pre-industrial times: seven of the 10 lakes were estimated to have had an original pH_0 <6 (Lakes 012, 023 (West Lake), 028, 042, 044, 054 and 056); the other three lakes have estimated original pH_0 values of 6.02 (Lake 006 – End Lake), 6.11 (Lake 022), and 6.00 (Lake 047).

Our risk assessment framework (Section 8.6.4), is based on CL exceedance. To assess the impact of KMP upon surface waters in the *overall study area*, and determine the percent of lakes and lake area potentially affected (a key metric for the risk assessment framework), we first need to estimate the number and area of lakes >1 ha in the study area, and then discuss the risks of exceedance in the unsampled area. To ensure consistency with our risk assessment framework and criteria in the Canadian Acid Rain Strategy, we focus on exceedance of critical loads using the SSWC model rather than pH change >0.1 using the modified ESSA/DFO model. Both methods, however, yield a similar number of lakes (i.e., eight lakes using SSWC and seven lakes using modified ESSA/DFO).

9.4.2.1 Number and area of lakes in the overall study area

We estimated the number and area of 'true lakes' in the study area as follows:

1. Of the 57 candidate lakes that were considered for sampling, 41 (or 71.9%) fulfilled the study's design criteria for 'true lakes' (i.e., depth >0.75 m, true pelagic zone, not a wetland or stream, not confounded by urban influences), as described in Section 8.6.1.
2. These 41 sampled lakes have a total lake area of 2,732 ha (Table 8.6-2).
3. GIS analyses indicate that there 134 lakes in the study area, with a total area of 3,089 ha (Table 8.6-2).
4. Assuming that the same proportion of lakes in the overall study area would fulfill the design criteria, we estimate that there are **96.4** 'true lakes' >1 ha in size (i.e., 134 * 0.719) in the study area.
5. The area of unsampled lakes in the study area is 327 ha (i.e., 3,089 ha (total area of lakes) minus 2,732 ha (sampled area) minus 30 ha (lakes within sampled region that were excluded based on the design criteria for 'true lakes')).
6. Applying the 0.719 proportion to the unsampled lake area of 327 ha indicates that there should be about 235 ha of 'true lakes' that fulfill the design criteria.
7. Adding 235 ha to the 2,732 ha of lakes already sampled, we get a total area of **2,967 ha** of 'true lakes' >1 ha in the study area.

9.4.2.2 Risk of exceedance in unsampled areas

The 2012 sampling design focused on regions with the highest level of predicted acidic deposition and greatest bedrock sensitivity to acidification. Of the 77 lakes in the unsampled area, most fall into the less sensitive ASC 3 and 4 zones (66 and three lakes respectively), with eight lakes in the more sensitive ASC 2 in the southeastern part of the study area (Figure 8.6-4; Table 9.4-11). There are no lakes within the unsampled zone in ASC 1. We believe that it is very unlikely that any of the lakes outside of the sampled area will receive deposition in excess of their critical load, and show an exceedance, for reasons given below. We discuss ASC 3 and 4 first, and then ASC 2.

ASC 3 and 4 had median critical loads of 223 and 248, respectively; these are higher values than for ASC 1 and 2, which had median critical loads of 83 and 173, respectively (Table 9.4-6), though the critical load distributions do overlap (Figure 9.4-13). The key issue is whether the maximum level of sulphate deposition is expected to exceed the minimum critical load within unsampled ASC 3 and 4 zones. The median sulphate deposition under KMP at lakes in unsampled ASC 3 and 4 zones is predicted to be 13% and 16% (respectively) of the median sulphate deposition under KMP at lakes in the sampled ASC 3 and 4 zones (Table 9.4-11). The maximum predicted level of sulphate deposition under KMP in unsampled ASC 3 and 4 zones is 23 meq/m^2/yr (Table 9.4-11). In the sampled area, 44 of the 45 sites in ASC 3 and ASC 4 had CL >23 (includes both lakes and streams), and therefore could tolerate a deposition level of

23 meq/m^2/yr without acidifying below the critical ANC limit (i.e., no exceedance). The one lake in ASC 3 with CL <23 in ASC 3 (Lake 054; an organically dominated lake with CL=0) was <1 km from an ASC 2 zone and may actually have been in ASC 2, given the resolution of the bedrock geology map. If the statistical distribution of critical loads in ASC 3 and 4 were similar in unsampled zones to sampled zones, then it would be very unlikely that any of the unsampled lakes in ASC 3 and ASC 4 would receive deposition in excess of their critical load. However, critical loads are likely to be higher in the unsampled ASC 3 zone than in the sampled zone, due to higher runoff (critical load is proportional to runoff). Most of the unsampled area of ASC 3 is at higher elevations, and the median level of runoff for lakes in the unsampled area is 2.1 times that for sampled lakes in ASC 3 (Figure 8.6-7; Table 9.4-11), which would increase their critical loads proportionately, thereby reducing even further the likelihood of critical load exceedance.

Table 9.4-11: Predicted annual sulphate deposition under KMP and estimated annual runoff at each lake in the study region, sorted by bedrock acid sensitivity class (ASC).

			KMP SO_4 deposition at lake (meq/m^2/yr)			Runoff at lake (m/yr)		
ASC	**Sample Class**	**# lakes**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**
1	sampled	4	16.53	16.10	33.64	0.61	0.59	0.76
1	unsampled area	0	-	-	-	-	-	-
2	sampled	9	10.18	4.65	12.58	1.73	0.84	2.44
2	unsampled area	8	0.78	0.58	1.24	1.75	1.69	2.70
3	sampled	24	33.19	5.23	66.60	0.91	0.74	1.60
3	unsampled area	66	4.16	0.45	22.99	1.93	0.77	3.00
4	sampled	4	87.71	33.20	106.78	1.51	0.75	1.67
4	unsampled area	3	13.91	13.71	14.29	0.64	0.63	0.64
	Total (sampled lakes plus lakes in unsampled area)	**118**	**7.56**	**0.45**	**106.78**	**1.72**	**0.59**	**3.00**

Deposition and runoff are estimated for the centre point of each of the 118 lakes in the study region greater than 1 ha in area, excluding the 16 lakes which were excluded from 2012 sampling due to wetlands, anthropogenic influence, shallow depths and other factors (i.e., 134 lakes in study region – 16 excluded lakes = 118 lakes). The centre point of each lake was used rather than the entire watershed area since many watersheds of the unsampled lakes would extend outside of the study area and involve extrapolation.

Deposition under KMP in the unsampled ASC 2 zone in the southeastern part of the study region will also be too low to cause exceedance. All of the lakes within the unsampled ASC 2 zone are predicted to have a deposition level <1.24 meq/m^2/yr (Table 9.4-10). Only two isolated lakes in the sampled areas of ASC 2 had CL <1.24 (Lake 047 with CL = 0 and Lake 056 with CL = 1.2); the other eight lakes in the sampled ASC 2 zone had CL >72. Lakes 047 and 056 did show exceedance, but these lakes are predicted to receive much higher levels of deposition under

KMP (8 and 13 meq/m^2/yr, respectively) than would occur in the unsampled ASC 2 zone (<1.24 meq/m^2/yr). The median runoff at lakes in sampled and unsampled ASC 2 zones is similar (1.73 vs. 1.75 m/yr; Table 9.4-10), though the minimum runoff in the unsampled ASC 2 zone (1.69 m/yr) is more than twice what occurs at lakes in the sampled ASC 2 zone (0.85 m/yr). Runoff is likely to increase critical loads in the unsampled ASC 2 zone to levels somewhat higher than at lakes in the sampled ASC 2 zone.

In summary, it is very unlikely that any of the lakes outside of the sampled area will receive deposition in excess of their critical loads, and show an exceedance.

9.4.2.3 Percent of lakes and lake area with/without critical load exceedance in the overall study area

Based on all of the above arguments, we assert that the eight sampled lakes (with a total area of 26.5 ha) are the best estimate of the total number and area of CL exceedances within the overall study area. Thus we estimate that **8.3%** of the lakes (8 / 96.4) and **0.9%** of the lake area (26.5 ha / 2,967 ha) in the study area will show exceedance[23]. The flip side is that we estimate that **91.7%** of the lakes, and **99.1%** of the lake area will not show exceedance. In particular, Lakelse Lake and all of the sampled streams and rivers are predicted to receive deposition well below their critical loads.

As discussed at the end of Section 8.6.3.4, calculations by Jeffries et al. (2000) in support of Environment Canada's Acid Rain Assessment excluded any lakes from their analysis if they were estimated to have had an original pH_0 <6, in recognition of natural acidification processes. As discussed above, six of the eight lakes with CL exceedances in the Kitimat Valley also were estimated to have had an original pH_0 <6 and are either dominated or influenced by organic anions. Therefore, application of the methods of Jeffries et al. (2000) would yield a lower bound estimate of 2.2% of the lakes with CL exceedance (i.e., (8 - 6) / (96.4 - 6) = 0.022).

9.4.2.4 Application of risk assessment framework

Table 9.4-12 and Table 9.4-13 are the result of applying the risk assessment framework (presented in Section 8.6.4) to the study's results. The sampled lakes differed in their degree and likelihood of critical load exceedance, and therefore occupy different rows of the risk assessment framework:

- Since the percentage of affected lakes is less than 10%, and neither Lakelse Lake nor any of the sampled streams are predicted to exceed their CLs, the three consequence

[23] The percentage of lakes with CL exceedance changes from 0.9% to 1.5% if the area of Jesse Lake (1,167 ha) is excluded from the total area of lakes. Similarly, the area of lakes without CL exceedance changes from 99.1% to 98.5% if Jesse Lake is excluded.

columns on the right hand side of Table 9.4-12 (3-serious, 4-major, 5-catastrophic) are not applicable.

- The decision on whether to consider the consequences to be minor or medium depends on whether all lakes are included in the analysis (which leads to a judgement of 'medium' as 8.3% of lakes exceed their CL), or whether the analysis includes only those lakes estimated to have an original pH_0 >6 (as per Jeffries et al. (2000), which leads to a judgment of 'minor' as then only 2.2% of lakes exceed their CL).
- We have chosen the more precautionary approach and placed all lakes in column 2 - medium consequence. We note however that the other approach is perfectly valid and indeed has been used by Jeffries et al. (2000) for Environment Canada's Acid Rain Assessment.
- six sampled lakes (6.2% of the # lakes; 0.6% of the lake area) are *almost certain* to show exceedance (predicted deposition >10 meq/m^2/yr above their critical load), and are placed in cell A2 of Table 9.4-12, which is coded orange. The percent of affected area is <5% and therefore coded yellow. These 6 lakes are placed in cell A2 to be precautionary, though based on lake area or the procedure of Jeffries et al. (2000) they would be put in cell A1.
- two sampled lakes (2.1% of the # lakes; 0.3% of the lake area) are *likely* to show exceedance (predicted deposition 0-10 meq/m^2/yr above their critical load). Lake 042, one of these lakes, has an exceedance of just 0.2 meq/m^2/yr. These 2 lakes are placed in cell B2 of Table 9.4-12 to be precautionary, though based on lake area or the procedure of Jeffries et al. (2000) they would be put in cell B1.
- one of the sampled lakes (1% of the # lakes, 0.2% of the lake area) is *unlikely* to show exceedance (predicted deposition 10-20 meq/m^2/yr below its critical load), and is placed in cell D2 of Table 9.4-12.
- The remaining sampled lakes and all of the sampled streams and rivers are *very unlikely* to show exceedance (predicted deposition more than 20 meq/m^2/yr below their critical load), and are placed in cell E2. Based on the arguments in Section 9.4.2.2, we assume that all *unsampled* 'true' lakes fall into cells E2 or D2, both in the low impact green zone.

Table 9.4-12: Application of risk assessment framework to results of the surface water critical load assessment. Percentages of number of lakes are shown in regular type; *percentages of the area of lakes are shown in italics with appropriate impact colour*.

	Consequence				
Likelihood (Deposition in meq/m^2/yr)	**1 – Minor** **<5 %** of study area lakes exceed CL AND **0** sampled streams exceed CL AND Lakelse Lake does not exceed CL	**2 – Medium** **5-10 %** of study area lakes exceed CL AND **0** sampled streams exceed CL AND Lakelse Lake does not exceed CL	**3 – Serious** **>10-15 %** of study area lakes exceed CL OR **1-2** sampled streams exceed CL AND Lakelse Lake does not exceed CL	**4 – Major** **>15-25 %** of study area lakes exceed CL OR **3-4** sampled streams exceed CL AND Lakelse Lake does not exceed CL	**5 – Catastrophic** **>25 %** of study area lakes exceed CL OR **5+** sampled streams exceed CL OR Lakelse Lake exceeds CL
A – Almost Certain Deposition ≥ 10 **above CL**		**6.2% of # lakes;** ***0.6% of lake area***			
B – Likely Deposition 0-10 **above CL**		**2.1% of # lakes;** ***0.3% of lake area***			
C – Possible Deposition 0-10 **below CL**					
D – Unlikely Deposition 10-20 **below CL**		**1.0% of # lakes;** ***0.2% of lake area***			
E – Very Unlikely Deposition ≥ 20 **below CL**		**90.7% of # lakes;** ***98.9% of lake area*** **20 streams & rivers of high interest**			

Not applicable to KMP outcomes

9.4.2.5 Conclusions

The distribution of lakes and lake areas is shown in Table 9.4-13 across the different impact categories.

Table 9.4-13: Summary of risk assessment for surface waters. Percentages of the area of lakes are shown *in italics* with appropriate impact colour highlighted.

Level of Impact	Percent of Lakes and Lake Area Affected
Low: No impact or acceptable impact; routine monitoring	91.7 % of # lakes; *99 % of lake area* 20 streams and rivers of high interest
Moderate: Acceptable impact but in need of closer scrutiny; moderate monitoring	
High: Unacceptable impact; contingency/ response action; intensive monitoring	6.2 % of # lakes; *0.7 % of lake area* 2.1 % of # lakes; *0.3 % of lake area*
Critical: Extremely unacceptable impact; critical response action; very intensive monitoring	None

The overall conclusion is that the impact of KMP on surface waters is predicted to be **moderate** (yellow), that is, an acceptable impact but in need of closer scrutiny, with moderate monitoring.

Our rationale for the conclusion of moderate impacts is that:

1. 91.7% of the sampled lakes (99% of the lake area, including Lakelse Lake and Jesse Lake) are very insensitive to acidification, and are predicted to show no or negligible pH and biological changes due to KMP (all less than 0.1 pH unit), and therefore would have no impact from KMP.
2. All of the 20 sampled streams of high public interest (including Wathl Creek, the water supply for Haisla Village) are very insensitive to acidification, are predicted to show no or negligible pH changes (all <0.012 pH units), and would have no impact from KMP.
3. Based on the SSWC model, eight lakes (8.3% of the lakes and 1% of the total area of lakes in the study area) have predicted exceedances of their critical loads (two likely and six almost certain). We consider the impacts on these acid-sensitive lakes to be moderate (an acceptable impact but in need of closer scrutiny with moderate monitoring) for the following reasons:
    a. three of the eight lakes with predicted exceedance are naturally acidic due to dominance by organic anions from wetlands and vegetation, and are estimated

to have an original pH_0 <5 even in the absence of any sulphate deposition (Lakes 042, 054 and 056);

b. three of the eight lakes with predicted exceedance are predicted to show a pH change <0.1 pH units (Lakes 047, 054 and 056), and are therefore not expected to show any biological changes under KMP;

c. five of the eight lakes with predicted exceedance are isolated without any road access within 200 m, and are therefore not likely to be frequently used by the public;

d. it is very unlikely that any lakes outside of the sampled area would receive deposition in excess of their critical loads (show exceedance), which means that estimates of % lakes and % area of exceedance derived from sampled lakes can safely be applied to the entire study area; and

e. outside of the sensitive subset of eight lakes with exceedance, the region's lakes are insensitive to acidification: sensitivity analyses showed that even with a doubling of predicted sulphate deposition, the number of lakes with predicted exceedance would only increase by two, from eight to 10.

4. There are seven lakes which are predicted to have a decrease in pH >0.1 units under KMP: five of the eight lakes with predicted exceedance under KMP (Lakes 006, 023, 028, 042, 044), plus two lakes which only have predicted exceedance under 2*KMP and 1.5*KMP (Lakes 012 and 022, respectively). The predicted pH changes are moderate (average of 0.38 pH units for the seven lakes; range from 0.13 to 0.54 pH units), but sufficient to warrant close scrutiny as biological effects are possible.
5. As discussed in Section 9.4.1.4, the highest priority for monitoring is on the seven lakes with predicted pH change greater than 0.1 units, five of which are also predicted to exceed their CL. If biologically significant pH declines were to actually occur in any of these seven lakes, these lakes could be either: (a) monitored to gain an understanding of their chemical and biological changes (we are confident that impacts would be restricted to these lakes without significant regional impacts); (b) restored by reducing levels of sulphate deposition, which has restored many Sudbury area lakes (Schindler 1997; Keller et al. 2007); or (c) restored through a carefully-designed, well-monitored, long term liming program (Olem 1990; Downey et al. 1994; Schreiber 1996).
6. The extent and magnitude of predicted changes in lake chemistry indicate that the potential effects of KMP on fisheries and aquatic biota are not regionally significant. We would therefore infer that indirect effects on wildlife via changes in aquatic prey are also not regionally significant.
7. The outcomes of KMP are consistent with the goals of the Canada-Wide Acid Rain Strategy (CCME 1998) of "keeping clean areas clean", and "maintaining 5% of lakes with a pH <6". At first this might seem counter-intuitive since we have identified a total of 10

potentially vulnerable lakes with either predicted CL exceedance (eight lakes) and/or >0.1 pH unit decline (seven lakes, five of which also have predicted CL exceedance), and 10/96 = 10.4%, clearly greater than 5%. However, the goal of "maintaining 5% of lakes with a pH <6" implicitly assumes that most lakes would have a pH >6 in the absence of acidic deposition. While all of the 10 acid-sensitive lakes discussed above are predicted to have an eventual steady state pH <6 under KMP, seven of these 10 lakes are also predicted retrospectively to have had an original pre-industrial pH_0 <6 in the absence of any sulphate deposition (and three lakes are estimated to have had a pH_0 <5). They were naturally acidic due to their low base cations and high organic acid contributions from wetlands and vegetation. The other three lakes are predicted to have originally had a pH very close to 6 (6.00, 6.02 and 6.11). Therefore the lower bound estimate of KMP effects is that only 3.1% of the region's lakes (3 / 96) are predicted to change from an original pre-industrial pH_0 >6 to an eventual steady state pH_∞ <6 due to smelter activity; the remaining seven lakes were naturally below pH 6 prior to any industrial activity (though also would experience varying levels of acidification due to KMP). This approach to estimating the lower bound of impacts (i.e., excluding lakes with a pH_0 <6) is exactly the same as that used by Jeffries et al. (2000) in estimating the effects of different deposition scenarios on the acid status of lakes in eastern Canada.

8. There is no risk of indirect health effects through elevated metal concentrations, since the lakes with predicted pH declines would not decrease to pH levels low enough to increase metal concentrations to a level of concern.

9.4.2.6 Critical uncertainties and priorities for AM phase

Further discussions with the B.C. Ministry of Environment are required to determine whether to focus the AM phase only on the seven highest priority lakes (i.e., those with predicted pH change >0.1 unit – Lakes 006, 012, 022, 023, 028, 042, 044), or to also include the three lakes with CL exceedance but predicted pH change <0.1 unit (Lakes 047, 054, 056). It would be straightforward to sample the average water chemistry of all of these lakes by helicopter, as was done in 2012 (see second rightmost column of Table 9.4-8). However, as shown on the rightmost column of Table 9.4-8, only two of the lakes (West Lake and End Lake) have good road access for fish sampling. Of the remaining seven lakes, three lakes (Lakes 012, 042, 044) have fair access for fish sampling (i.e., hiking 100-200 m with an inflatable boat from the nearest road), four isolated lakes (Lakes 022, 028, 054, 056) have no viable means of access for fish sampling (i.e., no safe place to land a helicopter, far from any road which would allow access by hiking), and one alpine lake (Lake 047) is known to be inaccessible to fish.

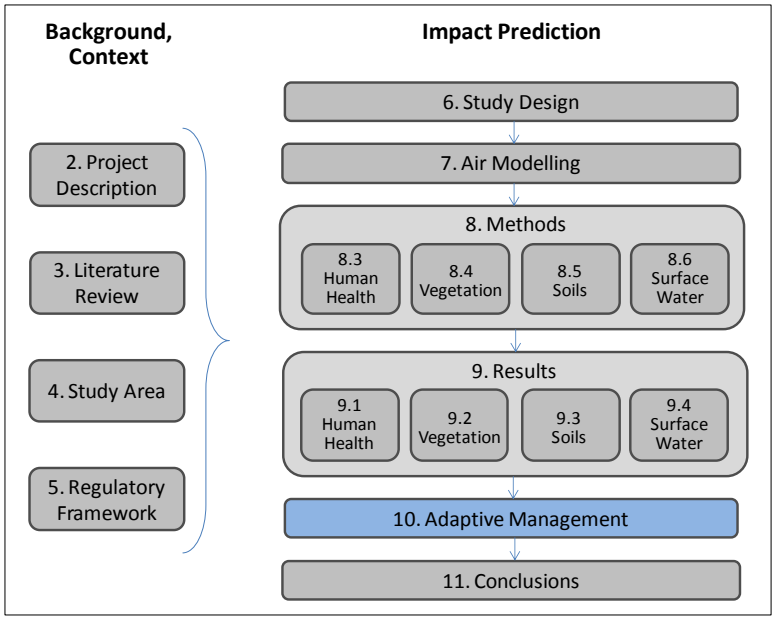
The critical uncertainties for surface waters are as follows:

1. How do uncertainties in deposition and surface water models affect the predicted extent and magnitude of critical load exceedance post-KMP?

2. How many of the seven to 10 potentially vulnerable lakes included in the AM plan actually acidify, and to what extent?
3. What is the current status of the fish community in the five potentially vulnerable lakes that can be safely accessed for fish sampling?
4. If some of the five lakes that can be safely sampled for fish show an acidifying trend, then do they also show changes in their fish communities?

The logical steps for reducing these uncertainties include: (1) reassessing surface water model uncertainty based on new SO_2 and deposition monitoring data collected in the AM phase; (2) carefully monitoring the chemical status of the seven to 10 potentially vulnerable lakes to see if they actually acidify to the levels that have been predicted; (3) determining the density of fish populations in five of the 10 lakes (i.e., those that can be safely sampled); and (4) if significant pH changes do occur (>0.30 pH units), determining what changes have occurred to fish populations in lakes that can be safely sampled, and deciding if any mitigative actions are appropriate (e.g., lake liming, reductions in SO_2 emissions).

10.0 Adaptive Management



10.1 PRINCIPLES OF ADAPTIVE MANAGEMENT

Practitioners of adaptive management use a variety of definitions, but all share important elements that are included in the following **definition** from Nyberg (1998):

> *Adaptive management is a systematic process for improving management policies and practices by learning from the outcomes of operational programs.*

The most effective form—"active" adaptive management—employs management actions that are designed to experimentally compare selected policies or practices, by evaluating alternative hypotheses about how the system being managed will respond. The key characteristics of adaptive management include:

- Acknowledgement of uncertainty about what policy or practice is "best" for achieving management objectives.
- Thoughtful selection of the policies or practices to be applied in order to reduce this uncertainty.
- Careful implementation of a plan of action designed to obtain critical knowledge needed to reduce this uncertainty.
- Monitoring of key response indicators.

- Analysis of the outcome in consideration of the original objectives.
- Incorporation of the results into future decisions.

Unfortunately the term 'adaptive management' has been widely misused and applied to largely ad hoc approaches, diluting its original rigorous intent. Common misconceptions about adaptive management include (Murray et al. 2011):

- It is the same as trial-and-error, or simply means adapting your policies as-you-go (whereas it is a very rigorous and systematic process).
- It is something only scientists do (whereas involvement of managers and policy-makers is also essential as it is their uncertainties that should drive adaptive management, and stakeholders must also be involved).
- It can solve all problems, or resolve all uncertainties (whereas it is only one tool for resolving uncertainty, best suited for questions about what management actions will best achieve management objectives at an operational scale where contrasts can be created and compared).
- It requires consensus from all stakeholders (whereas there should be agreement on desired outcomes, but it does not require agreement on how to achieve those outcomes – this is what adaptive management can help resolve).

Taylor et al. (1997) list some of the benefits of adaptive management:

- Well-designed experiments allow managers to evaluate reliably the effectiveness of alternative management actions.
- Adaptive management increases understanding of how ecosystems function.
- Adaptive management allows managers to proceed systematically and responsibly in the face of uncertainty, gaps in understanding, and disagreement.
- Management experiments may provide the only opportunity for learning about large-scale, ecosystem-level relationships.
- Adaptive management encourages more efficient and effective monitoring.
- Adaptive management helps to define the boundaries between activities that are ecologically sustainable and activities that are not.

Adaptive management is not needed for all environmental management situations, but can be very useful where there is significant uncertainty about the effectiveness of policies and practices. Applying the rigor of adaptive management often requires a considerable commitment of effort and resources, but can lead to better decisions more quickly than the status quo (Murray et al. 2011).

The process for undertaking adaptive management is often depicted as a simple six-step cycle (Figure 10.1-1). The first step (Assess) involves clearly defining and bounding the problem. This includes identifying: management objectives (desired outcomes); possible suites of actions that

could be taken to achieve the objectives; indicators or performance measures that could be monitored to determine whether the actions are achieving desired objectives; relevant spatial limits and resolution of the actions and indicators; relevant temporal horizon and resolution of the actions and indicators; critical uncertainties about how the actions will affect the indicators; hypotheses regarding the uncertainties (predictions about how the indicators may be affected by various actions); and what to do under each possible set of outcomes, outlining 'if-then' decision rules to guide managers.

Depending on both the outcomes and the level of certainty in their causes, these if-then decision rules could include triggers for more detailed analyses to better craft appropriate actions, or triggers to immediate implementation of urgent actions (e.g., as described in NOAA 2009). Including decision rules in the assessment step helps to fine-tune the design of monitoring and evaluation plans to provide the critical inputs required for future decisions. Conceptual models (e.g., source-pathway-receptor diagrams) are important tools for framing, organizing, exploring and conveying these elements in Step 1.

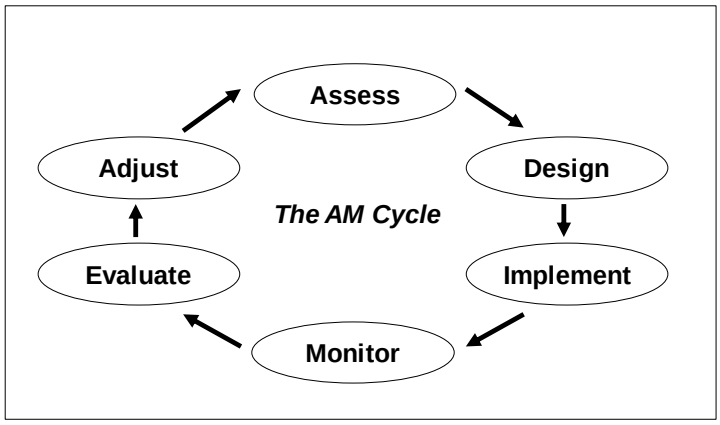


Figure 10.1-1: The six steps of the adaptive management cycle.

The second step (Design) involves designing a plan that details what specific actions will be taken to move concurrently toward achieving the stated objectives and testing hypotheses about the critical uncertainties.

The third step (Implement) is to carry out the plan. All aspects of the plan must be adhered to. Unavoidable deviations from the plan, and their rationale, must be clearly documented, otherwise it will compromise the interpretation of results.

Step 4 (Monitor) includes monitoring implementation to ensure that activities were undertaken as prescribed, monitoring indicators to learn whether the objectives were achieved, and monitoring indicators to test alternative hypotheses for critical uncertainties.

In the fifth step (Evaluate), monitoring data are analysed to learn what happened – which hypotheses can be rejected, which are strongly supported, which activities moved the system toward the desired objectives, and whether predicted outcomes were accurate.

In the sixth step (Adjust), policy, plans, practices, and/or prescriptions are altered as warranted based on what was learned (from Murray and Marmorek 2003).

Table 10.1-1 lists the elements in each of six steps in the adaptive management cycle. Inclusion of all listed elements in each step is the ideal, although in practice some may be left out for reasons of feasibility or the specifics of the particular situation. However each element has an important function and there are consequences for leaving any out. As more elements are dropped, the application of adaptive management becomes less rigorous and begins to move out of the domain of adaptive management into a less formal and potentially much less effective learning paradigm.

Table 10.1-1: Elements within each step of the adaptive management cycle (Murray et al. 2011).

AM Steps	Ideal Elements within each Step
Step 1. Assess and define the problem	a. Clearly state management goals and objectives b. Review existing information to identify critical uncertainties & management questions c. Build conceptual models d. Articulate hypotheses to be tested e. Explore alternative management actions (experimental 'treatments') f. Identify measurable indicators g. Identify spatial and temporal bounds h. Explicitly state assumptions i. State up front how what is learned will be used j. Involve stakeholders, scientists, and managers
Step 2. Design	a. Use active adaptive management where possible b. When and where possible, include contrasts, replications, controls c. Obtain statistical advice, building on analyses of existing data d. Predict expected outcomes and level of risk involved e. Consider next steps under alternative outcomes f. Develop a data management plan g. Develop a monitoring plan h. Develop a formal AM plan for all of the remaining steps i. Peer-review (internal, external) the design j. Obtain multi-year budget commitments k. Involve stakeholders
Step 3. Implement	a. Implement contrasting treatments b. Implement as designed (or document unavoidable changes) c. Monitor the implementation

AM Steps	Ideal Elements within each Step
Step 4. Monitor	a. Implement the monitoring plan as it was designed b. Undertake baseline ('before') monitoring c. Undertake effectiveness and validation monitoring
Step 5. Evaluate results	a. Compare monitoring results against objectives b. Compare monitoring results against assumptions, critical uncertainties, and hypotheses c. Compare actual results against model predictions d. Receive statistical or analysis advice e. Have data analysis keep up with data generation from monitoring activities
Step 6. Adjust hypotheses, models, & management	a. Meaningful learning occurred, and was documented b. Communicate this to decision makers and others c. Actions or instruments changed based on what was learned

Questions commonly arise about how adaptive management differs from research. This can best be answered in the context of its relationship to both research and regular management. In very general terms, conventional management is focused on achieving management objectives rather than learning; and while learning is the primary goal of basic research, the learning rarely targets questions plaguing managers. Adaptive management applies research approaches and principles to key management questions at an operational scale, as depicted in Figure 10.1-2 (with the expected reduction in reliability, precision and controllability when applying these principles across broader spatial and temporal scales). Adaptive management therefore embodies a high degree of learning that is highly relevant to management, using well-structured operational management actions as the learning vehicle.

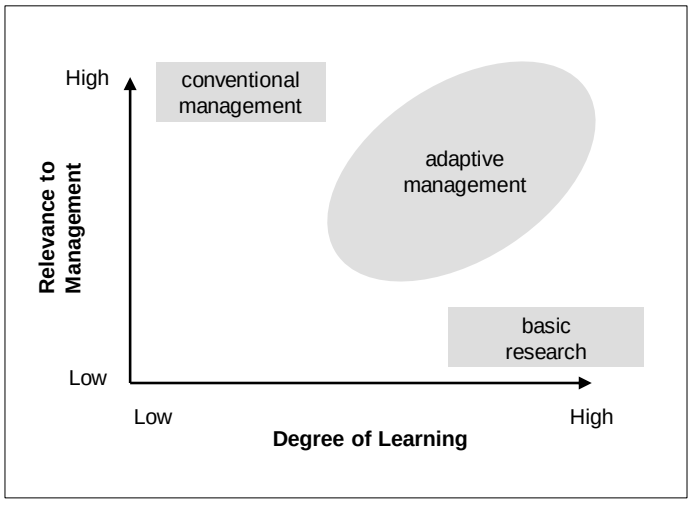


Figure 10.1-2: The relationship between adaptive management, conventional management and basic research (adapted from Murray and Marmorek (2003) for numerous ESSA training workshops on adaptive management).

One of the challenges of adaptive management is to find the right balance between management objectives and learning objectives, which may require compromises. For example, undertaking a range of timber harvesting treatments to maximize learning will almost certainly result in some areas not achieving management objectives as well as others. The trick is to know when and where this risk is and is not acceptable. For example, exploration of fire-based ecosystem restoration treatments might be more suited to broad experimentation away from human settlements and structures than in a fire-prone forest at the edge of town. Adaptive management practitioners must walk the sometimes fine line between maximizing learning and minimizing risk (from Murray and Marmorek 2003).

The rigor of adaptive management combined with the complexity of the ecosystems being managed typically requires practitioners to be aware of a range of potential technical tools and approaches for undertaking adaptive management. A selection of these is described in detail by Sit and Taylor (1998), including experimental design principles and considerations, non-experimental study methods, retrospective studies, measurement methods, error types, Bayesian statistical methods, and decision analysis.

10.2 APPLICATION OF ADAPTIVE MANAGEMENT TO SO_2 EMISSIONS

Similar assessment cycles have been used in the management of SO_2 emissions in both North America and Europe, without explicitly calling it adaptive management. These assessment cycles, which were not specifically developed for the management of one single source but for global emissions from power generation, have included the design of emission reduction strategies, monitoring of receptors to learn the results of those strategies, evaluating what has been learned and then revising the strategies accordingly.

For example, the 1990 Clean Air Act Amendments in the United States set targets for the reduction of sulfur emissions from industrial sources as a means of reducing the acidity in deposition. The objective was to increase the ANC and pH of low ANC and acidic surface waters, and improve their biological condition. The amendments included the creation of the Acid Rain Program, and required periodic assessment and reporting to Congress on implementation of the Program, the most recent scientific information related to acid deposition and its effects, and additional decreases in acid deposition necessary to prevent adverse ecological effects.

The U.S. Environmental Protection Agency undertook an assessment of changes in surface water chemistry in the northern and eastern U.S. from 1990 to 2000. The results (Stoddard et al. 2003) revealed that SO_4 deposition declined significantly, and SO_4 concentrations also declined significantly in surface water, consistent with declines in sulphate deposition. ANC also increased in three of the five regions studied. However, declines in base cation levels (in both deposition and surface waters) resulted in less recovery of ANC than anticipated. The authors concluded that the Clean Air Act Amendments were successful in reducing the emissions of SO_2 and deposition of SO_4, and that in some regions the number of acidic lakes and streams has

declined significantly while others remain acidic. The authors also present uncertainties and future data needs in order to understand why some areas are not showing expected signs of recovery.

A more recent assessment (Burns et al. 2011) of the Acid Rain Program determined that it has been successful in reducing emissions of SO_2 from power generation to the levels set by Congress. As a result of these emission reductions air quality has improved, providing significant human health benefits, and acid deposition has decreased to the extent that some acid-sensitive areas are beginning to show signs of recovery. However, the authors caution that additional emission reductions are necessary in order to protect acid-sensitive ecosystems, and they analyse a range of SO_2 emission-reduction scenarios to evaluate the extent to which further reductions could achieve additional environmental recovery and minimize the adverse ecological effects associated with acid rain.

10.3 RTA ADAPTIVE MANAGEMENT PLAN FOR SO_2 EMISSIONS

The Qualified Professionals (QPs) responsible for this assessment, under the coordination of ESSA, have developed an Adaptive Management Plan for addressing the critical uncertainties that emerged from the technical assessment. "Critical uncertainties" are those which, when resolved, *may* result in a predicted impact shifting up or down one or more levels in either of the dimensions in the risk assessment framework, which could result in a different impact category. Resolution of critical uncertainties may also change decisions on whether or not to implement mitigative actions. This plan clearly identifies the critical uncertainties, alternative hypotheses for each uncertainty, steps that need to be taken to learn which hypothesis is supported by actual outcomes under KMP, and management responses should these outcomes be unacceptable according to the assessment framework.

10.3.1 Adaptive management objectives, scope and timeframe

The goal of the adaptive management plan is to keep KMP SO_2 emissions below a level that would cause unacceptable impacts on water, vegetation, soils, and human health. The objectives underlying this goal are to:

- keep SO_2 emission levels below those which would result in sulphur *concentrations* harming human health or unacceptably damaging vegetation and wildlife; and
- keep SO_2 emission levels below those which would result in sulphur *deposition* exceeding critical loads for the most sensitive soils, surface waters, and vegetation.

The scope of the adaptive management plan extends to the critical uncertainties for each of the receptors as identified in the technical assessment for these receptors. The timeframe extends for as long as it takes to sufficiently reduce the critical uncertainties. We expect an intensive "adaptive management phase" during 2013 to 2018, followed by a continuation of adaptive

management in subsequent years for those uncertainties not yet sufficiently resolved after the first five years of operation.

Figure 10.3-1 illustrates how the adaptive management plan for KMP fits into the adaptive management cycle. This Technical Assessment Report focuses on the **Assess** and **Design** steps in the cycle, identifying: the critical uncertainties, hypotheses, indicators, and monitoring needed to reduce the critical uncertainties; how monitoring results will be evaluated; and triggers for more intensive study or mitigations if what is learned is that unacceptable impacts are expected.

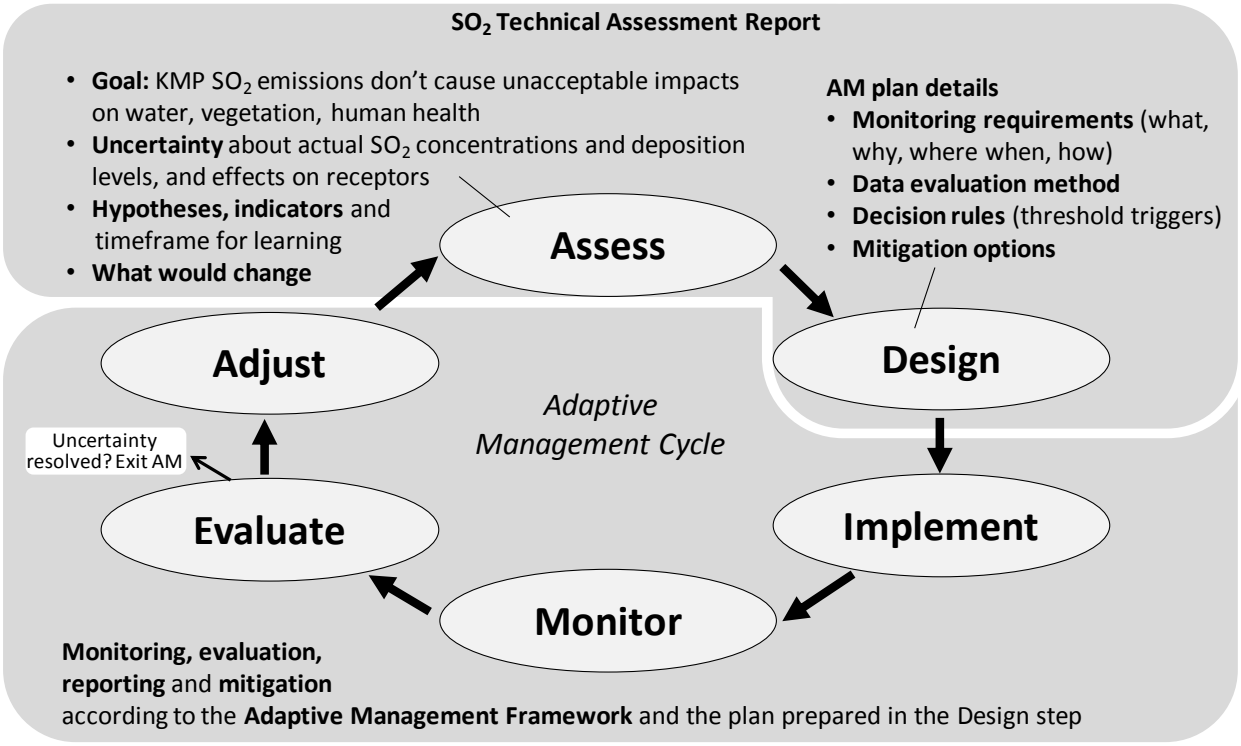


Figure 10.3-1: Conceptual illustration of the KMP adaptive management plan according to the six-step adaptive management cycle.

10.3.2 Adaptive management framework

The Adaptive Management Framework for KMP is presented in Figure 10.3-2. It is divided into three overall phases: pre-KMP, ramp-up and initial KMP operation (2013-2018), and 2019 onward.

The first phase begins pre-KMP with the technical assessment of the receptors presented in previous chapters of this report. Impact conclusions from the assessment of those receptors (Section 9.0) fall into either the green or yellow impact categories:

Low	No impact or acceptable impact; routine monitoring
Moderate	Acceptable impact but in need of closer scrutiny; moderate monitoring
High	Unacceptable impact; contingency/response action; intensive monitoring
Critical	Extremely unacceptable impact; critical response action; very intensive monitoring

There is also some uncertainty with these impact estimates:

- The risk may be *over*estimated or accurately estimated, which means the assessment predictions are either conservative (too high), or correct – indicated in the framework as "thumbs up".

- The risk may be *under*estimated, which means the assessment results are overly optimistic – indicated in the framework as one or two "thumbs down", depending on the implications of the underestimation.

- We don't know yet if the risk is underestimated or overestimated – indicated in the framework as "thumbs down" with a question mark.

Any impact estimations falling in the yellow, orange or red impact categories, as well as any critical uncertainties, become subject to the adaptive management plan.

The second phase starts in 2013 with monitoring and modelling during KMP ramp-up, and continues into the first years of full operation to reduce these critical uncertainties, and to evaluate the monitoring results at regular intervals appropriate for the uncertainty and the indicators. For each uncertainty, the evaluation will lead to one of three outcomes:

- Evidence that the technical assessment *underestimated* risks to receptors ( ) **and/or** revised estimates of risk are now high ( ) or critical ( ).

  → This will require mitigation and modifications to monitoring, either to increase the frequency or number of monitoring locations, or both.

- Evidence that the assessment correctly or *over*estimated risk to receptors ( ), or *under*estimated the risk ( ) **but** revised estimates of risk are still low **(** **)** or moderate ( ).

    → This will require no mitigation or modifications to monitoring.

- Unclear evidence in either direction due to lack of time for effects to be manifested (e.g., to observe that a lake is acidifying) or insufficient monitoring ( ), and the risk is currently estimated to be no more than moderate ( ).

    → This will require no mitigation, but may require modifications to monitoring, either to increase the frequency or number of monitoring locations, or both.

Regardless of the outcome, annual reports will be produced that describe the evaluation results as well as any mitigation that has been undertaken.

In 2018, a report will be produced that synthesizes what has been learned during this second phase, and assesses which uncertainties have been sufficiently resolved and which have not. Those that have been sufficiently resolved will exit the adaptive management plan, however long-term tracking of key performance indicators will continue throughout the life of the smelter.

From 2019 onward regular iterations of the same cycle in the previous phase will continue for the remaining critical uncertainties: monitoring and modelling, evaluating monitoring results, and responding with adjustments as necessary depending on the evaluation results. The requirements for action from each of the three evaluation outcomes will be the same as for the previous phase, with the exception that persistent green or yellow outcomes may warrant a decrease in monitoring frequency or locations.

Regardless of the outcome, annual reports will continue to be produced that describe the evaluation results as well as any mitigation that has been undertaken.

Every five years a report will be produced that synthesizes what has been learned over the preceding 5 years, and assesses which uncertainties have been sufficiently resolved and which have not. Those that have been sufficiently resolved will exit the adaptive management plan, however long-term tracking of key performance indicators will continue throughout the life of the smelter.

The adaptive management plan will end when all of the critical uncertainties have been sufficiently resolved.

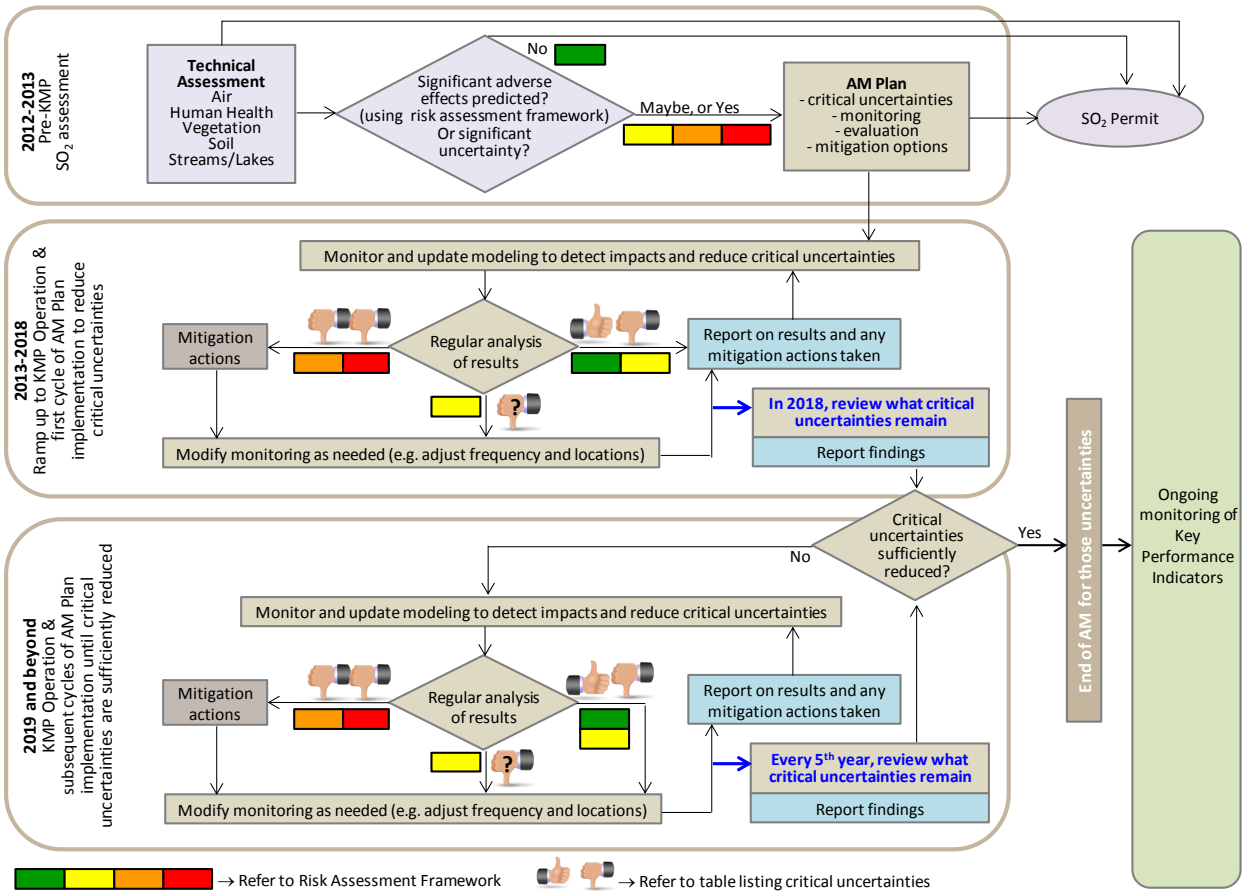


Figure 10.3-2: Adaptive management framework for KMP.

10.3.3 Critical uncertainties, hypotheses and monitoring needs

Critical uncertainties are summarized in Figure 10.3-3 and listed in greater detail in Table 10.3-1. (For more information on these uncertainties, please refer to Section 9 of this assessment report.) While we are ultimately concerned about risks to the receptors, some of the uncertainties apply to pathways in the source-pathway-receptor model. Each uncertainty is framed as a question. At least two hypotheses representing alternative outcomes are provided for each uncertainty (where applicable), along with a brief description of what would need to be measured or modelled to provide evidence of which of these is most strongly supported. The duration of modelling or monitoring is also noted, providing an estimate of how long it would take to answer each question. Table 10.3-2 summarizes these modelling or monitoring activities year-by-year over the next six years. Section 10.3.4 provides further details on the monitoring design, data evaluation method, and outcome thresholds warranting either more intensive study or mitigation for each of these uncertainties.

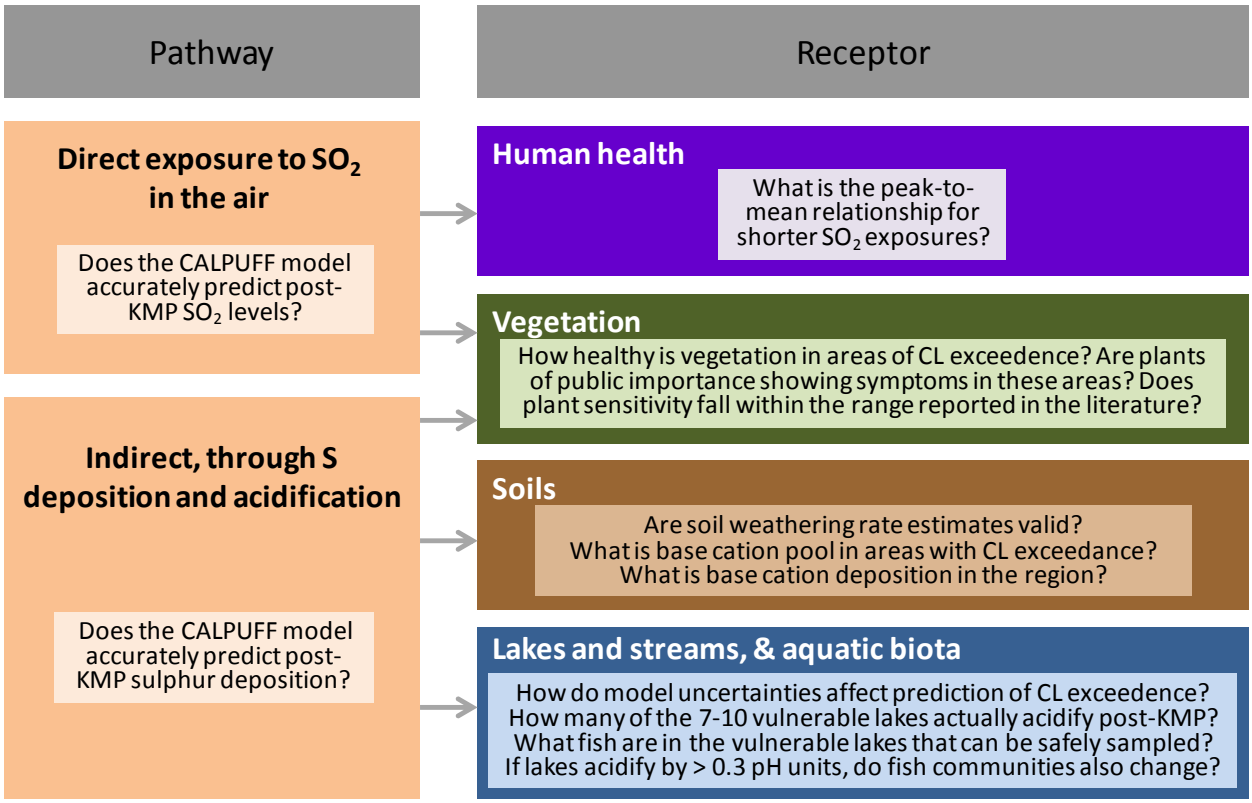


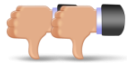
Figure 10.3-3: Critical uncertainties, by pathway and receptor.

Table 10.3-1: Critical uncertainties, pertaining either to receptors or pathways in the source-pathway-receptor model.

Pathway or Receptor	Critical Uncertainties	Hypotheses	Modelling and Monitoring Needs
Atmospheric Concentrations	**A1.** Does CALPUFF accurately represent post-KMP SO_2 air concentrations? *Affects predictions for all receptors, either directly (i.e., sulphur exposure impacts) or indirectly (i.e., acidification impacts).*	H_1. CALPUFF model predictions fall within an acceptable range when compared to actual SO_2 concentration data. H_2. CALPUFF model predictions fall outside an acceptable range when compared to actual SO_2 concentration data.	Gather data from the four continuous monitoring locations; compare 1-hour estimates from those monitoring data with 1-hour model predictions, complemented by data from passive samplers in a redesigned network, once a pilot program has proven the reliability of passive samplers. Duration: assess over 1 year after KMP fully implemented and at steady state operation, with further monitoring if uncertainty not sufficiently resolved after 1 year. Conduct updated CALPUFF modelling using post-KMP actual SO_2 emissions data if human health or environmental risks are not acceptable as modelled and less uncertainty is needed to more precisely predict risk. Updated CALPUFF modelling using post-KMP actual emissions may also be desired in order to refine the model's capability to more closely predict measured concentrations. A refined model would be useful if CALPUFF modelling is needed to predict concentrations from various mitigation options.

Pathway or Receptor	Critical Uncertainties	Hypotheses	Modelling and Monitoring Needs
Atmospheric Deposition	**D1.** Does the CALPUFF model accurately predict post-KMP total sulphur deposition? *Affects predictions of acidification for soil, lakes and streams.*	H_1. Total sulphur deposition measurements show an acceptable level of agreement with CALPUFF predictions. H_2. Total sulphur deposition measurements are lower than CALPUFF predictions (i.e., CALPUFF was conservative). H_3. Total sulphur deposition measurements are higher than CALPUFF predictions.	Wet deposition at 2 locations (Haul Road and Lakelse Lake) will provide reliable empirical estimates of deposition. These data will support evaluations of CALPUFF predictions, and regional estimates of total deposition to assess critical load exceedance. Duration: 4-5 years of monitoring. Conduct updated CALPUFF modelling using post-KMP actual SO_2 emissions data if environmental risks of sulphur deposition are not acceptable as modelled and less uncertainty is needed to more precisely predict risk. Updated CALPUFF modelling using post-KMP actual emissions may also be desired in order to refine the model's capability to more closely predict measured deposition. A refined model would be useful if CALPUFF modelling is needed to predict deposition rates from various mitigation options.
Human Health	**HH1.** How conservative is the CALPUFF model in predictions of SO_2 levels?	H_1. Model predictions are conservative or similar to actual post-KMP conditions in residential areas.	See **A1**.

Pathway or Receptor	Critical Uncertainties	Hypotheses		Modelling and Monitoring Needs
		H_2. Pre-KMP model predictions underestimate SO_2 levels in residential areas (i.e., greater SO_2 concentrations post-KMP).		
	HH2. What is the peak-to-mean relationship for shorter duration exposures?	H_1. The peak-to-mean ratios observed post-KMP are equal to or less than that produced by the model.		Analysis of continuous monitoring data, and comparison of 5-minute SO_2 concentrations with 1-hour SO_2 concentrations. Duration: assess over 1 year after KMP fully implemented and at steady state operation, with further monitoring if uncertainty not sufficiently resolved after 1 year.
		H_2. The observed peak-to-mean ratios post-KMP are greater than what is modelled.		
Vegetation	**V1.** Validation of the dispersion model – are we looking in the right place?	H_1. Post-KMP passive and continuous monitoring measurements show a similar SO_2 concentration distribution to that predicted by the model.		See **A1**.
		H_2. Post-KMP passive and continuous monitoring measurements show a different SO_2 concentration distribution to that predicted by the model.		

Pathway or Receptor	Critical Uncertainties	Hypotheses	Modelling and Monitoring Needs
	V2. How healthy is vegetation in sites with predicted exceedance of critical loads of soil and/or lakes and streams south of Lakelse Lake?	No hypotheses to test; answering the question requires monitoring for damage in areas of highest predicted critical load exceedance.	Add those locations into visual inspection program.
	V3. Are plants of public importance showing symptoms in areas with highest exceedances of soil critical loads?	H_1. Negligible or no effects. H_2. Indirect effects on plants via changes in soil base cations and Al are moderate. H_3. Indirect effects on plants via changes in soil base cations and Al are significant. 	Monitor plants in areas with highest predicted exceedances of soil critical loads (add these locations into visual inspection program). Visual inspection every second year of areas identified by soil critical load analyses. Vegetation samples of western hemlock bark, needles and wood can be taken for analysis of base cation content if plants show signs of impact. Duration: For 3-5 years after critical loads have been exceeded in an area.
	V4. Do plants at Kitimat that have unknown sensitivity to SO_2 and associated pollutants (acidic deposition) fall within the range of variation in the literature?	H_1. Yes, the scientific literature accounts for the responses of the most sensitive plants. H_2. No, symptoms indicate that plants at Kitimat may be more sensitive than those reported in the literature.	Continued inspections in the vicinity of KMP and at distance. Duration: Every other year for 6 years.

Pathway or Receptor	Critical Uncertainties	Hypotheses	Modelling and Monitoring Needs
Soils	**S1.** Are estimates of average weathering rates by bedrock type valid for vulnerable areas (e.g., where lakes have low base cations)?	H_1. Estimates of soil weathering rates used in this assessment are applicable to vulnerable areas such as lakes with low base cations. H_2. Estimates of soil weathering rates used in this assessment are too high for the most vulnerable areas, resulting in underestimates of exceedance of soil critical loads.	Additional soil sampling and analysis of the two most critical bedrock categories, and the orthogneiss metamorphic bedrock category in the unsampled southern portion of the study domain (maximum 10-15 samples divided equally between the bedrock categories) to expand the weathering estimates for these rock types. Three locations: (1) in quartz diorite bedrock type south of Lakelse Lake, co-located with lakes that had very low base cation concentrations (highest priority); (2) in calc-alkaline bedrock type near the smelter to support current weathering estimates that were based on extrapolation from other sites (lower priority as unlikely to change conclusion of high exceedance); and (3) orthogneiss metamorphic bedrock category in the unsampled southern portion of the study domain consistent with the region receiving high modelled S deposition (southwestern study domain). Duration: 1 week of sampling plus lab and modelling analyses.

Pathway or Receptor	Critical Uncertainties	Hypotheses	Modelling and Monitoring Needs
	S2. What is the current buffering capacity (base cation pool) of the soils in exceeded areas?	H_1. The current buffering capacity of soils is large and under post-KMP deposition it will take many decades to be depleted. H_2. The current buffering capacity of soils is small and under post KMP deposition it will take only a few years to be depleted.	Additional measurements of the exchangeable base cation pools for comparing pool sizes with deposition in exceeded areas; and samples collected in regions with low base cation lakes. Duration: 1 to 2 weeks of sampling before KMP start-up, followed by basic chemical analyses of soils.
	S3. What are the base cation deposition values in the study region?	H_1. Measurements of base cation deposition result in reduced estimates of magnitude or extent of exceedance of soil and water critical loads (or no change in predictions). H_2. Measurements of base cation deposition result in increased estimates of exceedance of soil or water critical loads.	Obtain estimates of base cation deposition, ideally at 2 wet deposition sites (1 close to the facility, and 1 at Lakelse Lake). Duration: 4-5 years of monitoring.
Lakes and Streams	**W1.** How do uncertainties in deposition and surface water models affect the predicted extent and magnitude of critical load exceedance post-KMP?	H_1. Predicted extent and magnitude of exceedances are reasonable, or are overestimates. H_2. Predicted extent and/or magnitude of exceedances are underestimates.	Assess uncertainties in SSWC and modified ESSA/DFO models (estimates of deposition, F); and analyses after completion of **A1** and **D1**. Links directly to **S3**.

Pathway or Receptor	Critical Uncertainties	Hypotheses	Modelling and Monitoring Needs
	W2. How many of the 7-10 potentially vulnerable lakes <u>actually</u> acidify under KMP, and to what extent?	H_1. Changes in water chemistry post-KMP (acidification) are similar to SSWC and modified ESSA/DFO predictions. H_2. Changes in water chemistry post-KMP are less than predicted. H_3. Changes in water chemistry post-KMP are greater than predicted.	Slightly smaller set of parameters than sampled in 2012; survey 7-10 potentially vulnerable lakes (see Section 9.4). Seven high priority lakes are Lakes 006 (End Lake), 012, 022, 023 (West Lake), 028, 042, 044. For 2 of the lakes with good road access (West Lake – Lake 023 and End Lake – Lake 006), could also examine water chemistry after snowmelt and storm events to assess if acidic episodes are occurring. Duration: focus on 7 lakes with predicted pH change >0.10 pH units, sampling annually during KMP ramp-up until lake chemistry stabilized (probably within 2-3 years), then once every 3 years for 2 more cycles.
	W3. What is the current status of the fish community in the potentially vulnerable lakes that can be safely accessed for fish sampling?	Establish baseline conditions of fish communities prior to implementation of KMP.	Establish baseline biological conditions prior to KMP start-up in safely accessible lakes (which could include Lakes 023 (West Lake), 006 (End Lake), 012, 042 and 044, to be confirmed by reconnaissance). Resample if pH declines by 0.30 pH units or more relative to 2012 pH. Of the other 5 lakes, 1 is an alpine lake inaccessible to fish

Pathway or Receptor	Critical Uncertainties	Hypotheses	Modelling and Monitoring Needs
			(Lake 047), and the other 4 lakes have no safe means of access for fish sampling (022, 028, 054 and 056).
	W4. If some of the potentially vulnerable lakes that can be safely accessed for fish sampling show an acidifying trend, then do these lakes also show changes in their fish communities?	H_1. No effects. H_2. Some loss of diversity but community is still functional. H_3. Major loss of diversity and function.	Repeat monitoring of fish contingent upon detecting chemical change >0.30 pH units relative to 2012 sample. If pH change is <0.30 pH units, then there would be no resampling of lake fish communities.

The following paragraphs summarize why each of these uncertainties is important for inclusion in the adaptive management plan: why it matters, and how it might change the assessment.

A1. *Does the CALPUFF model accurately predict post-KMP SO_2 air concentrations?*

Modelled estimates of post-KMP concentrations of SO_2 are used to assess effects of sulphur on human health and vegetation, and also drive deposition estimates (see **D1**). The accuracy of the SO_2 concentrations predicted in the CALPUFF model therefore affects the accuracy of the assessment for all of the receptors. If CALPUFF underestimated post-KMP SO_2 concentrations, impacts on receptors may be greater than predicted; alternatively if CALPUFF overestimated SO_2 concentrations, impacts may be less than predicted.

Conducting updated CALPUFF modelling using post-KMP estimates of SO_2 concentration will reduce uncertainty regarding SO_2 exposure impacts, and provide a reliable, empirically-calibrated tool which can be used to explore mitigation options.

D1. *Does the CALPUFF model accurately predict post-KMP total sulphur deposition?*

Modelled estimates of post-KMP sulphur deposition are used to predict critical load exceedances for soils and lakes and streams. If CALPUFF underestimated post-KMP SO_2 concentrations, impacts on receptors may be greater than predicted; and if CALPUFF overestimated these concentrations then impacts may be less than predicted.

Conducting updated CALPUFF modelling using post-KMP estimates of sulphur deposition will reduce uncertainty regarding exceedance of critical loads and acidification impacts, and provide a reliable, empirically-calibrated tool which can be used to explore mitigation options.

HH1. *How conservative is the CALPUFF model in predictions of SO_2 levels?*

See **A1.**

HH2. *What is the peak-to-mean relationship for shorter duration exposures?*

Respiratory responses in individuals with restrictive airway diseases are most closely linked to short-term peaks of SO_2 exposure. The shortest time period over which monitoring data are available is a 1-hour average. Therefore the relationship between 1-hour averages and these shorter-term peaks must be determined in order to accurately predict the risk.

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

See **A1.** Conclusions about impacts (currently predicted unlikely and minor, and therefore green) on vegetation from direct exposure to SO_2 based on evidence of vegetation damage may be underestimated if damage surveys are not done in the areas where highest concentrations of SO_2 are expected.

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

Conclusions about indirect impacts on vegetation from soil acidification are currently predicted to be low (green). Sensitivity analyses of soil critical loads based on *minimum* estimates of mineral weathering rates (as opposed to *average* weathering rates) suggest that a few areas in quartz diorite bedrock south of Lakelse Lake could exceed the soil critical load post-KMP (see **S1**). Extension of existing vegetation surveys to these areas would help to detect any indirect soil-mediated effects on vegetation (i.e., symptoms of base cation depletion or aluminum toxicity in the rooting zone of plants).

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

Same as **V2**, but applicable to exceedances elsewhere than just south of Lakelse Lake, and explicitly focusing on plants of particular value to stakeholders.

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

If the only plants showing symptoms of direct impacts are found in locations with SO_2 concentrations *greater than* literature thresholds for damage (i.e., one would expect plants to show damage based on literature thresholds), then all plants fall within the range of variation in the literature. If however plants show symptoms of direct impacts in locations with SO_2 concentrations *lower than* literature thresholds, then it suggests that some plants may have a greater sensitivity than those plants used in dose-response experiments and other studies to derive damage thresholds in the literature.

S1. *Are estimates of average weathering rates by bedrock type valid for vulnerable areas (e.g., where lakes have low base cations)?*

Weathering rates for base cations are a source of uncertainty for all critical load studies. Critical loads for soils in this assessment were estimated using a limited number (four to six) soil pits within each bedrock category, therefore there are areas in the study region where weathering rates are underestimated. Reducing this uncertainty is most important for two bedrock types in an area south of Lakelse Lake where exceedance is not predicted using estimates of average weathering rates, but is predicted using estimates of minimum weathering rates. This work would likely not change the predictions of high exceedance for a very small area near the smelter, or the overall impact category currently predicted to be moderate (yellow), as the potentially affected area is a very small percentage of the study region. It would however lend greater certainty to the assessment, and more informative estimates of exceedance risks, including how long it would take for soils to reach various thresholds (see **S2**).

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

The mass balance models used to determine whether critical loads will be exceeded do not provide information on *when* exceedance will occur. Estimating how long it will take to use up the base cation reservoir will provide a temporal element to the interpretation of the impacts of exceedances. The current predicted impact category of moderate (yellow) could be elevated to high (orange) if exceedance and resulting acidification impacts are expected to occur within 10 years, or reduced to low (green) if not expected for many decades.

S3. *What are the base cation deposition values in the study region?*

Deposition values for base cations in the study region are uncertain. This is more important for the water critical load analyses than the soil critical load analyses (see **W1**). In the absence of any reliable estimates, the soil critical load analyses conservatively assumed that base cation deposition was zero, meaning that any base cation deposition will increase soil critical loads and reduce estimates of exceedance, thereby also potentially reducing the impact category from moderate (yellow) to low (green) in some locations.

W1. *How do uncertainties in deposition and surface water models affect the predicted extent and magnitude of critical load exceedance post-KMP?*

Predictions of sulphur deposition affect estimates of both critical loads and exceedances, so the answer to **D1** is important. Similar to the soil critical loads analyses, the water critical loads analyses also assumed that deposition of base cations was zero, *but* implicitly capture any base cation deposition as part of the measured base cation concentration in the lake, and ascribe all of this to mineral weathering in the calculation of original pre-industrial base cation concentrations ($[BC^*]_0$). Changes in base cation deposition could affect the estimates of critical loads and exceedance for acid-sensitive lakes, but are unlikely to affect the extent of exceedance because such a high proportion of lakes and lake area in the study area is insensitive to acidification. After several years of monitoring water chemistry, if $[SO_4^*]$ has changed, it will be easy to empirically estimate an F-factor for each lake ($\Delta[BC^*] / \Delta[SO_4^*]$).

W2. *How many of the seven to 10 potentially vulnerable lakes actually acidify under KMP, and to what extent??*

There are uncertainties inherent in the assumptions in the deposition and surface water models from which impact predictions are derived. Existing information and sensitivity analyses (described under **W1**) give us a high level of confidence in the potential extent of acidification (low to moderate), but less certainty in the magnitude of acidification (i.e., observed versus predicted exceedance and pH change). Monitoring lakes that are potentially susceptible to acidification will help to reduce this uncertainty in model predictions. Monitoring results could reduce the impact category from moderate (yellow) to low (green), but are unlikely to increase the impact category beyond moderate (yellow). The highest priority is to monitor the seven lakes with a predicted pH change >0.10 pH units; the three other lakes are already naturally acidified and the prediction of the model shows almost no impact from KMP emissions (pH change <0.10).

W3. *What is the current status of the fish community in the subset of potentially vulnerable lakes that can be safely accessed for fish sampling?*

This is important because the acceptability of impacts of possible acidification in the acid-sensitive lakes will depend on the fish communities present in those lakes, and how important these fish communities are to stakeholders. At present we only have limited empirical information on fish composition for two of the 10 lakes being considered for the AM Plan (West Lake and End Lake). Three of the other lakes have fair access for fish sampling (safety of access needs to be confirmed by reconnaissance), four have no safe

access for fish sampling and one lake (an alpine lake at 1,440m) is definitely not accessible to fish. Having a baseline is essential for evaluating potential future changes (**W4**), and such a baseline could be safely established in five of the 10 lakes.

W4. *If some of the potentially vulnerable lakes that can be safely sampled for fish show an acidifying trend, then do these lakes also show changes in their fish communities?*

This follows from **W2** and **W3**. If some of the lakes which can be safely sampled for fish show pH declines sufficient to potentially affect fish (i.e., a pH decline >0.30 units, evaluated under **W2**), then it may be appropriate to resurvey the fish composition of these lakes in the future. This would provide more certainty in the actual *magnitude* of impacts in susceptible surface waters, but is unlikely to affect estimates of the *extent* of impacts, as explained under **W1**. Therefore the impact category is not expected to change.

Table 10.3-2: Summary of adaptive management activities over the next six years. Further details on the AM Plan are in the text of Sections 10.3.3 and 10.3.4, with mitigation discussed in Section 10.3.5.

Line of evidence	Associated uncertainties	2013	2014	2015	2016	2017	2018
Atmospheric Modelling / Monitoring: SO_2		Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting
SO_2 Concentrations	A1, HH1, HH2, V1	Maintain existing 4 continuous SO_2 analysers Conduct annual comparison to model output	Maintain existing 4 continuous SO_2 analysers Conduct annual comparison to model output	Relocate KMP ambient air and meteorology station to Lakelse Lake Conduct annual comparison to model output	Maintain 4 continuous SO_2 analysers Conduct annual comparison to model output	Maintain 4 continuous SO_2 analysers Conduct annual comparison to model output	Maintain 4 continuous SO_2 analysers Conduct annual comparison to model output
Passive Diffusive SO_2 Monitoring	A1, V1, S2, S3, W1, W2	Small, low cost pilot program with non-TEA based samplers at 2 sites to see if they correlate well with continuous SO_2 monitors	If (and only if) pilot program shows good correlations with continuous monitors, then develop revised passive diffusive SO_2 monitoring program to augment SO_2 analysers, and conduct passive monitoring Otherwise, continue low cost pilot program		If methodology proven to be effective in 2013-2014, conduct passive monitoring		If methodology proven to be effective in 2013-2014, conduct passive monitoring program
Atmospheric Modelling / Monitoring: Deposition		Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting
Wet Deposition	D1, S2, S3,	Maintain 2 rain chemistry	Maintain 2 rain	Maintain 2 rain	Maintain 2 rain	Maintain 2 rain	Maintain 2 rain

Line of evidence	Associated uncertainties	2013	2014	2015	2016	2017	2018
	W1, W2	stations (Haul Road and Lakelse Lake)	chemistry stations (Haul Road and Lakelse Lake)	chemistry stations (Haul Road and Lakelse Lake)	chemistry stations (Haul Road and Lakelse Lake)	chemistry stations (Haul Road and Lakelse Lake)	chemistry stations (Haul Road and Lakelse Lake) Conduct annual comparison to model output Assess number of rain chemistry stations
Dry Deposition	A1, S2, S3, W1, W2	Develop methodology for estimating dry deposition using existing data	Continue to estimate dry deposition at Haul Road	Relocate Campsite KMP ambient air and meteorological station to allow for estimating dry deposition at Lakelse Lake	Continue to estimate dry deposition at both Haul Road and Lakelse Lake stations	Continue to estimate dry deposition at both Haul Road and Lakelse Lake stations	Continue to estimate dry deposition at both Haul Road and Lakelse Lake stations Conduct annual comparison to model output
Vegetation		Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting
Vegetation Survey	V2, V3	Review, and if necessary, revise vegetation monitoring program	Visible injury; (include safely accessible high elevation sites and sites predicted to exceed CL)		Visible injury; (include safely accessible high elevation sites and sites predicted to exceed CL)		Visible injury; (include safely accessible high elevation sites and sites predicted to exceed CL)
Lichens	V4	Conduct study review; B.C. MOE Pilot project to determine distribution of sensitive lichens in the Kitimat Valley	Complete B.C. MOE lichen pilot study				
Soils		Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting
Detailed AMMP component design	S1 to S3	RTA/MOE/QP collaboration on details of study design					

Line of evidence	Associated uncertainties	2013	2014	2015	2016	2017	2018
		for this component					
Additional soils sampling and geomorphology considerations	S1, S2	Just work on design in 2013; do sampling in 2014	Conduct additional soil sampling to fill data gaps (QD bedrock type in sensitive lake areas S of Lakelse Lake accessible by road; CA bedrock type near smelter; OM bedrock type in SW part of region; and possibly (but not likely) glaciofluvial landforms)	Refine the soils critical load analysis with added data from 2013 soil samples and with critical load mapping			
Current buffering capacity	S2	Analyse 2012/13 soils samples to determine total amount of base cations in soils (cation exchange capacity and base saturation)					Conduct round of soil sampling for the indicator(s)
Lakes and Streams		Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting
Detailed AMMP component design	W1 to W4	RTA/MOE/QP collaboration on details of study design for this component					
$[SO_4]_0$; F-factor	W1					Reduce the uncertainties of these factors based on lake chemistry and deposition data	
Sample water chemistry in 1 of 5 additional Lake	W2	Sample water chemistry of 1 lake that meets scope in					

Line of evidence	Associated uncertainties	2013	2014	2015	2016	2017	2018
Areas proposed by MOE		study criteria. If this lake is vulnerable to acidification (exceeds CL or predicted pH change >0.1 unit), add it to the set of 7 high priority lakes sampled annually					
Biological sampling in the subset of the 10 vulnerable lakes that are safely accessible	W3, W4	Baseline biological conditions (fish and benthos) for safely accessible lakes			Resample biota if lake pH decreases by more than 0.30 pH units relative to 2012 pH		
Helicopter sampling of 7 high priority lakes that are predicted to have pH change >0.1 units: Lakes 006 (End Lake), 012, 022, 023 (West Lake), 028, 042, 044	W2	**Lab:** pH, major anions and cations, DOC, dissolved and inorganic monomeric Al, alkalinity, Gran ANC **Field**: pH, temp, O_2, TDS	Same as 2013	Same as 2013	Same as 2013	If lake chemistry stablilzed, switch to sampling every 3 years	If lake chemistry stablilzed, switch to sampling every 3 years
Snow melt and fall storm episodic acidification in safely accessible lakes	W2	none	Initiate study design	Finalize study design	Implement study	none	Implement study
Other		Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting	Annual reporting
Sensitive Ecosystem Mapping		Review PEM and TEM mapping to see if there are any sensitive ecosystems within the plume that were not covered by existing network of vegetation, soil and surface water sampling sites					

10.3.4 Adaptive management plan details

This section provides greater details about how the uncertainties described in Section 10.3.3 will be reduced, building on the information provided in Table 10.3-1 and Table 10.3-2. This includes information on what performance measures are needed, why, where, and how, and the risks of not collecting these data; how the data will be evaluated; 'decision rules' for any necessary additional actions; and mitigation actions if needed (which are further described in Section 10.3.5). Issues that arose through the consultation process may lead to the addition of new uncertainties to be addressed in the adaptive management plan.

10.3.4.1 Reducing uncertainty regarding atmospheric concentrations

A1: *Does CALPUFF accurately represent post-KMP SO_2 air concentrations?*

1. Monitoring data required to answer A1:
   - What performance measures are essential?
     - Continuous analyser measurements of SO_2 air concentrations.
     - Passive sampling measurements of SO_2 concentrations.
   - Why?
     - Comparing continuous analyser data to predicted concentrations can verify that the model predictions accurately and/or conservatively represent post-KMP SO_2 concentrations at locations of interest.
     - Comparing passive SO_2 sampling data to predicted concentrations can verify that the model predictions accurately represent the spatial distribution of post-KMP SO_2 concentrations (locations of maximum and minimum concentrations).
   - Where (what are the essential sampling locations)?
     - Essential locations: three of the four current continuous analyser sites (Haul Road, Riverlodge, Kitamaat Village (Haisla)). Monitoring at the KMP Camp should also be continued until the analyser is relocated to Lakelse Lake; and then monitoring is also recommended at the new Lakelse Lake site (however this is a lower priority than the three essential sites, due to low predicted impacts).
     - Passive sampling is essential at the two continuous monitoring locations for the pilot program (more on this below).
     - Passive sampling is needed at all continuous monitors and additional near-field locations expected to capture concentration variability.
   - When (at what sampling duration and frequency, and essential years and times)?

    - Maintain operation of continuous analysers through 2018 (this assumes that KMP will be fully implemented and at steady-state operations by the end of 2017).
    - Conduct a pilot program for passive sampling in 2013. If the pilot program is successful, implement at a larger scale in summer of 2014, 2016, and 2018. If the accuracy of passive samplers is unclear after 2013, continue the pilot program in 2014.
  - How (using what monitoring protocols and sampling methods)?
    - Continue to follow the monitoring protocol for continuous analysers including maintenance, calibration, and data collection and quality review.
    - Follow the protocol for the passive sampling pilot program for 2013 and possibly 2014.
    - If the passive samplers are proven effective, follow a revised passive monitoring program to be developed by the first quarter of 2014.
  - What are the risks of not collecting these data?
    - There would be no way to assess the accuracy of model predictions about atmospheric concentrations of SO_2.

2. How and when monitoring data will be evaluated to address A1:
   - Using continuous analyser data from 2014 to 2018, monitoring data analysis comparing measured concentrations to modelled concentrations will be completed in the first quarter of each year from 2015 to 2019. (This timeline assumes that KMP will be fully implemented and at steady-state operations by the end of 2017.)
   - Passive sampling data from 2013 (and possibly 2014) will be compared to continuous analyser data to assess the accuracy of passive samplers.
   - If a full-scale passive sampling program is implemented, data from 2014, 2016, and 2018 will be used to evaluate the distribution of CALPUFF modelled concentrations compared to the distribution of measured concentrations at the passive samplers.
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
     - High confidence level for specific monitoring locations;
     - Moderate confidence level for other near-field locations;
     - Low confidence level for long range concentrations.

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:

- If measured concentrations exceed 150% of the concentrations modelled in CALPUFF for the 1-hour, 3-hour, 24-hour, or annual averaging periods, updated modelling to more accurately represent air concentrations should be considered.[24]

- Trigger for implementing mitigation actions:
  - As per the assessment frameworks for human health and vegetation in Sections 8.3 and 8.4, respectively, and mitigation action triggers for HH2, V2 and V4.

4. Mitigation options:
   - Refer to mitigation options listed for human health (Section 10.3.4.3) and vegetation (Section 10.3.4.4).

10.3.4.2 Reducing uncertainty regarding atmospheric deposition

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

1. Monitoring data required to answer D1:
   - What performance measures are essential?
     - Establishment of wet deposition monitoring stations at two locations (Haul Road and Lakelse Lake) to provide measurements of deposition comparable to other locations in Canada.
     - Establishment of a regional network of passive samplers to provide reliable measurements of SO_2 concentrations and estimates of dry deposition.
   - Why?
     - These data will support evaluations of CALPUFF predictions, and provide regional estimates of total deposition needed to assess critical load exceedance. Further data will support assessment of base cation wet deposition used in the determination of critical loads.
   - Where (what are the essential sampling locations)?
     - Essential sites for wet deposition monitoring are Haul Road (near field, existing) and Lakelse Lake (far field, to be established).
     - The location of passive monitoring sites to be determined in conjunction with MOE following further evaluation of passive samples.

[24] Other triggers related to health and vegetation impacts are provided in the assessment frameworks for health and vegetation in Sections 8.3 and 8.4, respectively.

- When (at what sampling duration and frequency, and essential years and times)?
  - Wet deposition monitoring to commence as soon as possible, and continue through 2018 (assuming KMP is fully implemented and at steady-state operations by the end of 2017), and to occur year-round and continuously.
  - Evaluation of SO_2 passive samples to be carried out during 2013, with establishment of a network during 2014, and monitoring during 2014, 2016 and 2018; measurements anticipated for two calendar quarters within each year.
- How (using what monitoring protocols and sampling methods)?
  - According to wet deposition and passive sampler monitoring protocols, including maintenance, calibration, and data collection and quality review.
- What are the risks of not collecting these data?
  - There would be no way to evaluate the predicted S deposition from the CALPUFF model, and the associated extent of exceedance. There would remain an uncertainty and citizen concern as to how acidic deposition in the KMP-impacted region compares with the rest of Canada and North America.

2. How and when monitoring data will be evaluated to address D1:
   - Data collected from 2013 to 2018 will be used to:
     - Estimate total S deposition, using observations of wet deposition combined with estimates of dry deposition based on observations of atmospheric SO_2 (e.g., from continuous SO_2 monitors and strategically-deployed passive samplers).
     - Evaluate modelled and observation-based estimates of S deposition.
     - Estimate base cation wet deposition.
   - Data analysis comparing measured deposition to modelled deposition should be completed by the first half of 2019, assuming KMP is fully implemented and at steady-state operations by the end of 2017.
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
     - High confidence level for specific monitoring locations;
     - Moderate confidence level for other locations.

3. Proposed decision rules for alternative actions:
   - Early warning threshold triggering more intensive studies:

- Observation-based estimates of total S deposition are sufficiently greater than modelled estimates to suggest that CL exceedance for soils or water may be higher than predicted **or**, if observation-based estimates of total S deposition are more than 50% greater than modelled estimates.

- Trigger for meetings with MOE on implementing mitigation actions:
  - As per the assessment framework for soils and water in Sections 8.5 and 8.6; i.e., if observation-based total S deposition measurements are higher than CALPUFF predictions and will lead to elevated estimates of critical loads exceedance for these receptors.

4. Mitigation options:
   - Refer to mitigation options listed for soils (Section 10.3.4.5) and lakes and streams (Section 10.3.4.6).

10.3.4.3 Reducing uncertainty regarding impacts on human health

HH1: ***How conservative is the CALPUFF model in predictions of SO_2 levels?***

1. Monitoring data required to answer HH1:
   - Please refer to the information for uncertainty A1.

2. How and when monitoring data will be evaluated to address D1:
   - Please refer to the information for uncertainty A1.

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - After 1 year of KMP being fully implemented and operating at steady-state, observation-based estimates of mean hourly averages, 90^{th}, or 99^{th} percentile and short-term (5-minute) peak SO_2 concentrations that exceed the modelled levels by more than 25%. Given that the modelling data are expected to be somewhat conservative, it is not expected that the modelled data would underestimate by as much as 25%. The more intensive studies would be to attempt to understand the discrepancy between the modelled concentrations and the actual observations to determine what model predictions may need to be reconsidered.
   - Trigger for implementing mitigation actions:
     - Due to the continuous nature of the dose-response relationship, there is no natural threshold or trigger for determining an elevated level of concern.

Mitigation options that relate to public advisories can be based on sustained (or a prediction of sustained) high levels of SO_2.

4. Mitigation options:
   - Meteorological forecasts of conditions associated with sustained high levels of SO_2 could be used to provide public advisories of elevated SO_2 with a corresponding health message associated with reduced intensity of exercise and staying indoors for those with chronic respiratory conditions. This is consistent with the advice given for other pollutants in other jurisdictions and could also be applied to those which are similarly monitored at Kitimat (such as particulate matter).
   - After several years of observations, if possible, established patterns of elevated SO_2 (times of day, months of year, meteorological conditions) could be used as part of educational materials to provide ongoing advice to manage restricted airway responses to SO_2 through avoidance of known or expected peak periods (e.g., a parent managing a child's asthma and wanting to schedule daily outdoor activities, elder caregivers scheduling activities, etc.).

HH2: *What is the peak-to-mean relationship for shorter duration exposures?*

1. Monitoring data required to answer HH2:
   - What performance measures are essential?
     - Continuous analyser measurements of SO_2 air concentrations (see A1), from which actual peak-to-mean ratios can be calculated.
   - Why?
     - Higher peak-to-mean ratio values lead to a higher probability of respiratory response. The model made assumptions based on pre-KMP operations that have the potential to underestimate the peak-to-mean relationship.
   - Where (what are the essential sampling locations)?
     - This calculation to be done for all monitors in residential and commercial areas, with the calculations to be reviewed annually.
   - When (at what sampling duration and frequency, and essential years and times)?
     - Monitoring data will be available to provide for much improved estimation of the peak-to-mean relationships, as well as direct observations of short averaging periods (such as 5 minute or 10 minute averages). The monitoring data for all residential or business area monitoring locations should be reviewed after 1 full year of steady state operations, and again after 3 full years of steady-state operations. Given continuous monitoring, the peak-to-

mean extrapolation can be replaced by direct observation of short averaging time exposures for areas sufficiently proximal to the residential monitors. This would allow for the risk assessment to be recomputed using direct observation of short averaging time exposures to determine if the overall risk estimates were sufficiently conservative.

- How (using what monitoring protocols and sampling methods)?
  - Calculating the ratio of the highest 5-minute average peak concentration within each hour to the corresponding hourly average concentration and determining if the distribution of peak-to-mean results is markedly different than what was assumed in the model.
- What are the risks of not collecting these data?
  - There will be no way of knowing the actual peak-to-mean ratios and thereby the actual risks of respiratory response.

2. How and when monitoring data will be evaluated to address HH2:
   - Calculated hourly from continuous sampling data using the method described in Section 8.3.1, and reviewed annually.
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
     - This uncertainty will be reduced completely at monitoring sites. Some relatively minor uncertainty will remain in extrapolating these results to other residential locations. Relative to current uncertainty (extrapolating from Haul Road site based on pre-KMP operations), the uncertainty will almost certainly be significantly reduced.

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - The mean or the 95^{th} percentile of the peak-to-mean ratio is more than 100% higher than the relationship assumed in the risk assessment.
   - Trigger for implementing mitigation actions:
     - In the post-KMP environment, consideration of human health risk should be driven primarily by directly relevant continuously monitored SO_2 observational data rather than the current risk assessment that is based on modelled concentrations and extrapolations from hourly averages to short term peaks. Any mitigation options to be considered by appropriate authorities would be best informed by an updated human health risk

assessment based on observational data. This risk assessment could be completed after 1 full year of observational data becomes available, and would be an appropriate update to the human health risk assessment, even without a specific trigger.

4. Mitigation options:
   - As for HH1.

10.3.4.4 Reducing uncertainty regarding impacts on vegetation

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

1. Monitoring data required to answer V1:
   - Please refer to the information for uncertainty A1.

2. How and when monitoring data will be evaluated to address V1:
   - Please refer to the information for uncertainty A1.

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - SO_2 concentrations are 50% higher (or more) than expected, in which case the uncertainty regarding vegetation response would warrant an increase in the frequency of inspection to detect direct effects (i.e., more than once every 2 years and more than once per growing season – up to 3 times per growing season depending on the actual concentrations).
   - Trigger for implementing mitigation actions:
     - Widespread injury to plants in the Kitimat area.

4. Mitigation options:
   - Emissions reduction (refer to Section 10.3.5).

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

1. Monitoring data required to answer V2:
   - What performance measures are essential?
     - Visual evaluation and documentation of symptoms of stress (including acute and chronic SO_2 injury, acidic deposition injury, insect feeding, plant diseases, and other environmental stresses).

- Why?
  - Plants respond to stresses with characteristic and diagnostic symptoms and signs.
- Where (what are the essential sampling locations)?
  - Locations where critical loads in soils are predicted to be exceeded.
- When (at what sampling duration and frequency, and essential years and times)?
  - Visual inspection and evaluation should occur every other year, near the end of the growing season (late August to early September).
- How (using what monitoring protocols and sampling methods)?
  - According to protocols documented in Laurence (2010).
- What are the risks of not collecting these data?
  - There will be no information on the health of vegetation in areas where expected deposition exceeds a critical load and effects on vegetation through soil acidification might occur.

2. How and when monitoring data will be evaluated to address V2:
   - Data from 2014, 2016 and 2018 will be used to determine whether the health of vegetation is significantly affected compared to the condition at locations remote to KMP.
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
     - High confidence level.

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - Symptoms of acute or chronic effects of SO_2 or acidification on vegetation.
   - Trigger for implementing mitigation actions:
     - Widespread visible injury on multiple species at distances further than the service centre or on the east side of Minette Bay.

4. Mitigation options:
   - Emissions reduction (refer to Section 10.3.5).

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

Please refer to the information provided for V2. V3 will be addressed by assuring that plants of public importance are included in the inspections proposed under V2.

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

1. Monitoring data required to answer V4:
   - What performance measures are essential?
     - Symptoms characteristic of SO_2 or acidic deposition, including acidic mists or fog.
   - Why?
     - While there is substantial literature concerning the sensitivity of plant species to SO_2 or acidic deposition, the sensitivity of most plant species in the Kitimat area is not documented in the scientific literature. However, there is good reason to believe that those species will respond in a characteristic manner, even though the species' sensitivities have not been established under controlled conditions.
   - Where (what are the essential sampling locations)?
     - Locations described in Laurence (2010) and areas of predicted soil critical load exceedance.
   - When (at what sampling duration and frequency, and essential years and times)?
     - Visual inspection every other year in late August or early September.
   - How (using what monitoring protocols and sampling methods)?
     - According to protocols described in Lawrence (2010).
   - What are the risks of not collecting these data?
     - RTA will not be able to document the health of vegetation in the vicinity of Kitimat.

2. How and when monitoring data will be evaluated to address V4:
   - Data from 2014 to 2018 will be used to establish whether there are plant species in the vicinity of KMP that are more sensitive than those that have been used to establish air quality standards in North America and Europe.
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
     - High confidence level.

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - Unexpected symptoms on plants in the vicinity of KMP.
   - Trigger for implementing mitigation actions:

- Widespread visible injury on multiple species at distances further than the service centre or on the east side of Minette Bay.

4. Mitigation options:
   - Emissions reduction (refer to Section 10.3.5).

10.3.4.5 Reducing uncertainty regarding impacts on soils

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

1. Monitoring data required to answer S1:
   - What performance measures are essential?
     - Additional soil sampling and analysis of the two most critical bedrock categories, and the orthogneiss metamorphic bedrock category in the unsampled southern portion of the study domain (maximum 10–15 samples divided equally between the bedrock categories) to expand the weathering estimates for these rock types. Three locations associated with: (1) quartz diorite bedrock south of Lakelse Lake, spatially co-located with lakes that had very low base cation concentrations (highest priority); (2) calc-alkaline bedrock near the smelter to support current weathering estimates that were based on extrapolation from other sites (lower priority as unlikely to change conclusion of high exceedance; however this is the only region showing exceedance as such site estimates are warranted); and (3) orthogneiss metamorphic bedrock in the unsampled southern portion of the study domain consistent with the region receiving high modelled S deposition (southwestern study domain).
   - Why?
     - Within the current study domain, there were areas identified as: (1) potentially vulnerable (critical loads are exceeded); (2) soils not sampled during the initial survey that were in areas with low base cation concentration lakes; or (3) regions that were not considered during the initial site selection. As such, there is uncertainty in the estimated base cation weathering rates for these regions.
   - Where (what are the essential sampling locations)?
     - Sites to be determined in consultation with MOE and RTA.

- When (at what sampling duration and frequency, and essential years and times)?
  - Sampling to be conducted during the summer of 2014 in a single field campaign. Sampling may also be carried out to take advantage of synergies with water sampling.
- How (using what monitoring protocols and sampling methods)?
  - All field measurements to follow the 2012 protocol described in Section 8.5.2 (with maximum of five soil pits per supplemental study region sampled from three fixed depths: 0 to 10 cm; 15 to 25 cm, and 40 to 50 cm). Samples from each pit to be combined into one composite sample for each depth.
  - Laboratory analyses for pH, loss-on-ignition (LOI), particle size (sand, silt and clay), moisture content, bulk density.
  - Composite soil samples for each site to be analysed for major oxides, and subset analysed for qualitative mineralogy.
- What are the risks of not collecting these data?
  - Uncertainty in base cation weathering rates and hence critical loads in these potentially vulnerable areas will remain.

2. How and when monitoring data will be evaluated to address S1:
   - Data collected in 2014 will be used to estimate weathering rates for the new sample sites and revise the regional critical load and exceedance maps. The new weathering map may be revised to incorporate information on surficial geology if digitally available, and if deemed more appropriate.
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
     - High confidence level.

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - Sites in vulnerable areas have low critical loads and have S deposition that exceeds the critical load.
   - Trigger for implementing mitigation actions:
     - Based on the assessment framework for soils in Section 8.5; i.e., if there is an increase (to unacceptable level) in the forest area predicted to receive S deposition in excess of the critical load.

4. Mitigation options:
   - Reduced emissions, liming (refer to Section 10.3.5).

S2: *What is the current buffering capacity (base cation pool) of the soils in exceeded areas?*

1. Monitoring data required to answer S2:
   - What performance measures are essential?
     - Laboratory analyses for exchangeable calcium, magnesium, potassium and sodium on soil samples collected from vulnerable or exceeded areas in 2012 and in 2014.
   - Why?
     - The steady state critical load models do not provide an indication as to when the critical chemical level in soil solution will be reached in exceeded areas. Analysis of pool size will provide an estimate of time to potential impacts.
   - Where (what are the essential sampling locations)?
     - Use soil samples from exceeded or vulnerable (low weathering rate) areas.
   - When (at what sampling duration and frequency, and essential years and times)?
     - Base cation pools could be estimated in 2013 for soil samples already in hand, or in 2014 when supplemental soil samples are available (as described under S1).
   - How (using what monitoring protocols and sampling methods)?
     - Archive soil samples (all three layers from the relevant site composite samples) analysis for exchangeable cacium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), sodium (Na^{+}) and aluminum (Al^{3+}) using an unbuffered ammonium chloride extraction (soil samples and extraction solution are skaken for 2 hours and filtered), using flame atomic adsorption spectrometry or inductively coupled plasma optical emission spectrometry.
   - What are the risks of not collecting these data?
     - Potential mitigation actions will occur in areas that will not acidify to the critical level during lifespan of KMP operation.

2. How and when monitoring data will be evaluated to address S2:
   - Soil data will be used to measure calcium, magnesium, potassium and sodium pools in soils. Modelled exceedance levels will be used to calculate net loss of base cations and the time taken for base cation pools to deplete to critical levels.
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:

- High confidence level.

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - Base cation pools in soils from exceeded or vulnerable areas are low and impacts are expected in the near-term.
   - Trigger for implementing mitigation actions:
     - Based on the assessment framework for soils in Section 8.5; i.e., if the forest areas predicted to receive S deposition in excess of the critical load have low base cation pools and will be depleted in the near-term.

4. Mitigation options:
   - Reduced emissions, liming (refer to Section 10.3.5).

S3: ***What are the base cation deposition values in the study region?***

1. Monitoring data required to answer S3:
   - What performance measures are essential?
     - Monitoring of base cation deposition within the Kitimat Valley; the NADP site at Haul Road and proposed site at Lakelse Lake will provide data to evaluate regional base cation deposition. Regional observations may be supplemented with exisiting observations from western North American networks, and regional maps of rainfall volume.
   - Why?
     - The current implementation of critical load models does not include base cation deposition, as such they are conservative.
   - Where (what are the essential sampling locations)?
     - Haul Road and Lakelse Lake, noting that Lakelse Lake provides the most relevant data to define background base cation precipitation chemistry.
   - When (at what sampling duration and frequency, and essential years and times)?
     - Establishment and continued monitoring at two NADP stations providing data for 3+ years to evaluate background base cation deposition. In this respect, Lakelse Lake provides the most valuable data.
   - How (using what monitoring protocols and sampling methods)?
     - Wet deposition monitoring to be carried out by the NADP following standard NADP network protocols for sample collection, handling and analysis

(http://nadp.sws.uiuc.edu). The analysis of wet deposition samples to include calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and sodium (Na^{+}).

- What are the risks of not collecting these data?
  - Current estimates of critical load may be overly conservative as they do not include base cation deposition.

2. How and when monitoring data will be evaluated to address S3:
   - Base cation precipitation chemistry maps will be used to revise regional critical load and exceedance maps to incorporate base cation deposition.
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
     - High confidence level.

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - Revised regional critical loads still show exceedance following incorporation of base cation deposition.
   - Trigger for implementing mitigation actions:
     - Based on the assessment framework for soils in Section 8.5; i.e., mineral forest soils are predicted to receive S deposition in excess of the critical load (following incorporation of base cation deposition).

4. Mitigation options:
   - Reduced emissions, liming (refer to Section 10.3.5).

10.3.4.6 Reducing uncertainty regarding impacts on lakes and streams

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

1. Monitoring data required to answer W1:
   - What performance measures are essential?
     - S deposition monitoring – please refer to D1 in Section 10.3.4.2.
     - Base cation deposition monitoring – please refer to S3 in Section 10.3.4.5.
     - Major cations ([Ca^{2+}], [Mg^{2+}], [Na^{+}], [K^{+}], [NH_4^{+}], [H^{+}], dissolved Al) and acidic anions ([SO_4^{2-}], [NO_3^{-}], [A^{-}], ANC, DOC) from field samples – this is a subset of the parameters described under W2.

- Why?
  - The SSWC model is most strongly affected by current base cation concentrations and sulphate deposition, whereas the modified ESSA/DFO model is driven by current ANC, the estimated F-factor (Δ base cations / Δ SO_4), and sulphate deposition.
- Where (what are the essential sampling locations)?
  - Lakes where the models show that deposition is expected to exceed, or be very close to, critical loads, and lakes with predicted pH change greater than 0.10 pH units (10 lakes altogether).
  - Kitimat River.
- When (at what sampling duration and frequency, and essential years and times)?
  - Lakes: as described for D1, S3 and W2.
  - Kitimat River: monthly water sampling, for two years after KMP startup; then revisit sampling frequency based on observed changes (i.e., does it appear to have reached a steady state?).
- How (using what monitoring protocols and sampling methods)?
  - As described for D1, S3 and W2.
- What are the risks of not collecting these data?
  - The risk assessment is based on the extent, magnitude and likelihood of critical load exceedance. The sensitivity analysis showed that even a doubling of acidic deposition would not increase the number of vulnerable lakes beyond the 10 lakes identified as vulnerable. So, the risk is not so much that some vulnerable lakes may not be flagged as potentially at risk (though this is possible if deposition patterns are very different from those predicted), but rather that the magnitude of pH change in the identified vulnerable lakes will be under- or over-estimated due to uncertainties in the F-factor values.

2. How and when monitoring data will be evaluated to address W1:
   - The acidification models will be re-run annually in 2017 and 2018 with the latest input parameters from the sampling described under D1, S3 and W2. (A few years of data are needed in order to estimate the F-factor.)
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
     - High confidence level.

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - If results of the deposition monitoring suggest that there is a greater extent and/or magnitude of exceedance than predicted (unlikely, but possible) then it may be necessary to sample some additional lakes.
   - Trigger for implementing mitigation actions:
     - Not applicable for W1 (see W2, W3 and W4).

4. Mitigation options:
   - Reduced emissions, liming (refer to Section 10.3.5).

W2: ***How many of the 7 to 10 potentially vulnerable lakes <u>actually</u> acidify under KMP, and to what extent?***

1. Monitoring data required to answer W2:
   - What performance measures are essential?
     - Lab analyses of major anions ($[Cl^-]$, $[F^-]$, $[NO_3^-]$, $[HCO_3^-]$*, $[CO_3^{2-}]$*, $[SO_4^{2-}]$, $[OH^-]$*, DOC, Total Alkalinity, Gran ANC), major cations ($[Ca^{2+}]$, $[Mg^{2+}]$, $[Na^+]$, $[K^+]$, $[NH_4^+]$, $[H^+]$, dissolved Al)[25].
     - Field measurements of temperature, dissolved oxygen, total dissolved solids, pH.
     - Mean depth (done once by taking depth measurements from the helicopter along a transect).
   - Why?
     - The above-indicated ions are needed to assess the form, rate and magnitude of changes in lake chemistry in 10 sensitive lakes, estimate a key SSWC model parameter (F-factor = Δ base cations / Δ SO_4), compare deposition-predicted change in SO_4 vs observed change (an additional way to test D1), confirm QA/QC of water samples by examining charge balance.
     - Ion exchange processes in the watershed can exchange H^+ for other cations such as Ca, Mg, Na, K, Al.
     - Dissolved Al is an indicator of toxicity of water to fish.
     - Field measurements are helpful for QA/QC (e.g., very low oxygen might explain pH shifts).

[25] Ions with * are calculated from other measurements.

- Mean depth helpful for estimating water residence time in lakes (i.e., (mean depth × lake area) / (watershed area × model-based runoff), and how quickly lakes will equilibrate to new deposition level. Also can be used as index of fish production (TDS / mean depth).

- Where (what are the essential sampling locations)?
  - Essential locations: the 10 vulnerable lakes shown to either have CL exceedance or predicted pH Δ > 0.10. These include: Lake 006 (End Lake), Lake 023 (West Lake), Lake 028, Lake 042, Lake 044, Lake 047, Lake 054, Lake 056, Lake 012, Lake 022.
- When (at what sampling duration and frequency, and essential years and times)?
  - To understand chronic or long term acidification, sample 10 vulnerable lakes annually during 2014 to 2018 during the same seasonal timeframe as in 2012 (i.e., mid-August) to track any increase in sulphate and changes in other ions as KMP ramps up, and be able to demonstrate leveling-off to steady state; minimum emissions likely to occur in the early part of 2014.
  - Depending on ramp-up rate, it may be appropriate to change to sampling every 3 years after 2018.
  - To understand episodic acidification, sample the 5 accessible, vulnerable lakes during both snowmelt and fall storm events to see if acidic episodes occur and their frequency, magnitude and duration (would be worthwhile doing this before full ramp-up of KMP to have a solid baseline). Also perform intensive monitoring of one stream near KMP to assess frequency, magnitude and duration of acidic episodes (e.g., Anderson Creek).
  - Reconnaissance of lakes for episode sampling should occur in 2013 (W3 & W4); look for subset of lakes (and one stream) with easy access for frequent monitoring.
- How (using what monitoring protocols and sampling methods)?
  - Essential methods: the same as in 2012 for the above-listed parameters.
- What are the risks of not collecting these data?
  - There would be no way to assess model predictions and actual rate of acidification.
  - We would not understand the frequency and magnitude of acidic episodes.

2. How and when monitoring data will be evaluated to address W2:
   - Data from 2014 to 2018 will be used to:
     - Estimate expected time to steady state for SO_4 based on residence time.

- Examine actual ΔSO_4, ANC and pH for all lakes over time relative to steady state predictions of exceedance from SSWC, predicted ANC and pH change at steady state from the ESSA/DFO model, and expected lake [SO_4] from CALPUFF post-KMP predictions of SO_4 deposition / model-based runoff estimates.
- Estimate F-factor from Δ base cations / ΔSO_4 and compare to the assumed F-factor.
- Refine estimates of magnitude of acidification for these lakes.
- Assess frequency, magnitude and duration of acidic episodes relative to baseline period and toxicity thresholds for biota.

▪ Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
- High confidence level.

3. Proposed decision rules for alternative actions:
   ▪ Early warning threshold for triggering more intensive studies:
     - If Δ pH ≥0.30, then consider re-sampling the fish community (if this can be done safely) as per W4.
   ▪ Trigger for implementing mitigation actions:
     - If a lake's production of fish and fish food is considered to be important to public (see W3) *and* significant change in pH and fish density has been observed (see W4) *and* liming is feasible given access.

4. Mitigation options:
   ▪ Reduced emissions, liming (refer to Section 10.3.5).

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

1. Monitoring data required to answer W3:
   ▪ What performance measures are essential?
     - Baseline conditions of fish communities: catch per unit effort estimates of fish densities using gill nets; presence/abundance of fish species; benthic invertebrate community structure in either inlet or outlet streams.

- Why?
  - We need a baseline description of the aquatic biota both to understand their importance to fishers, and to provide a comparison for later evaluations (if required) under W4.
- Where (what are the essential sampling locations)?
  - In safely accessible lakes, which is likely to include Lakes 023 (West Lake), 006 (End Lake), 012, 042 and 044, to be confirmed by reconnaissance.
- When (at what sampling duration and frequency, and essential years and times)?
  - In late summer of 2013, prior to KMP start-up, coincident with water sampling.
- How (using what monitoring protocols and sampling methods)?
  - Gill net sampling for fish; CABIN protocol for benthos.
- What are the risks of not collecting these data?
  - Not knowing the fish communities within each lake would make it difficult to prioritize both monitoring and mitigation.
  - Not having a baseline would make it impossible to assess biological changes due to KMP.
  - Not having benthos data would make it impossible to assess the cumulative effects of acidic episodes.

2. How and when monitoring data will be evaluated to address W3:
   - Data from 2013 or 2014 will be used to clarify for the public the fish communities present in each of the vulnerable lakes, and classify the health of both the fish and benthic communities.
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
     - High confidence level for sampled lakes.
     - Low confidence for lakes that cannot be safely sampled (determination made by other factors including accessibility by fish, chemical and physical indicators of lake productivity).

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - Not applicable.
   - Trigger for implementing mitigation actions:
     - Please refer to the triggers for W2.

4. Mitigation options:
   - Reduced emissions, liming (refer to Section 10.3.5).

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

1. Monitoring data required to answer W4:
   - What performance measures are essential?
     - As per W3.
   - Why?
     - As per W3.
   - Where (what are the essential sampling locations)?
     - As per W3.
   - When (at what sampling duration and frequency, and essential years and times)?
     - If the W2 trigger occurs (>0.30 pH unit decline), then sample during the same late summer sampling period.
   - How (using what monitoring protocols and sampling methods)?
     - As per W3.
   - What are the risks of not collecting these data?
     - Not knowing what the actual impacts are on fish; mitigating unnecessarily.

2. How and when monitoring data will be evaluated to address W4:
   - Compare fish and benthic measurements against the baseline to see how much change has occurred, and determine the advisability of mitigation.
   - Level of confidence that these data and analyses will sufficiently reduce this uncertainty:
     - Moderate, due to natural year-to-year and spatial variability in biological data (i.e., changes will have to be large to be statistically significant).

3. Proposed decision rules for alternative actions:
   - Early warning threshold for triggering more intensive studies:
     - If there is a more intensive study triggered in W2 by a pH change greater than 0.30.
   - Trigger for implementing mitigation actions:
     - As per the mitigation trigger for W2.

4. Mitigation options:
    - Reduced emissions, liming (refer to Section 10.3.5).

10.3.5 RTA mitigation response for unacceptable impacts

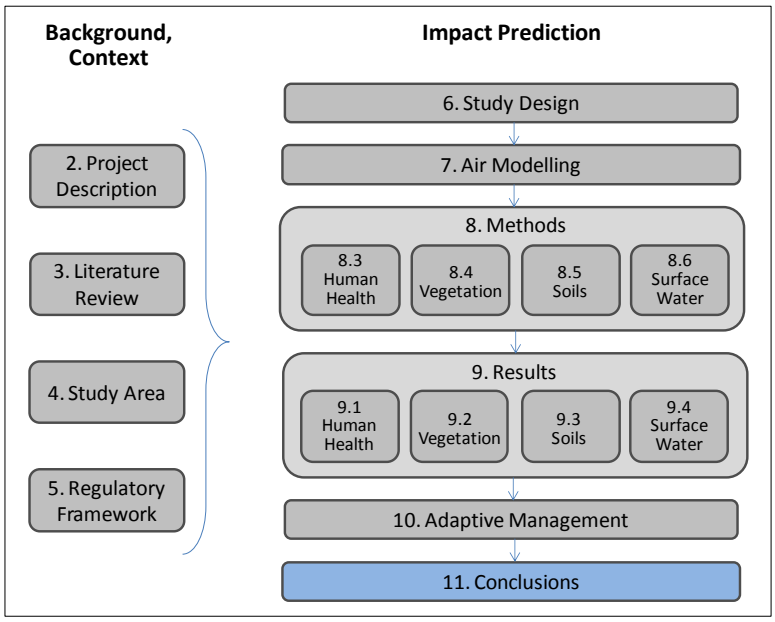
RTA will be developing and implementing the following SO_2 mitigation strategies if, once the smelter is commissioned and operating at steady state, the outcomes of monitoring for ambient air, vegetation, water and soil show adverse impacts related to SO_2 that are considered to be unacceptable.

- In the event of occasional SO_2 concentration levels contributing to restricted airway events for sensitive people, a KMP Episode Management Plan will be activated and air quality advisories will be released. This will be done with appropriate health messaging, to be developed collaboratively with the Northern Health Authority and others, recommending that under adverse atmospheric conditions people vulnerable to restricted airway events do not partake in outdoor activities.
- If the impacts on vegetation, water or soil are of sufficient extent and magnitude to be considered unacceptable given provincial and national standards, then RTA will meet with the Ministry of Environment to consider alternative mitigation strategies, including the following potential actions:
    - If pH changes in a few lakes are of sufficient magnitude to potentially affect fish populations (≥0.30 pH units), RTA could develop and implement a process to modify the lake chemistry to compensate for the acidification created by KMP SO_2 emissions. One of the options used to mitigate acidic conditions in surface water is the addition of alkaline materials like limestone (calcium carbonate). Depending on lake access, safety and other environmental considerations, liming could be done on the whole lake, its running water or on its watershed using a boat, truck or helicopter (Olem 1990).
    - RTA could decrease smelter SO_2 emissions sufficiently to reduce SO_2 concentration and/or S deposition at sensitive receptor locations to a level which would allow for acceptable impacts, given provincial and national standards. There are three main sources of SO_2 emissions from the smelter: the coke calciner, the anode bake furnace, and the treatment centres for potroom gases. There are two primary options to control SO_2 emissions:
        - First, lower sulphur coke could be used, with the market challenges previously described in Section 2.8.2.
        - Second, an SO_2 scrubbing system could be installed. Different technologies can be applied depending on the source to be treated (Strømmen et al. 2000). The few commercially available scrubber technologies include wet scrubbing and dry scrubbing. Wet scrubbing includes seawater scrubbing or alkali slurry scrubbing, which can be

applied to all emission sources. The liquid effluent containing sulphate would be discharged directly into the ocean. The dry scrubbing technologies are commercially available for the coke calciner flue gas (Brown et al. 1991), but there is no such technology developed to treat the SO_2 from potroom gases. Dry scrubbing uses a dry alkali reactant and generates a by-product which has to be deposited in a landfill site.

- These technologies require significant capital investment and operational costs. A saltwater scrubber may not be possible or feasible in Kitimat due to the ocean water being brackish. A dry scrubber would generate a significant quantity of wastes that would need to be shipped offsite for landfilling.

11.0 Conclusions



In this report, we have used a structured and transparent risk assessment framework with two dimensions: the probability or likelihood of an impact, and the consequence of such an impact. We applied this framework to converge on one of four possible impact categories for each receptor:

Low	No impact or acceptable impact; routine monitoring
Moderate	Acceptable impact but in need of closer scrutiny; moderate monitoring
High	Unacceptable impact; contingency/response action; intensive monitoring
Critical	Extremely unacceptable impact; critical response action; very intensive monitoring

11.1 DISPERSION MODELLING

The estimates of impacts on humans, vegetation, soils and water were driven by predictions of concentrations of SO_2 and deposition of S from a recognized atmospheric dispersion model (CALPUFF), following protocols developed and agreed with the B.C. Ministry of Environment, and iterative improvements in both the input data and assumptions. CALPUFF simulated both pre-KMP and post-KMP conditions, identifying worst-case results in order to ensure the project will not result in exceedances of air quality requirements or detrimental impacts to human health or the environment. Pre-KMP predictions of [SO_2] averaged more than twice observed [SO_2], confirming the conservative nature of the CALPUFF model.

Comparisons to the B.C. PCOs do not provide conclusions related to impacts on the environment or human health, and are not classified according to the risk assessment framework. These comparisons are nevertheless of regulatory interest. The modelling analysis predicts that the maximum number of offsite exceedances will decrease as a result of KMP, from 254 to 53 for the 1-hour PCO minimum and from 45 to 7 for the 1-hour PCO maximum. Conversely, the model predicts that the number of exceedances in residential areas will increase as a result of the project, from 14 to 30 for the 1-hour PCO minimum and from 1 to 3 for the 1-hour PCO maximum.

11.2 HUMAN HEALTH

We assessed potential health risks associated with SO_2 releases in Kitimat on the basis of a short-term concentration-response relationship developed by the U.S. EPA for peak 5-minute exposures and lung function changes in exercising individuals with asthma or chronic obstructive pulmonary disease (COPD). We performed the calculations using the log-logistic concentration response curve, which is the more conservative of two approaches used by the U.S. EPA. (i.e., more likely to overestimate rather than underestimate health risk). We converted atmospheric CALPUFF predictions of 1-hour averaged outdoor SO_2 concentrations under KMP into 5-minute peak concentrations using a peak-to-mean ratio based on Kitimat air monitoring stations. We then converted outdoor 5-minute peak concentrations to indoor concentrations based on ratios determined in studies completed in Alberta. We used 10,000 as the total population of the Kitimat area, and based on community health data, we estimated that there were 1,200 susceptible individuals in Kitimat with either asthma or COPD.

Results. Under a conservative baseline scenario, SO_2 exposures post-KMP could cause between 150 and 200 restricted airway responses per year among physically active susceptible individuals with asthma and/or chronic obstructive pulmonary disease. When exploring various alternate assumptions associated with patterns of exercise frequency and location, the number of predicted airway responses falls within a range from 50 to 500. The net effect of the various conservative assumptions is to generate an estimate of risk that is likely to be somewhat higher than the actual risk.

The predicted levels of SO_2 in the Kitimat area are well below the B.C. Ministry of Environment PCOs, with the exception of less than 100 hours per year. It is important to note that these PCOs do not correspond to thresholds for health effects. The predicted numbers of exceedances of PCOs are not an indication of the number of predicted respiratory responses. The full distribution of SO_2 exposures must be taken into account to predict health risk.

Restricted airway responses are reversible, common among the susceptible individuals and can be caused by exposures other than SO_2 (allergens, cold temperatures, physical exercise). They would generally be treated by reducing the level of physical activity, relocating indoors (where SO_2 levels should be lower) and through use of medication either before exercise or after symptoms are detected.

Conclusions. We conclude that people with either asthma or chronic obstructive pulmonary disease (about 12% of the population) are likely to be *infrequently* affected by *medium* consequence, reversible events. The remainder of the population (88%) in the study area is expected to be *unaffected* by increased SO_2 emissions under KMP.

The increase in specific airway resistance among those affected may or may not be detectable by the susceptible individual. Given the mildness of the predicted health outcomes, the characterization of the consequence as medium could be considered somewhat conservative. The increase in the number of restricted airway events due to SO_2 in this population is expected to be less than 1%. Exposure to SO_2 causing restricted airway responses will result in a continuum of potential health consequences ranging from very mild to serious (e.g., emergency room visits); however, increasingly severe health outcomes are also increasingly infrequent. The overall health impact is characterized as **moderate** (yellow) – acceptable but in need of closer scrutiny with moderate monitoring.

Critical uncertainties. The two critical uncertainties in the assessment are: (1) uncertainty with respect to the predicted levels and spatial and temporal patterns of SO_2 concentrations that will occur in the post-KMP situation (also important for vegetation, soil and water assessments); and (2) uncertainty in the relationship between the peak exposures and the hourly average exposures.

11.3 VEGETATION

Our review of 14 years of vegetation observation, collection and analysis concluded that sulphur concentrations at most sampling sites in the Kitimat valley are at or near background concentrations of 0.08 to 0.12%. At some sites near the smelter, or in the major growing season dispersion pattern, concentrations of up to 0.24% S in needles have been measured. While above reported background, these concentrations are within those reported to be normal in the scientific literature. We found that while symptoms associated with SO_2 injury to vegetation have been noted on rare occasion over these 14 years, such symptoms have not been wide-spread or severe. There are two impact pathways of interest for vegetation: (1) direct effects of [SO_2]; and (2) indirect effects on vegetation via exceedances of the critical loads of soils. We discuss each in turn.

Direct effects of [SO_2] on vegetation. We compared predicted levels of [SO_2] under KMP with concentrations and durations of exposures that have been reported to cause injury to sensitive vegetation, as well as to U.S. and Canadian regulations for the protection of vegetation. We found that the U.S. EPA National Secondary Air Quality Standard will not be exceeded and that there are only a few hours per growing season at a small number of sites when Canadian National Ambient Air Quality Guidelines and Objectives will be exceeded. There were many more hours at or above the SO_2 thresholds of concern during modelled pre-KMP conditions than are predicted to occur after KMP.

Indirect effects on vegetation via effects of sulphate deposition on soils. We discuss soils results in more detail below in Section 11.4. In summary, there was a very small area adjacent to the smelter property where soil critical loads are almost certain to be exceeded. Under worst-case assumptions for mineral weathering rates, exceedances of soil critical loads might occur in a few restricted areas on the quartz diorite bedrock geology type. Overall, there is a low risk of indirect effects on vegetation through sulphate deposition.

Conclusions. We conclude that the effects of KMP on vegetation are very unlikely and would be of minor consequence. Within the risk assessment framework, we consider the impact to be **low** (green) – an acceptable impact requiring routine monitoring.

Uncertainties. The major uncertainty associated with our conclusion is the accuracy of the dispersion modelling. If actual ground level concentrations of SO_2 are higher than predicted, then more substantial effects might be anticipated. Dispersion model predictions will be compared to observations during the adaptive management phase. However, given the past years of vegetation monitoring program results, and the fact that exposures under KMP are expected to be less than current pre-KMP conditions, it will still be unlikely that measureable and wide-spread direct effects on vegetation will occur.

11.4 SOILS

We estimated the critical load of acidity for mineral forest soils and compared these critical load estimates with modelled post-KMP acidic predicted deposition to identify areas that could potentially acidify to unacceptable levels. The approach incorporated soil base cation weathering, base cation harvesting removals (based on annual allowable cut) and an acceptable level of acid leaching that would not damage trees. Base cation deposition was not included due to the lack of data, which makes our critical load estimates conservative.

Exceedance assuming average weathering rates. Soils in the region are dominated by silicate minerals, are generally acidic and have a moderate sensitivity to acidic deposition. The areas with the lowest weathering rates and critical loads are in the southeast portion of the study area south of Kitamaat Village and at higher elevations south-west of Terrace. Under the post-KMP deposition scenario there is only a small area (0.25 to 0.41 km^2 on land mostly owned by RTA) that is predicted to receive S deposition in excess of the critical load; this area is immediately adjacent to the smelter facility and receives the greatest modelled S deposition. The level of exceedance in this area is very high, as such it is considered highly likely that soils will acidify beyond an acceptable level. However the area with exceedance of soil critical loads (0.25 to 0.41 km^2) represents 0.02% of the study area and is restricted to two of the bedrock categories. Soils in 99.98% of the study area will receive S deposition below critical loads.

Sensitivity analysis. We derived the above results using the average weathering rate for each bedrock type. We also explored the consequences of applying the lowest estimated weathering rate for each bedrock rock type rather than the average (an 'uncertainty scenario'). Under this

approach, exceedance of critical load increased to 2.19 km^2 (predominantly in the region adjacent to the facility), representing 0.1% of the study area. There was also an increase in the area receiving deposition close to critical load (6.58 km^2 with deposition 0 to 10 meq/m^2/yr less than the critical load; 0.3% of the study area). Under the uncertainty scenario, the total area with exceedance plus the area close to exceedance is far less than the 5% criterion used in critical load studies in Europe and North America (UNECE 2004).

Conclusions. Under the risk assessment framework, the risk of impact is **moderate** (yellow) – an acceptable impact but in need of closer scrutiny with moderate monitoring.

Critical uncertainties. There are three critical uncertainties to be addressed during the Adaptive Management phase:

1. Are estimates of average weathering rates by bedrock type valid for vulnerable areas (e.g., where lakes have low base cations and predicted exceedance)?
2. What is the current buffering capacity (base cation pool) of soils in exceeded areas, and when would this base cation reservoir be used up?
3. What are the base cation deposition values in the study region?

11.5 WATER

Our analysis to determine the potential impact of SO_4 deposition on lakes and streams involved 4 steps:

1. assessing how many lakes and streams are currently below pH 6, and the likely reasons for their low pH;
2. determining the critical load of deposition that each watershed could receive while maintaining a surface water pH greater than 6.0, or if its pH were already less than 6.0, to not acidify further;
3. examining how many lakes and streams would receive a level of sulphate deposition in excess of their critical load once KMP was fully implemented; and
4. predicting how much change in pH could be expected with KMP, and estimating the original, pre-industrial pH of each lake.

Current conditions. All 20 stream sites and 30 of the 41 lakes currently have a pH greater than 6.0. Of the 11 lakes with a current pH less than 6, we drew the following conclusions based on their anion content: four lakes were naturally acidified due to organic acids; five lakes show possible smelter influence in addition to natural organic acidification; one lake just north of Kitimat shows strong evidence of smelter effects; and one lake is a very acid-sensitive alpine lake with no dominant cause of acidification (pH 5.96).

Critical load estimates. With the exception of a few acid-sensitive lakes, most lakes in the Kitimat Valley (and all sampled streams) are very insensitive to acidification. We found that

with KMP fully implemented, all 20 stream sites and 32 lakes (making up 99% of the sampled lake area) are *very unlikely* to exceed their critical load. Of the remaining nine lakes in our sample, one lake is *unlikely* to exceed its critical load, two lakes would be *likely* to exceed their critical load, and six lakes are *almost certain* to exceed their critical load. The eight lakes with predicted exceedance of their critical loads make up 8.3% of the number of lakes, and 1% of the area of lakes in the study area. Three of these eight lakes are naturally acidic due to organic acids, and four others are influenced by organic acids.

Predicted pH change. All 20 stream sites, and 34 of the 41 lakes are predicted to have no significant change in pH with KMP (<0.1 pH units). Seven lakes were predicted to have pH declines greater than 0.1 unit due to KMP (ranging from 0.13 to 0.54 pH units), which are moderate pH declines that could potentially have biological effects. However, six of these seven lakes are estimated to have originally had a pre-industrial pH <6 due to organic acids. Analyses of deposition scenarios completed by Environment Canada for southeastern Canada have excluded lakes with an original, pre-industrial pH <6 (Jeffries et al. 2000). Excluding Kitimat Valley lakes with an original, pre-industrial pH <6 reduces the number of lakes with exceedance of their critical load from eight (8.3% of lakes in the study region) to two (2.1% of lakes). This is below the objective of 5% of lakes with a pH <6 set in the Canada-Wide Acid Rain Strategy.

Conclusions. Based on our analysis of both natural and KMP sources of acidification, we conclude that the impact of KMP on surface waters in the study area is **moderate** (yellow) – an acceptable impact but in need of closer scrutiny with moderate monitoring. There are likely to be no significant regional impacts on lakes or streams of high public importance, on fish production, on wildlife which depend on aquatic biota, or on human uses of water.

Critical uncertainties. We recommend careful monitoring of the chemistry of 10 lakes potentially vulnerable to acidification under KMP, baseline studies of their fish populations, and further biological studies if any of these lakes show biologically significant changes in pH (i.e., 0.30 pH units or more).

11.6 OVERALL CONCLUSIONS

Based on the results for vegetation (predicting a **low impact**), and the results of the human health, soils and water assessments (each predicting a **moderate impact**), our overall conclusion is that KMP will have a moderate impact (i.e., acceptable but in need of closer scrutiny with moderate monitoring).

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